Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

Abstracts Table of Contents

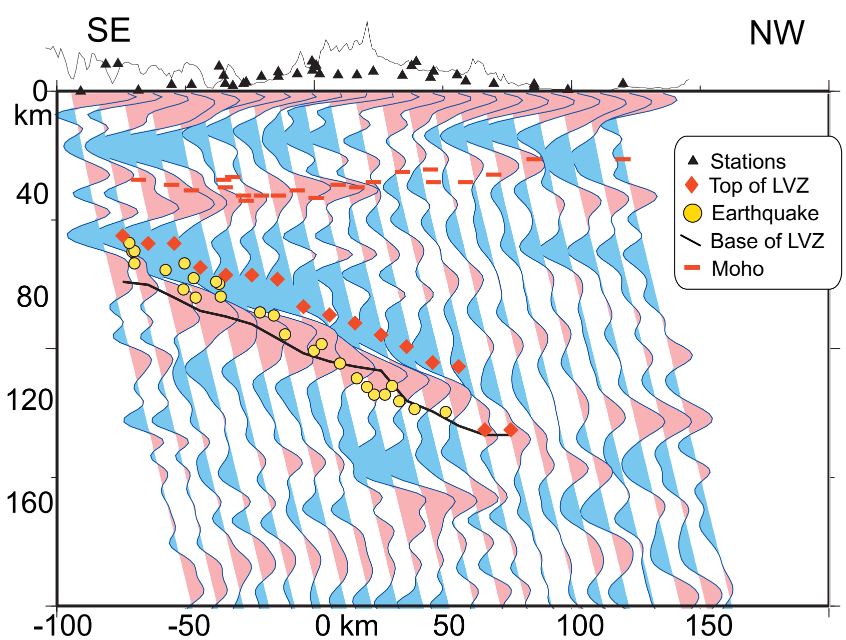
Imaging Subduction with EarthScope

Geoffrey Abers
Boston University

Subduction zones can offer the EarthScope facility with its best opportunity for spectacular images of the Earth's interior. The USArray facility is optimized for imaging the upper mantle, and upper mantle structure varies extraordinarily in subduction zones, which exhibit the largest lateral thermal (and chemical) gradients on Earth. They also provide known, ready sources of transient displacements over a wide variety of time scales accesible to PBO. The EarthScope observatory, provides a rich opportunity to compare a mature, seismically active subduction zone, Alaska, with Cascadia. Alaska and the Aleutians exhibit many of the features and range of subduction parameters that typify the process globally. The Cascadia system represents the global endmember of subduction of a young, hot plate, with little seismicity and very early dehydration of subducting crust. Recently, two sets of observations have suggested a richness in signal and a synergy between USArray components not obviously available elsewhere. High-resolution images of the teleseismic scattered wavefield over subduction zones have begun to map out the structure of subducting plates to great detail, showing that the subduction of crust can be seen to depths exceeding 100 km, and that seismicity occurs in direct association with its metamorphism. They are complemented by the recent discovery of episodic tremor and slip (ETS) episodes in Cascadia and Japan, which occur in the same parts of subduction systems.

We present results from BEAAR (Figure 1), a high-resolution broadband transect across the subducting Pacific plate in Alaska. The BEAAR array provided sampling at 10 km spacing across the Alaska range, where the Pacific plate is 60 to > 150 km deep. Images reveal a pronounced low-velocity layer atop the downgoing plate, probably subducting crust, which decreases in amplitude at 120 km depth, probably indicating the dehydration and eclogitization of the downgoing crust. Thermal modeling supports this notion. Seismic attenuation also can be imaged in the mantle wedge here, placing strong constraints on thermal models which, in turn, constrain the mechanical coupling between plates. In particular, a weak zone of localized, aseismic creep downdip from the thrust zone appears necessary to explain the thermal structure. Although episodic tremor and slip (ETS) seen elsewhere has not yet been detected here, this region of apparently aseismic, localized slip provides a good candidate site for such behavior, depending upon what causes it.

These results show that a denser, broader sampling of subduction zones in Alaska and the Pacific Northwest could easily provide significant new understanding of upper mantle dynamics. Complementary imaging and experiments designed to detect and locate ETS, in Alaska and Cascadia, could provide significant new insight into the interplay of subduction zone thermal and rheological structure, and the way in which mantle deforms.



Results from the 1999-2001 Broadband Experiment Across the Alaska Range (BEAAR) transect, showing the subducting Pacific plate. Receiver function image (Ferris et al., 2003), showing receiver functions back-projected in a 1D velocity model. Diamonds and solid line show top and bottom of subducted low-velocity crust, from waveform inversion, accounting for ray bending by dipping slab. Moho depths determined by separate inversion (Rossi, 2004). Note thick crust, probably subducting Yakutat terrane, and presence of earthquakes limited to parts of slab showing large-amplitude conversions (high velocity contrasts).

The Management of USArray Data and the EarthScope IDAS System

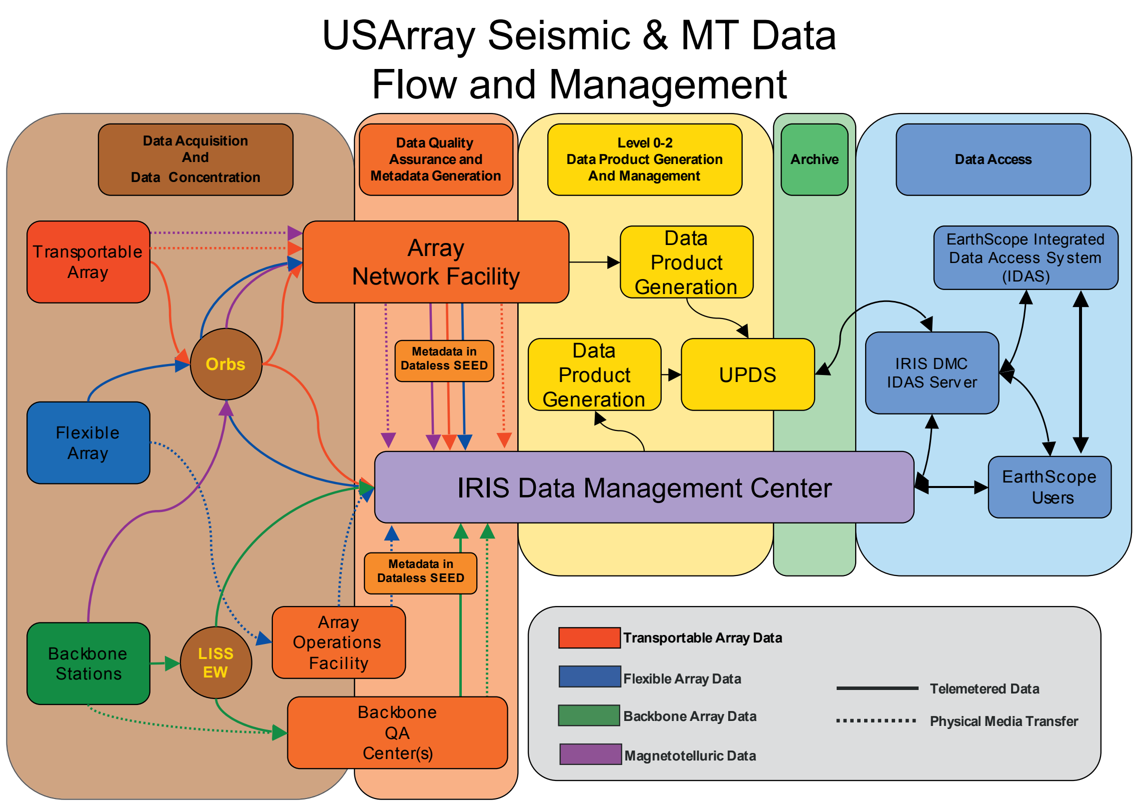
Tim Ahern
IRIS

Chad Trabant
IRIS

Linus Kamb
IRIS

The seismological component of EarthScope is USArray. USArray is the most ambitious seismological data acquisition project ever undertaken by the seismological research community. The Backbone network (BB), coordinated with the US Geological Survey, will ultimately see 100 permanent broadband continuously-recording stations in the United States. The Transportable Array (TA) will deploy 400 stations at a time totaling more than 2000 sites within the US over the next 10 years. The Flexible Array (FA) will allow individual investigators to focus on specific problems of interest. USArray will generate magnetotelluric data from some stations of the BB and TA. USArray will generate more than 65 terabytes of data over its ten years of operation. All data from USArray will be managed at the IRIS DMC.

The IRIS Data Management Center is responsible for archiving, data management, product generation, and distribution of all USArray data. This poster will summarize how the data will flow to the various nodes doing quality control on the USArray data and how the metadata will be generated and maintained. It will highlight how certain products will be produced, managed and distributed within the Uniform Product Distribution System (UPDS). Finally it will illustrate how information from the IRIS DMC will be made available through the rich suit of data access tools already at the DMC as well as through the Integrated Data Access System (IDAS) being developed as part of EarthScope.



This diagram shows the basic elements of data acquisition, data quality assurance, metadata generation, USArray data product generation, data archiving and data access being developed for USArray.

USArray Transportable Array Installations; From Concept to Practice

Mark Alvarez
IRIS

Jim Fowler
IRIS

Robert Busby
IRIS

Bruce Beaudoin
New Mexico Institute of Mining and Technology

Given that the period of operation for a typical Transportable Array (TA) in one location is less than two years, and that the number of good quality seismic events is to be maximized in order to reach our scientific objectives, efforts have been taken to construct the lowest noise broadband seismic installations possible within our budget. The advent of improved technology such as very low power instrumentation and wireless communications has greatly improved our ability to install stand-alone sites with near real-time communications within the USArray grid.

To date (February 15, 2005) eighteen new TA seismic stations have been installed in the western United States. This work is currently being accomplished by the close cooperation of the PASSCAL Instrument Center (Array Operations Center), Scripps Institute of Oceanography (Array Network Facility), private contractors and IRIS.

A typical site is composed of a plastic 1.1 meter diameter, 2.2 meter long pipe set vertically into a 1.9 cubic meter slug of concrete resting at the bottom of an excavated pit. Steps are taken to prevent water from entering vault such as the use of impermeable membranes around the bottom and top of the plastic pipe and the use of o-ring sealed tank lids. The ingredients that go into the recipe for a quite site include; good coupling to the earth, thermal stability near the sensor and avoidance of cultural noise. We have endeavored in the construction of these new installations to take into account these factors.

The broadband sensor used for TA stations is either Streckeisen STS2 or Guralp CMG 3T with a natural period of 120 seconds. The data acquisition system is a Quanterra Q330 with accompanying packet baler for onsite data backup. In most cases, data from USArray TA stations are telemetered in near real-time to the Array Network Facility at Scripps Institute of Oceanography in San Deigo. Real time communications is achieved using various methods depending on the given characteristics of a particular site. Due to the lower capital and recurring costs, cell phone internet technology (CDMA) is the preferred communication mode. Other methods used to transmit data real-time include a combination of ethernet radios, VSATS and local internet providers.

Preliminary observations of background noise levels from these new TA sites are encouraging when compared with other temporary installations and Anderson's low noise model. Major events such as the December 26, 2004 Sumatra-Andaman Islands earthquake were recorded on many of these new stations as well as other smaller teleseismic events. Examples of these are displayed in this report giving an indication of the expected detection threshold of this new continental scale broadband seismic observatory.

The Plate Boundary Observatory: Data Management Status and Plans

Greg Anderson
UNAVCO

Kathleen Hodgkinson
UNAVCO

Mike Jackson
UNAVCO

Eliot Lee
UNAVCO

Erik Persson
UNAVCO

Will Prescott
UNAVCO

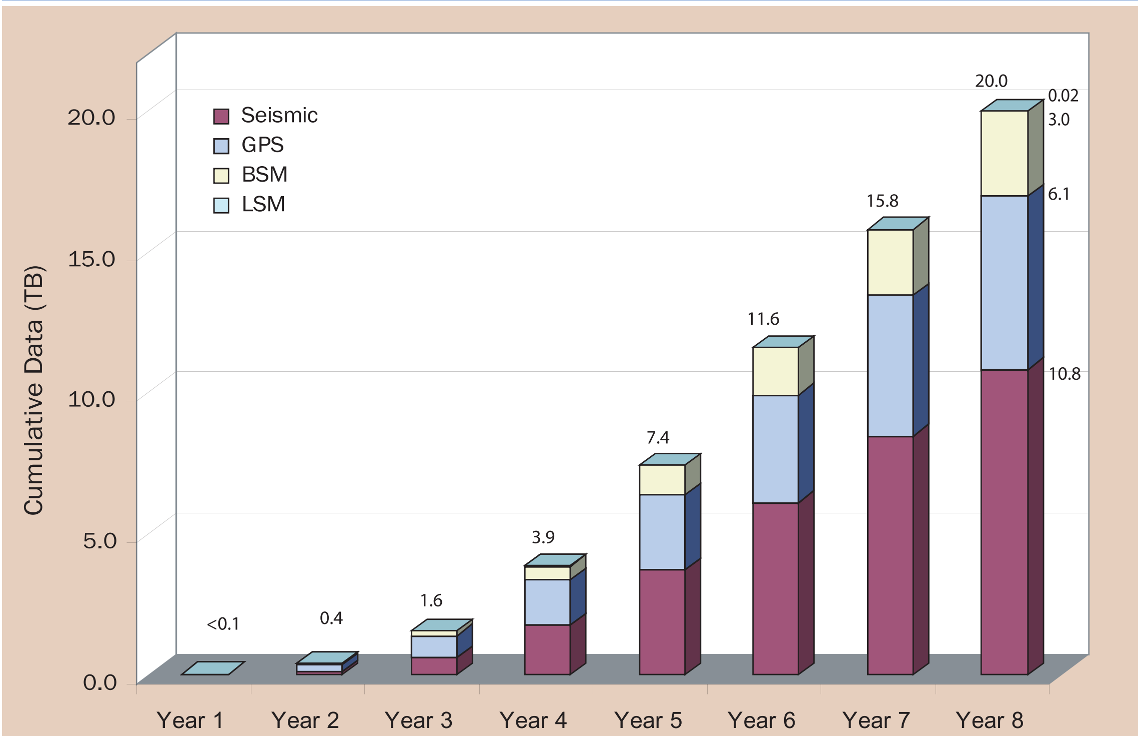
Jim Wright
UNAVCO

The Plate Boundary Observatory (PBO), part of the NSF-funded EarthScope project, is designed to study the three-dimensional strain field resulting from deformation across the active boundary zone between the Pacific and North American plates in the western United States. The science goals of PBO require that plate boundary deformation be adequately characterized over the wide range of spatial and temporal scales common to active continental tectonic processes.

PBO will meet these needs using 891 continuous GPS sites, up to 174 borehole strainmeter stations (143 of which have been prioritized by the scientific community), and five laser strainmeters, all installed over the next five years. In addition, there will be a pool of 100 portable GPS receivers available for survey-mode observations, and we anticipate incorporating 209 existing continuous GPS sites into PBO with funding under the PBO Nucleus. Currently, 91 of these stations are operating and collecting data, of which 61 are returning data automatically to the PBO data collection center in Boulder on a daily basis.

PBO GPS data will be processed by two Analysis Centers (at Central Washington University and the University of California, Berkeley) and the PBO GPS Analysis Center Coordinator (at MIT). PBO strainmeter data will be processed by the Strainmeter Data Analysis Center in Socorro, New Mexico, and PBO laser strainmeter data will be processed by the Laser Strainmeter Data Analysis Center at the University of California, San Diego. These groups will create a wide range of derived data products, including time series of strain and GPS station position, GPS velocity vectors, and strainmeter and GPS processing auxiliary information. All PBO GPS data and data products will be archived at the UNAVCO Facility and the IRIS Data Management Center; all strainmeter data products will be archived at the Northern California Earthquake Data Center and the IRIS DMC. All PBO data products will be made available to the community as rapidly and freely as possible through the PBO Archives and the EarthScope Integrated Data Access system.

PBO Cumulative Data by Data Type



InSAR Working Group Report: Education and Outreach

Jill Andrews
California Institute of Technology

The National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) jointly sponsored a workshop, titled simply "InSAR Workshop," in Oxnard, California, Oct. 20-22, 2004. The goal of this workshop was to define and codify the need for a scientific radar research program in the United States and internationally. This meeting, conceived by the InSAR Working Group, received over 350 applications from scientists, engineers, and educators around the world interested in radar, SAR, and InSAR (interferometric synthetic aperture radar). 260 members of the community attended the Workshop. The workshop's purpose was twofold: to inform the community of the state of the art in InSAR/SAR and mission opportunities, and to receive from the community an assessment of science challenges and needs for InSAR. The meeting lasted three days, and was organized around a series of discipline-oriented breakout sessions and a few informatory presentations.

A U.S. InSAR Program promises exciting new opportunities to pursue unanswered scientific questions related to Earth and space exploration. InSAR research, technologies, and data will also advance knowledge and enable efficient management of our natural resources from local to global scales. In order to achieve these goals, a comprehensive education and outreach plan is essential. The community believes in and supports fully a broad Education and Outreach (E&O) effort that operates as an integral part of a national program. Our first step should be to create an E&O working group devoted to ensuring the success of the ongoing InSAR misson. The primary charge to the E&O Working Group will be to create a strategic plan that clearly states our goals for serving the InSAR scientific community and also includes broad audience participation in InSAR-related programs outside the context of specific missions.

Our current goal is to develop a plan which will describe how we and our partners will

- Articulate a vision and mission statement for InSAR E&O
- set and prioritize E&O goals, based on the vision and mission statement
- raise public awareness of InSAR
- increase understanding of the uses and potential of InSAR
- develop partnerships
- seek funding as appropriate
- identify appropriate target audiences
    - o informal education (museums, articles, media)
    - o formal education (K-16)
    - o knowledge transfer (industry and InSAR professionals)
- evaluate the E&O effort

The broad goals of a successful E&O component include:

Awareness. We need to answer some very basic questions to raise public awareness, beginning with "Why InSAR?" What can InSAR provide that other technologies cannot? What was life like before InSAR? How will life improve with InSAR? In addition, we need to develop concrete examples linked to hooks such as "…single most valuable tool that Earth scientists can provide to world geological hazard mitigation."

- Provide examples of products for the public sector according to audience types
- Create products to publicize importance of InSAR (reports, brochures, news articles, TV/film/video production)

Understanding. Our goal to deepen understanding at all levels should result in programs that increase widespread use of InSAR in both science and industry as well as inspiring the next generation of scientists by stimulating science learning. We seek to advance public understanding of benefits of InSAR technology and uses and to promote understanding of the long term benefits of InSAR (i.e., space exploration/including Earth and beyond).

"Friend-raising" is the first step toward creating truly beneficial partnerships with sustainable results. In our outreach effort, we should aim to recruit potential collaborators in all sectors, thereby increasing potential use of research results and data output. Partnerships also may lead to increased awareness, understanding and provide pathways to finding additional resources.

Developed with strong participation by representatives from all sectors of the science, industry, education and public communities, the E&O strategic plan will support and increase use of radar imaging while also providing innovative educational opportunities intended to inspire the next generation of Earth explorers.

Characterization of Continental Mantle in an Active Rift Zone: Kilbourne Hole, New Mexico

Elizabeth Y. Anthony
University of Texas El Paso

This study reports on temperatures for three different groups of spinel peridotite from Kilbourne Hole, New Mexico. The groups are defined by a combination of texture, modal mineralogy, and chemical composition. The first group is fine-grained lherzolite with tabular, equigranular texture. Olivine and pyroxene have a strong grain shape preferred orientation (GSPO), suggesting large finite strain. The second group is protogranular to porphyroclastic lherzolite. Its chemistry is still fertile, whereas the fabric of the rock is different from the first group. For this group, recovery kept pace with deformation, impeding the development of grain shape preferred orientation. Most previous studies on Kilbourne Hole xenoliths have included only these two groups. A third group is porphyroclastic olivine-rich peridotite. Modal analyses indicate that the group includes lherzolite, dunite, and harzburgite. The xenoliths in this group are characterized by strongly porphyroclastic texture and whole-rock and mineral chemistry consistent with melt depletion. The rocks lack a grain shape preferred orientation and have amoeboid grain boundaries. These textures are consistent with grain boundary diffusion creep in olivine and suggest plastic deformation at high temperature. Temperatures for the three groups are distinct: fine-grained lherzolite has the lowest temperature (approximately 980º, calculated at approximately 2 GPa). Protogranular to porphyroclastic lherzolite has temperatures of 1020º to 1044ºC, and porphyroclastic olivine-rich peridotites have the highest temperatures (1052º to 1184ºC). The combined textural and thermometric data suggest that the sub continental mantle in the southern Rio Grande rift is both rheologically and chemically layered.

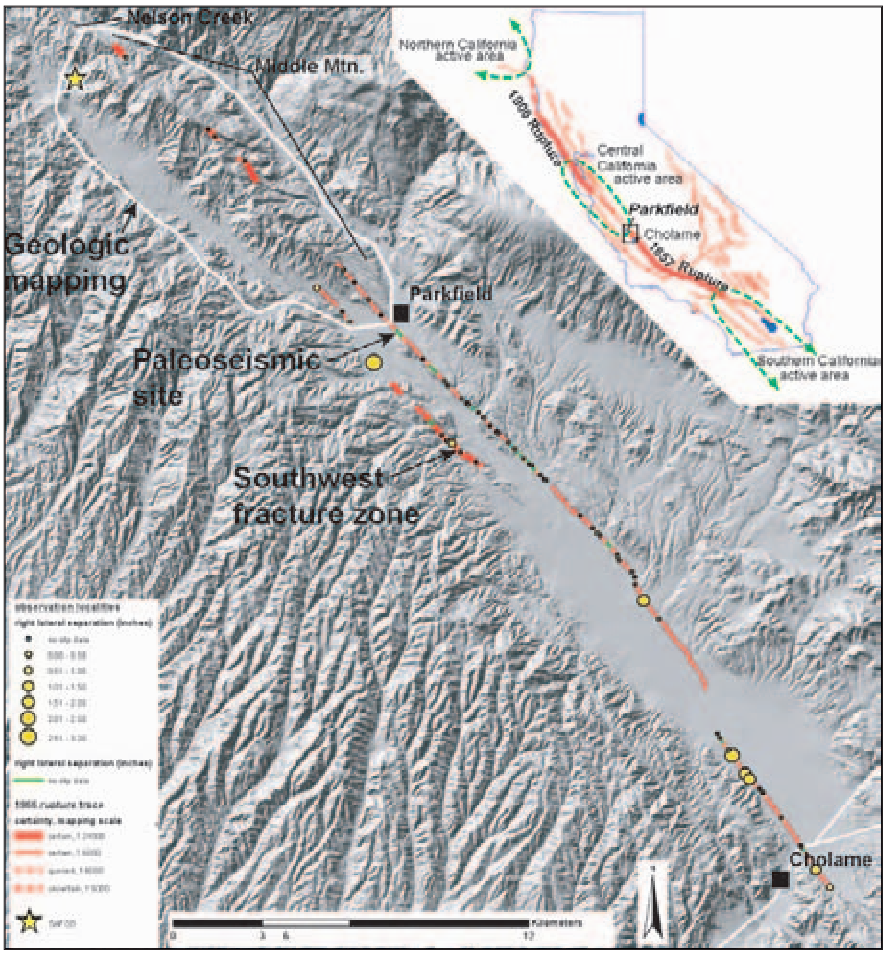
Integrated Studies of Fault Zone Structure and Earthquake Geology Along the San Andreas Fault at Parkfield

Ramon Arrowsmith
Arizona State University

Members ASU Team
Arizona State University

Michael Rymer
U.S. Geological Survey

Earthquakes are an increasing threat to societies globally because of continued urban development into earthquake-prone areas, yet our understanding of earthquake behavior is limited. Fundamental understanding of faulting requires detailed description of the geometry of rock bodies and structures and their motions within and adjacent to fault zones. We provide such an explanation for the heavily instrumented and geophysically-imaged Parkfield section of the San Andreas Fault (SAF). In addition, we are establishing the late Holocene earthquake history and assessing the relative roles of aseismic creep, moderate (i.e., 2004 Parkfield earthquake), and large earthquakes in strain release. The detailed geologic and geomorphic data sets and geometric and kinematic models are valuable for addressing the questions related to landscape development along strike-slip fault zones, the motions of blocks in the upper crust within and adjacent to strike-slip fault zones, and the material properties as defined by geologic history within and adjacent to this important fault zone. In addition, the data and inferences are essential for a complete understanding of the results from SAFOD.



Parkfield area shaded relief and major study area elements. Inset shows areas of contrasting behavior along the San Andreas Fault (SAF; modified from Allen, 1968). One of the first order features of the active SAF system is the contrast between seismically quiet and active areas (which include active fault creep in central and southern California). Parkfield is situated within an important transition zone between these two behaviors. The approximate extent of our 1:6000 geologic mapping is indicated by the white polygon. Our paleoseismic site is situated on a fluvial terrace 1 km SW of Parkfield. 1996 rupture mapping was digitized from Lienkaemper and Brown, 1985 by Chris Crosby as part of our project (Crosby, 2004) and will be compared with the 2004 earthquake slip.

Geophysical Constraints on Compositional Variations in the Continental Upper Mantle

Irina Artemieva

U.S. Geological Survey/ Copenhagen University Denmark

The study seeks to examine if geochemical constraints on global-scale compositional variations in the mantle are consistent with modern geophysical data. Compositional variations in lithospheric mantle are reflected in densities and seismic velocities as measured in laboratory studies of mantle xenoliths and should be present in global seismic tomography and gravity models. However, large-scale compositional variations in the mantle reflected in seismic tomography models and mantle gravity anomalies are substantially masked by temperature anomalies.

Thermal model for the continental upper mantle constrained by surface heat flow data (updated from Artemieva & Mooney, 2001, Fig. 1) permits to extract non-thermal signal from seismic and gravity models in order to distinguish compositional variations in the continental lithosphere. It outlines the same regions of cold thick continental lithosphere as seismic tomography models. Laboratory data which indicate strong T-dependence of seismic velocity are used to calculate temperature contribution into velocity anomalies observed in tomography models (Shapiro and Ritzwoller, 2002) and to separate compositional anomalies from thermally induced velocity variations (Fig. 2).

The results suggest that T-variations alone are sufficient to explain seismic V_s only in ca. 50% of continental regions. In cratonic lithosphere, compositional anomalies due to Fe-depletion can explain the misfit between seismic V_s and theoretical V_s (the latter was calculated from mantle temperatures based on experimental data on T-dependence of seismic parameters). In regions of active tectonics, partial melts and/or fluids are likely to affect V_s.

The gravity model (after the effect of thermal expansion being excluded from Bouguer gravity data, Kaban et al., 2003) reveals compositional density anomalies in continental lithospheric mantle, which however not always are well correlated with seismic constraints on compositional variations in the mantle. The discrepancies between seismic and gravity compositional constraints are caused by different dependencies of V_s and density on compositional variations and reflect processes of lithosphere formation and its later tectono-magmatic modification. Cross-sections of compositional variations in the upper mantle constrained by seismic and gravity data (with temperature effect excluded from both of them) permit to distinguish buried Precambrian cratons (e.g. the Sask craton), deep boundaries between terranes of different ages and cratonic margins, as well as to recognize cratonic roots affected by past magmatic and metasomatic processes (e.g. within the Superior Province).

References:

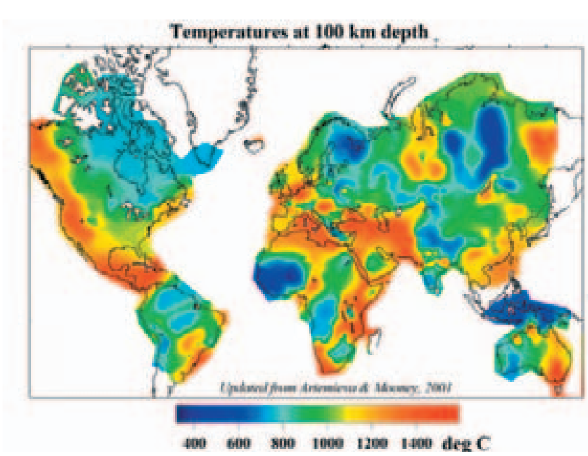
Artemieva, I.M. & Mooney, W.D., 2001. Thermal structure and evolution of Precambrian lithosphere: A global study. *J. Geophys. Res.*, v.106, 16,387-16,414.

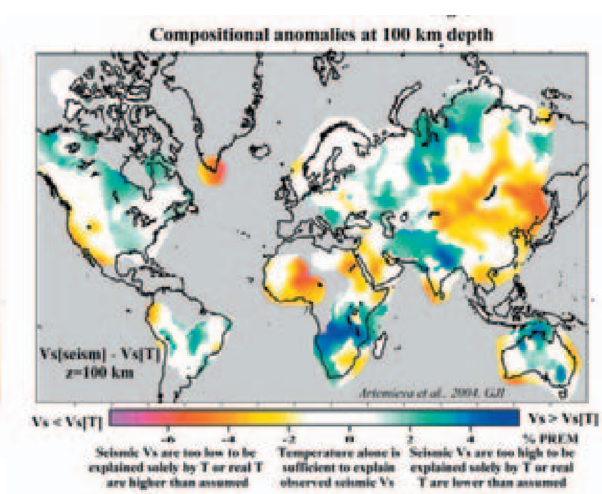
Artemieva I.M., Billien M., Leveque J.-J., and Mooney W.D., 2004. Shear-wave velocity, seismic attenuation, and thermal structure of the continental upper mantle. *Geophys. J. Int.*, 157, 607-628.

Artemieva, I.M. Lithospheric mantle of stable continents: Similarities and differences inferred from thermal, seismic, MT, and xenolith data. Submitted to *Phys. Earth Planet. Inter.*

Kaban M.K., Schwintzer P., Artemieva I.M., and Mooney W.D., 2003. Density of continental roots: compositional and thermal effects. Earth Planet. *Sci. Lett.*, 209, 53-69.

Shapiro, N.M. & Ritzwoller, M.H., 2002. Monte-Carlo inversion for a global shear velocity model of the crust and upper mantle. *Geophys. J. Int.*, 151, 1–18.





Temperatures at 100 km depth (updated from Artemieva and Mooney, 2001) and “compositional” (non-thermal) anomalies in the continental mantle at the same depth (from Artemieva et al., 2004).

Increasing Geoscience Literacy and Public Support for the EarthScope National Science Initiative: Museum Exhibits, Educational Programming, and Public Outreach

Jayne Aubele

New Mexico Museum of Natural History and Science

Introduction: Geology and geophysics are frequently perceived by the student, teacher, or adult non-geologist as "difficult to understand"; however, most non-geologists of all ages notice and appreciate landforms such as mountains, volcanoes and canyons, and are interested in phenomena such as earthquakes and the development of natural resources. The EarthScope Project is an opportunity to increase the non-geologist's understanding of Earth's dynamic processes and to excite the general public about geoscience research.

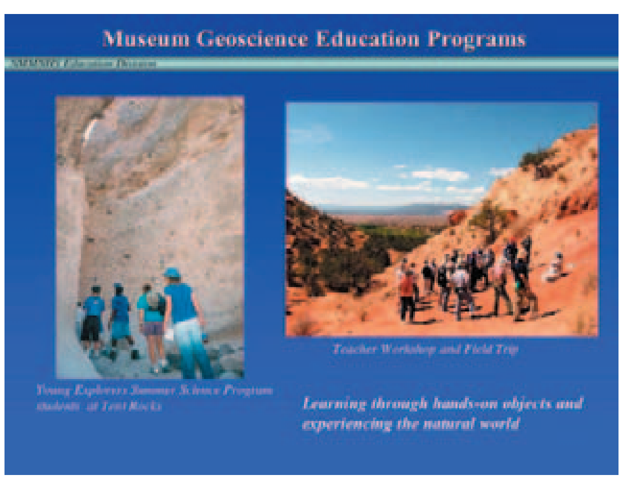
The Museum Advantage: Museums, as informal science education centers, have the following advantages in geoscience-related education: (1) graphics/display expertise; (2) flexibility in approach and programming; (3) family learning opportunities; (4) audience ranging from pre-K through Senior Citizen; (5) accessible, visitor-friendly and non-threatening resource site for science information for the community.

The general public is interested in the local and regional geology; however, most people don't know how or where to obtain this information. There is too much information, of unknown validity, on the web and too little in the popular media. Community members are frequently too intimidated to walk into their local university department and ask questions. Museums provide concise, factual, reliable and entertaining presentations of the relevant information. It is not enough to simply report on the scientific research, museums educate through object-based learning and experiential programming. By emphasizing the local or regional connection, museums allow people to make a personal connection to scientific research and new discoveries.

In addition, museums serve a wide audience, For example, the New Mexico Museum of Natural History and Science (NMMNHS) is a statewide institution, part of the New Mexico Department of Cultural Affairs. It serves a regional population that includes 38% Hispanic and 9% Native American, as well as a high percentage of rural communities, and therefore reaches an audience traditionally underrepresented in science. This audience is particularly important to reach with geoscience education.

K-12 teachers also need a resource for reliable information and are able to make use of Museum programs and objects to provide a "real world" approach to science in the classroom. Museum science curators and education staff can work together to sift through new research and materials available in order to provide teachers with a comprehensive, pre-selected set of concepts, and grade and age appropriate activities, while at the same time teaching the geoscience content to the teachers in a developmentally appropriate way. This has recently become particularly important in addressing the requirements of "highly qualified" teachers as mandated by the "No Child Left Behind" legislation.

Lessons Learned: The NMMNHS has created an extensive and interrelated number of public and educational programs for on-site visitors and off-site outreach. In addition to the 200,000 visitors who come to the museum annually, our targeted educational programs reach another 20,000 students, teachers and members of the general public each year. Our science education and public outreach is successful for the following reasons: (1) we promote and emphasize the local and regional connection to scientific research in order to allow the public to feel connected, proud and involved; (2) we meet community needs and expand participation by partnering with other science education providers and school districts; (3) we utilize our resources and expertise, including our ability to quickly produce exhibits, graphics and educational programming and curricula themed to specific topics; (4) we link all museum science education to inquiry-based learning and to the national science standards and the newly adopted State of New Mexico science standards; and (5) we involve elementary through high school classroom teachers in the development of our educational programs and materials.



K-12 teachers and elementary-age students participate in museum geoscience workshops and field trip programs.

Moho Topography and Lower Crustal Density in Southern Ontario from Linearized Gravity Inversion

Charly Bank
Colorado College

Dave Eaton
University of Western Ontario

Kadircan Aktas
University of Western Ontario

We have developed a linearized joint inversion of Bouguer gravity data and isolated crustal thickness estimates to obtain a map of Moho topography and density variations in the lower crust of Southern Ontario. The study area is crossed by the Grenville orogen, a mid-Proterozoic Himalayan type collisional zone. Our dataset consists of complete Bouguer gravity values from the GSC and PACES, and estimates of crustal thickness from semblance-weighted receiver function analysis and from seismic refraction studies. Our linearized gravity inversion parametrizes the Moho as discrete rectangular blocks sitting at a reference depth (mean of the seismic estimates). We assume that the mass of one block is concentrated at its base. We show that because our measurements are far enough from the reference depth we obtain a linear relationship between the height – or the density contrast – of the block and the vertical component of gravity measured at the surface.

In a first step we leave the density contrast constant and only allow the thickness to vary. Our results show the following tentative correlations with surface structural units: thin crust (~30 km) beneath the mid-continent rift is flanked by thick crust (~48 km) on either side, the Ottawa-Bonnechere graben has thick (~45 km) crust, and so has the Composite Arc Terrane of the Grenville Orogen. Some of these results contradict seismic estimates of crustal thickness.

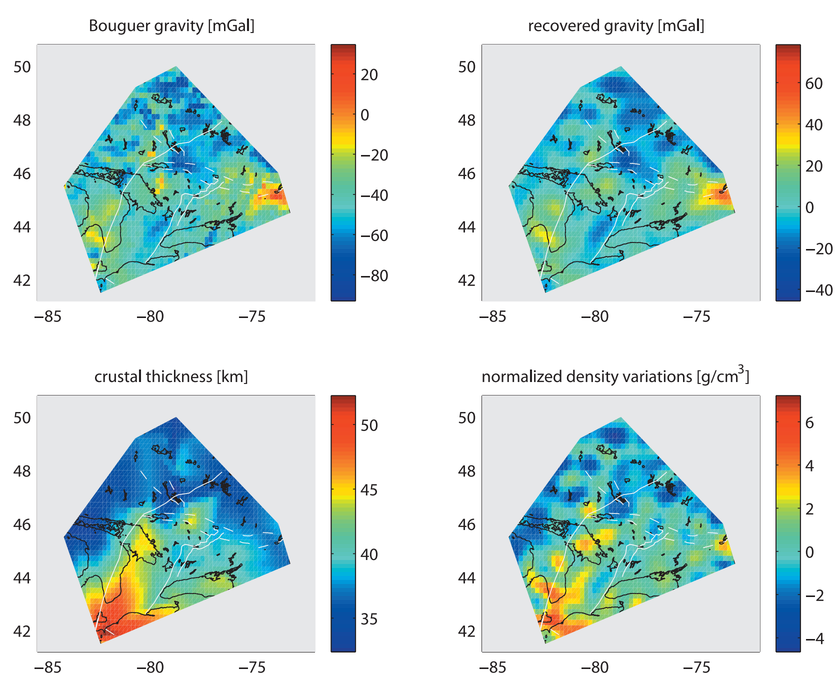
In a second step we grid all available seismic thickness estimates, calculate the resulting gravity field, subtract the latter from Bouguer gravity data, and invert the difference for density variations. The results show a clear distinction between dense lower crust of the Central Gneiss Belt and lighter lower crust of the Composite Arc Terrane in the NW and SE of the Grenville Orogen, respectively. The Abitibi belt of the Superior craton also seems to have lower density lower crust. High density beneath the Central Gneiss Belt coincides with high v_p/v_s values reported by Eaton et al.~[2005] in this area. Residual gravity maps display mainly short-wavelength anomalies which we believe to be caused by shallow anomalies.

The crustal thickness variations we obtain are not reflected in the generally flat surface topography of the area. Our results may support Fischer [2002], who argues that the density contrast between crustal roots of orogens diminishes over time and allows the preservation of a crustal root that does not produce a gravity anomaly.

References:

Eaton, D. W., S. Dineva, and R. Mereu, 2005. Crustal thickness and Vp/Vs variations in the central Grenville orogen (Ontario, Canada) from analysis of teleseismic receiver functions, submitted to *Tectonophysics*.

Fischer, K. M., 2002. Waning buoyancy in the crustal roots of old mountains. *Nature*, vol. 417, pg. 933-936.



Results of linearized inversion. X-axis in degree West, Y-axis in degrees North, lakes shown in black, and tectonic boundaries in white. Top left: Bouguer gravity map. Top right: recovered gravity (note baseline shift wrt left panel). Bottom left: crustal thickness from seismic data. Bottom right: result of second inversion step, density variation normalized to 1km high cells (red colour denotes higher density in lower crust).

BACKPAC: BAsin & range–Cascade–Klamath–PACific Geoscience Transect – The Accreted Crustal Section

Calvin Barnes
Texas Tech University

Harold Gurrola
Texas Tech University

Randy Keller
University of Texas El Paso

Art Snoke
University of Wyoming

The Klamath Mountains province (KMp; Fig. 1A) is a well-studied example of a west-directed, thin-skinned accretionary province. Such provinces consist of accreted terranes of chiefly oceanic affinity. They are end-members in our understanding of the construction, amalgamation, and accretion of "oceanic" terranes, and of how these processes relate to stabilization of continental lithosphere. Tectonostratigraphic terranes such as exposed in the KMp underlie much of the Pacific Northwest, and are the basement for, and possible contaminants of voluminous Tertiary and Quaternary magmas of the Cascade Range, High Lava Plains, and Columbia River Plateau. Unfortunately, holistic characterization of the paleogeographic, tectonic, magmatic, and sedimentary history of individual and composite terranes are few, which means correlation between widely separated terranes is difficult, if not impossible. Moreover, our incomplete understanding of the crustal parts of the accreted terranes means that there is little hope of relating them to any attached mantle lithosphere that might exist.

It is commonly assumed that the thin-skinned geometry preserved in the rock record is the initial accretion geometry. However, in the KMp and elsewhere, mounting evidence suggests that the thin-skinned geometry was acquired late in the tectonic history of such accreted provinces. For example, Figure 1B shows the structural equivalence of the low-grade western Jurassic terrane and the transitional blueschist-greenschist facies Condrey Mountain Schist (CMS). Both units are in thrust contact beneath the older, composite Rattlesnake Creek/western Hayfork terrane assemblage (RCt/wHt), similar to the geometry of the oceanic Pelona-Orocopia-Rand schists in southern California beneath older crystalline rocks. However, geochronologic and metamorphic data show these two footwall terranes to be unrelated, and the CMS to be 10–20 m.y. older than the western Jurassic terrane. How were these footwall terranes juxtaposed (e.g., multiple thrusts of different age; duplexing), what is their subsurface geometry, and what was their pre-thrusting geometry?

Magmatic events in the KMp were episodic and separated by regional thrusting, as shown in Figure 1B. All Mesozoic plutons in the province show arc affinities, but each plutonic episode has distinctive elemental and isotopic characteristics (Fig. 1C). Moreover, thermobarometric studies indicate that some magma differentiation was mid-crustal (~25 km) or deeper. Laser ablation ICP-MS dating shows that distinct age arrays of inherited zircon (Fig. 1C) characterize each episode. We conclude that in each plutonic episode, mafic arc magmas probed distinct crustal sections, which changed through time because of regional, deep-seated, accretion-related thrusting.

If this explanation is correct, then (1) study of inherited zircon populations and isotopic variation in KMp plutons provides the most robust indicator of changes in crustal architecture through time; (2) the exposed crustal section does not record the entire geologic history of the province, as commonly assumed; (3) much of the record has been excised by thrusts and is either "trailing" the KMp (e.g., beneath the Cascade or Basin and Range provinces) or was delaminated; (4) many of the thin-skinned structures in the KMp may be low-angle normal faults rather than thrust faults.

Structural, petrologic, and seismic investigations (passive and active sources) are needed to resolve these problems. Integrated seismic-structural-petrologic studies along a transect extending from the Pacific Coast, across the Klamath and Cascade Mountains, and ending in the western Basin and Range province (Fig. 1B) can provide tremendous insight into the origin and tectonic evolution of this classic example of tectonostratigraphic terrane accretion. Because this accreted crust continues in the subsurface to the Basin and Range province, any thorough understanding of basement for Tertiary volcanic provinces of the area must consider the geometry and composition of the KMp terranes.

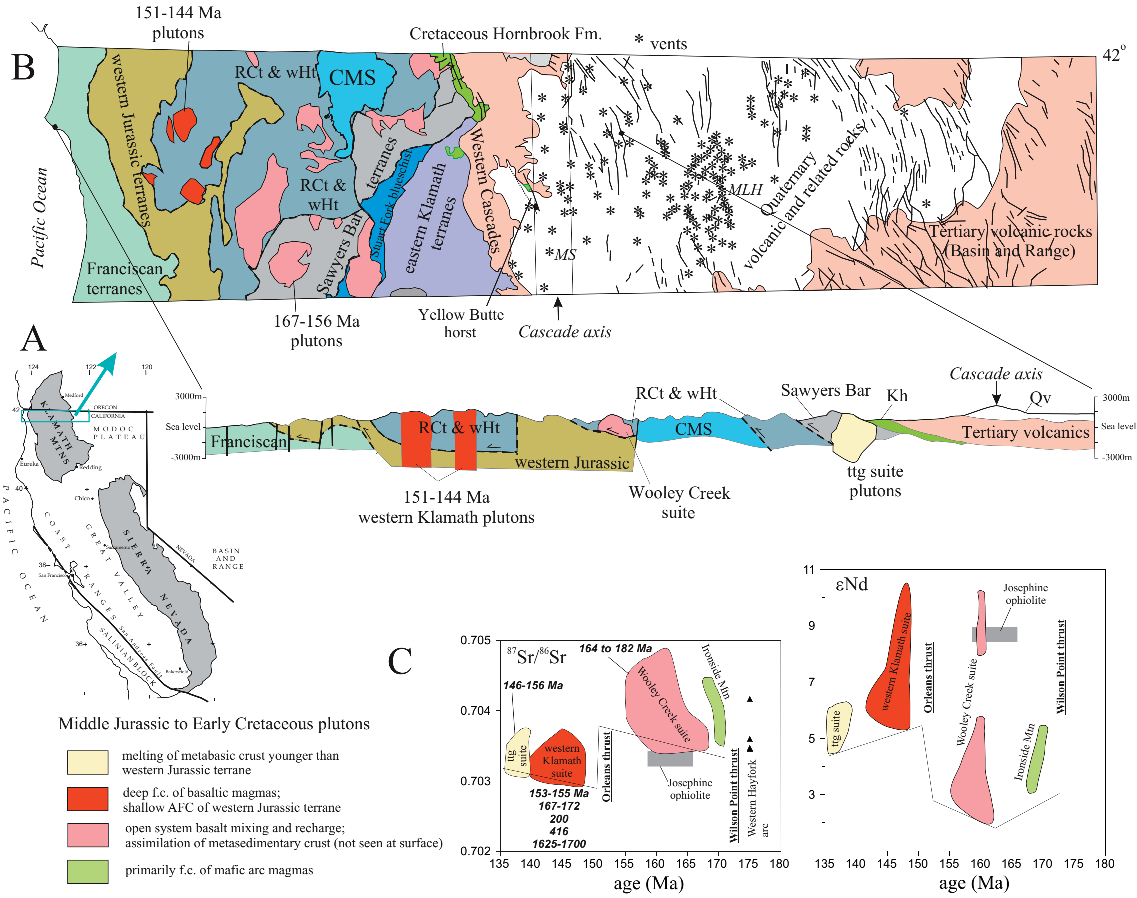
Figure on Page 72 >

Calvin Barnes
Texas Tech University

Harold Gurrola
Texas Tech University

Randy Keller
University of Texas
El Paso

Art Snoke
University of Wyoming



(A.) Location of the Klamath Mountain province relative to the Sierra Nevada, Modoc Plateau, Basin and Range, and Cascades. (B.) Simplified geologic strip map from the Pacific Ocean to the western Basin and Range Province, northern California. Accreted pre-Tertiary basement terranes are exposed in the Klamath Mountain province, between the Franciscan terranes to the west and Cretaceous and Tertiary strata to the east. The KMp accreted terranes are the exemplar of Cascade and Basin and Range basement rocks. The interpreted cross section is along a line just south of the California-Oregon border. Some plutonic units projected into the line of section. (C.) Relationships between isotopic compositions, inherited zircon populations, and time in Mesozoic plutons. Age ranges of inherited zircons shown in bold text. Plutonic suites are color coded to map and cross section.

EarthScope Interpretive Environment: Designing Portals for Scientific Research and Education

Chaitan Baru
University of California San Diego

Ramon Arrowsmith
Arizona State University

Randy Keller
University of Texas El Paso

Dogan Seber
University of California San Diego

Scientific portal environments provide distinctly different services than Web sites. While the front-end interfaces may look the same in both cases, portals are designed to provide authenticate, authorized access to a variety of on-line resources ranging from individual datasets and data collections; integrated information from heterogeneous, multi-disciplinary data sources; on-line scientific workbenches that provide a visual programming environment based on scientific workflow software; on-line tools and applications that support advanced search and data analysis, modeling, visualization, & integration; collaboration environments; downloadable tools; and, computational and storage capabilities.

Cyberinfrastructure projects such as, the Biomedical Informatics Research Network (BIRN) and the Geosciences Network (GEON), are developing advanced portal environments. Here, we provide an overview of these portal environments and propose a portal strategy for EarthScope to create the EarthScope Interpretive Environment, that would not only provide access to EarthScope data, but also to a broad range of auxiliary data and information, and to tools and services that will enable advanced search and information integration across this broad range of data.

We will describe portal frameworks and technologies – including the portlet-based architecture – that are now enabling us to design modular, extensible portals that support incremental addition of capability into a portal, thereby enabling community contributions (of data as well as tools), for example, in support of the ES Interpretive Environment. A novel approach, developed in GEON, is the creation of a common "core" portal framework, which is customizable to the needs of a specific group, sub-discipline, or applications. In this model, the EarthScope Interpretive Environment would be based on a core EarthScope portal, which is then extended and customized, as needed, to provide, say, an EarthScope Geochemistry portal, an EarthScope natural hazards portal, or a portal targeted to a specific education audience, etc.

We will provide suggestions for next steps that could foster the development of such an EarthScope Interpretive Environment by leveraging technologies and capabilities that have been developed in projects like GEON, BIRN, and other cyberinfrastructure efforts.

A snapshot of the GEON Portal.

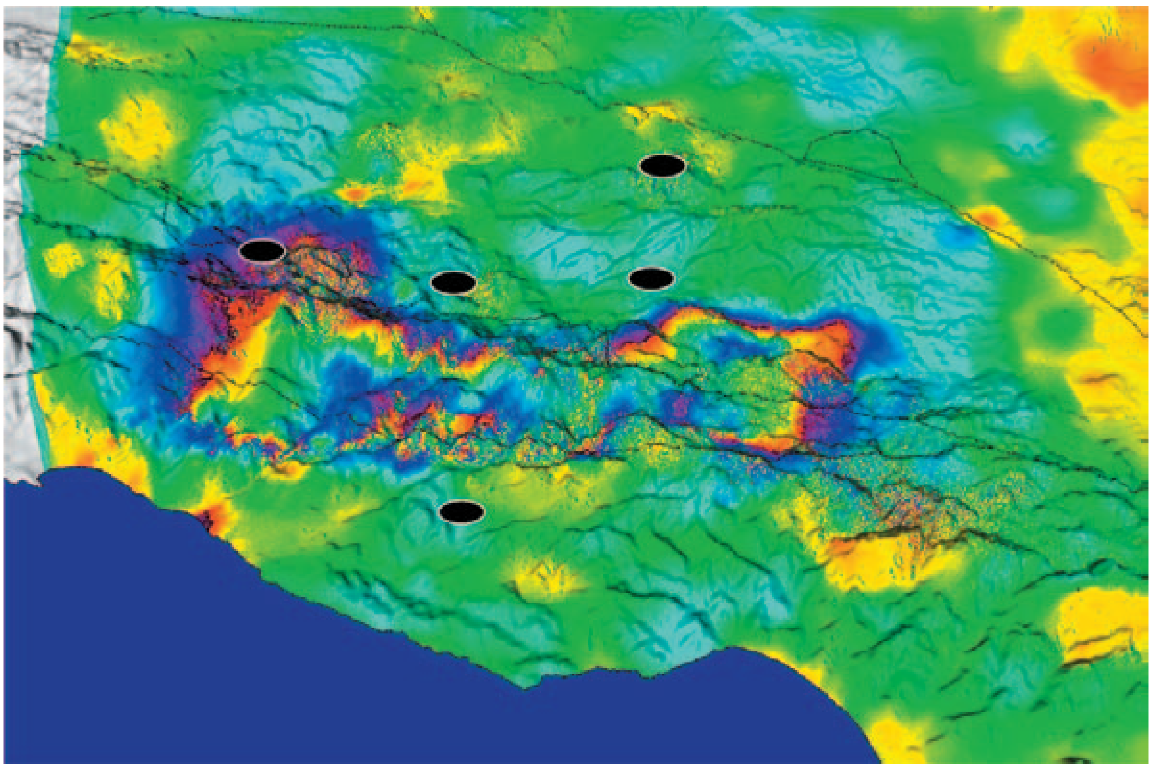
Using InSAR in the Plate Boundary Observatory Site Selection Process

Gerald Bawden
U.S. Geological Survey

Christian Walls
UNAVCO

Brian Coyle
UNAVCO

InSAR has become an invaluable tool for selecting GPS sites in the Plate Boundary Observatory's (PBO) Transform (San Andreas) footprint, with InSAR imagery aiding in the selection process of more than 30 sites. Ground-water, hydrocarbon, and geothermal activity throughout the United States produces horizontal and vertical land-surface deformation that often is much larger than the tectonic signal that PBO seeks. InSAR imagery is being heavily used in the Transform site selection process to minimize the effect of artificial non-tectonic motion on the GPS time-series. The strategy has been to (1) locate sites outside areas of known or InSAR-observed subsidence; (2) locate sites away from basin margins where horizontal deformation and InSAR gradients will be the steepest when siting is needed in an area with artificial uplift and subsidence to meet PBO science objectives; and (3) locate sites near the center of the basin to minimize the horizontal gradients for basins where ground-water development begins after the installation of PBO sites and where no observed InSAR surface motion is being observed. Imagery used in the selection of sites was acquired using the European Space Agency (ESA) ERS-1 and ERS-2 satellites; data were purchased through a ESA CAT-1 Project and the WInSAR archive.



InSAR image showing over 6 cm immediate postseismic slip uplift for the M 6.5 San Simeon Earthquake in Central California (December-February). The black circle are PBO sites that were installed immediately following the mainshock.

The USArray Array Operations Facility at the PASSCAL Instrument Center, New Mexico Tech

Bruce Beaudoin
New Mexico Institute of Mining and Technology

Rick Aster
New Mexico Institute of Mining and Technology

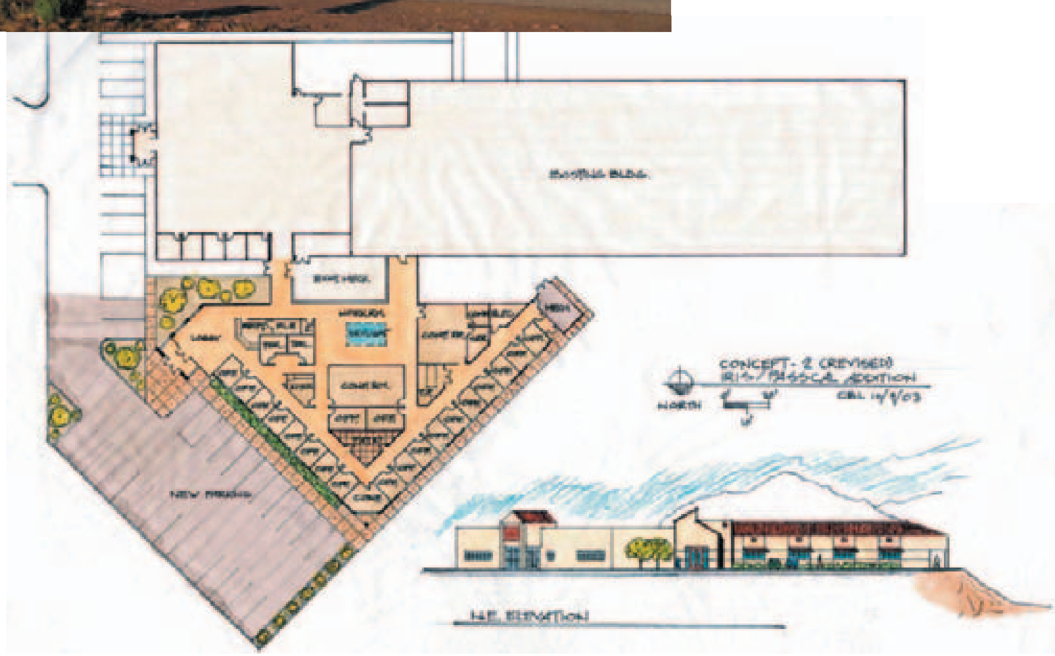
Jim Fowler
IRIS

Mark Alvarez
IRIS

The USArray Array Operations Facility (AOF) is operated by the PASSCAL Instrument Center at New Mexico Tech in Socorro, New Mexico. Since its inception in October 2003, the AOF has hired 9 FTEs to support both USArray Transportable Array (TA) and Flexible Array (FA) activities. Support for TA has included participation in the design and fabrication of the seimic vaults and power distribution systems, evaluation of communications systems, quality assurance of station equipment, software development and station installation. The AOF supports FA experiments much in the manner of PASSCAL experiments. The facility offers training, equipment quality assurance and maintenance, software development, and field support for FA experiments. In addition to traditional sytle PASSCAL support, the AOF will be responsible for archiving FA stand-alone experiment data with the IRIS Data Management Center.

New Mexico Tech has just completed an 11,500 ft^2 PASSCAL Instrument Center annex to house the AOF expansion. The annex is comprised of 22 offices, instrument and computer labs, a seismic pier, and training/conference facilities. For FA experiments, the AOF's current inventory consists of 80 3-channel digitizers, 40 broadband sensors, and 40 short-period sensors. The facility is actively testing a single-channel digitizer and expects to accept delivery of 400 units this spring. The AOF's TA equipment acquisitioin schedule is roughly 80 3-channel digitizers/year, 40 broadband sensors/year, 40 short-period sensors/year, and 400 single-channel digitizers/year. The full compliment of instrumentation consisting of 400 3-channel digitizers, 200 broadband sensors, 200 shortperiod sensors, and 2000 single-channel digitizers will be achieved by 2008.

To date the AOF has supported 3 FA experiments funded by the EarthScope Program: Paso Tres, a 13 station broadband array in Parkfield, CA collecting data in realtime; Parkfield Trapped Waves, a 3-month long, 70-staion combined short-period and active source experiment; and NW Nevada-Active, a 1100 channel active source experiment. For 2005, the AOF will continue support Paso Tres and support Sierra Nevada EarthScope Project (SNEP), a new 40 station stand-alone broadband experiment.



The Sierras Pampeanas of Argentina: A Modern Analog for the Laramide Rocky Mountains in the Western U.S.

Susan Beck
University of Arizona

Hersh Gilbert
University of Arizona

Lara Wagner
University of Arizona

Patricia Alvarado
University of Arizona

The South American Andean Mountain belt is a modern analog to the Mesozoic-Cenozoic history of the North American Cordillera in the western U.S. and may provide insights to the tectonic processes we often infer for the western U.S. The flat slab suduction of the Farallon plate beneath the western U.S. is thought to have contributed to the cessation of the arc magmatism and to the formation of Laramide basement-cored uplifts. The best modern analog to this process is occurring today at approximately 31°S in west-central Argentina where the Nazca slab subducts to a depth of 100 km and then extends horizontally for several hundred km inland before it descends into the mantle. The arc magmatism began shutting off approximately 8 Ma and the Sierras Pampeanas basement-cored uplifts became active approximately 5 Ma. There are many unanswered questions about flat slab subduction and how it has modified the western U.S. crust and upper mantle through time. The recent results from the CD-ROM experiment suggests the U.S. Rocky Mountains remain underlain by Proterozoic lithospheric mantle that has remained both fertile and weak as demonstrated by repeated deformational and magmatic events from 1.4 Ga to present. This raises the question of how such a weak mantle transmitted stress upward from a flat slab.

One of the intriguing aspects of the subduction of the Nazca plate beneath western South America is the along strike segmentation of the dip of the descending plate as defined by the slab earthquake distribution. At approximately 31°S the Nazca plate has a subhorizontal geometry and extends inland over 300 km beneath the Sierra Pampeanas of west-central Argentina. However, further south (south of 33°S) the Nazca slab dip is much steeper and the overlying active continental volcanic arc is more "typical" of subduction systems. Understanding what causes the dramatic changes in slab geometry, and its influence on the overlying lithosphere remains a fundamental goal. To this end, we deployed 22 PASSCAL broadband seismic stations with a station spacing of approximately 60 km across the Andes along two transects over the flat slab (30.5°S) and the steeper subduction zone (36°S) as part of the CHile ARgentina Geophysical Experiment (CHARGE). We find that most of the backarc region above the flat slab is in compression with thrust earthquakes in the depth range of 10-25 km. The most seismically active region is associated with Pie de Palo Range, a basement cored uplift of 1.1 Ga rocks near San Juan, Argentina. This region has produced the most recent damaging magnitude 7.4 earthquake. The earthquakes in the flat segment of the slab are predominantly normal fault events with ENE-WSW near horizontal tensional axis. Receiver function and regional surface wave analysis indicates that the eastern Sierras Pampeanas has a crustal thickness of 35 km and a V_p/V_s ratio of less than 1.75 while the western Sierras Pampeanas crustal thickness increases to 55 km with a V_p/V_s ratio greater than 1.8 (Figure 1). The western Sierras Pampeanas has a high velocity lower crust that we suggest represents higher density material that accounts for the similar elevation between the western and eastern Sierras Pampeanas despite the different crustal thickness. The change in crustal character (both thickness and seismic velocity structure) corresponds to a suture between accreted Precambrian terranes. Local seismic tomography indicates that the mantle between the crust and the flat slab has low P-wave velocities and high S-wave velocities that we interpret to be cold lithospheric mantle (Figure 1). It is not consistent with hydrated mantle and our study suggests that the Nazca slab does not dewater until further east after it descends into the mantle. Taken together the CHARGE results suggest that lithospheric structure still reflects Precambrian terrane boundaries and that the present day mantle under the Sierra Pampeanas is dry and strong and able to transmit basal shear from the underlying flat slab. The dry state of the mantle is in apparent contradiction to the CD results from the Rocky Mountains. This suggests that either different mechanisms can produce similar basement cored uplifts or that temporal changes in the hydration state of the mantle have led to the current differences we observe. We speculate that the weakening of the lithospheric mantle in the western U.S. may be due to temporal changes in the hydration state as flat slab subduction continued for nearly 35 Ma in the western U.S.

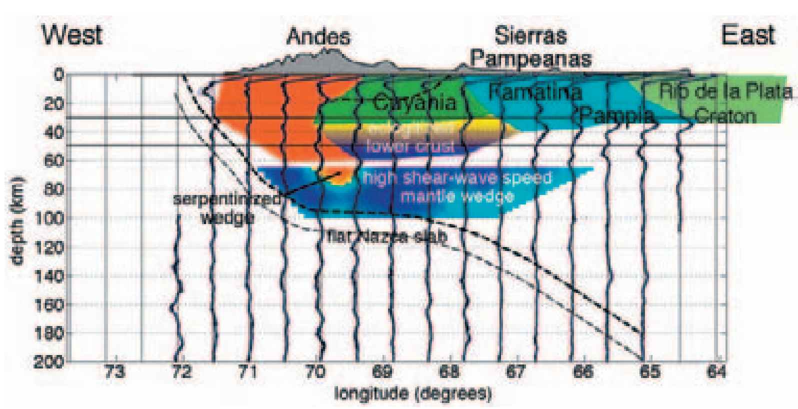


Figure 1. Cross-section at 30.5°S across western South America. The section crosses the region of flat slab subduction and shows the terrane boundaries traversed by the CHARGE northern seismic profile and a summary of tectonic features identified with receiver functions and S-wave travel time tomography from Wagner et al., [2005].

Imaging Upper Mantle Structure Beneath the Illinois Basin

Heather Bedle
Northwestern Univeristy

Suzan van der Lee
Northwestern Univeristy

The Illinois Basin is an oval-shaped cratonic basin approximately 285,000 km^2 in area (Figure 1), which covers parts of southern Illinois and Indiana, western Kentucky, Tennessee, and Missouri. The shallow structure of the Illinois Basin is well-defined from drill core data, and provides constraints, which may allow the separation of effects of crustal and upper-mantle structure on seismic waveforms during tomographic inversions. However, upper-mantle structure beneath the basin is uncertain (van der Lee, 2002).

We enhanced the resolving power for upper-mantle structure beneath the Illinois basin by analyzing a regional data set of S and surface waves that passed through or nearby the Illinois Basin. We fitted the waveforms of these waves, using Partitioned Waveform Inversion. Utilizing six mid-continent events, a total of 60 seismograms were fitted in this study. By using a high number of model parameters in the crust we separated the effects of shallow and deep crustal structure on the regional waveforms. The model parameterization and structure of the starting model are based on crustal constraints for the Illinois Basin from well-log data and seismic reflection surveys (Buschbach and Kolata, 1991). These constraints were then inverted along with the continent-wide constraints from S-velocity model NA00 (van der Lee, 2002).

The linear inversions resulted in model IL05. Figure 1 represents the deviation of calculated S-velocities for IL05 and NA00 from the one-dimensional Earth model, MC35, for two profiles across the Illinois Basin. NA00 shows a region of relatively neutral to low velocity among generally high velocities above 100 km below the Illinois Basin (Figure 1). Resolution tests demonstrate that this feature would have been resolved in IL05, which it was not. IL05 no longer shows this region, owing to the additional constraints from regional data and local studies.

Both NA00 and IL05 image relatively high seismic velocities beneath the Illinois Basin and surroundings, in accord with expectations based on the Proterozoic age of the region (Figure 1). However, the S-velocity is not as fast beneath the basin as beneath its surroundings at lithospheric levels. The lithosphere is about 200 km thick in the region. Below 200 km, however, IL05 shows slightly higher velocities beneath the Illinois Basin than the old model, NA00. These velocities, if resolved, could represent a thickened lithosphere beneath the Illinois Basin.

Further south, the lithosphere beneath the Reelfoot Rift is associated with a significantly thinner lithosphere, which is well resolved. This thinned lithosphere may be related to the original upwelling of the mantle during the formation of the Reelfoot Rift but contrasts starkly with the upper mantle structure observed beneath the Illinois Basin. However, this contrast could represent the difference between a relatively active rift and a geologically stable structure.

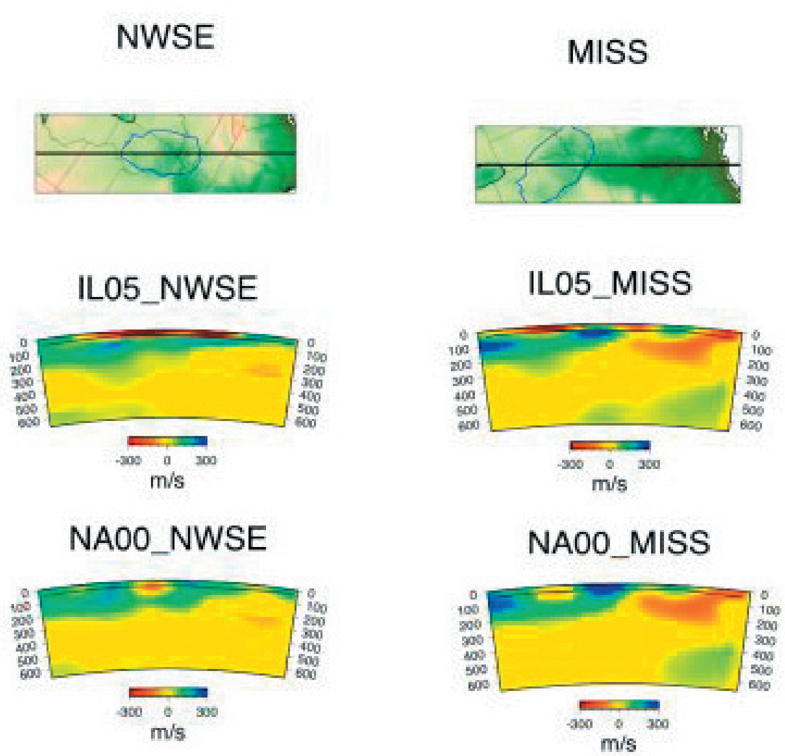


Figure 1: Profiles across the Illinois Basin, comparing models IL05 and NA00, scale shows S-velocity differences of 3D model with a standard 1D Earth model, MC35.

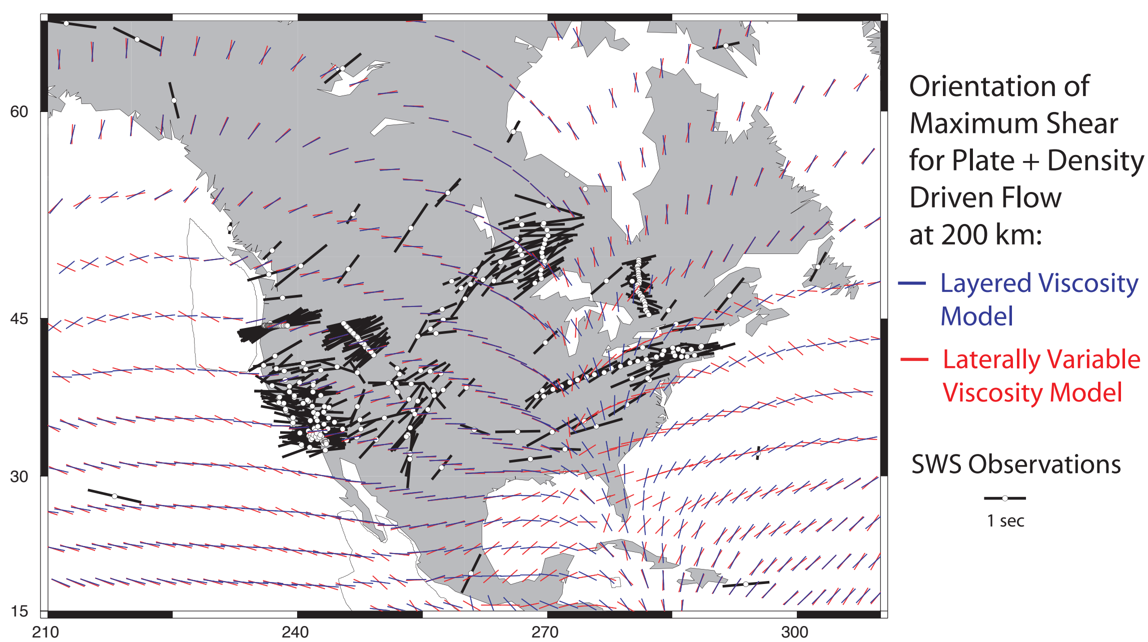
Seismic Anisotropy and Flow Across Continental North America

Mark Behn
Woods Hole Oceanographic Institution

Clinton Conrad
University of Michigan

Paul Silver
Carnegie Institution of Washington

Seismic anisotropy provides a direct estimate of flow in the Earth's upper mantle. In the ocean basins, measurements of anisotropy inferred from shear-wave splitting are extremely well fit by a global flow model that is driven by a combination of plate-motion and mantle density heterogeneity. Global mantle flow is determined from instantaneous flow calculations that assume a radially variable, but laterally homogeneous viscosity structure. However, while this global flow field can account for the anisotropy in the ocean basins, it is a very poor fit in many continental regions. For example, although observed anisotropy in western North America is well fit by the global flow model, the splitting observations in eastern North America are nearly orthogonal to the model predictions. Previous studies have attributed this poor fit to the influence of continental roots on the mantle flow field, a component of fossil lithospheric anisotropy, or some combination of these two effects. Here we evaluate these competing models using finite element calculations of global mantle flow that incorporate radial and lateral variations in viscosity associated with the depth- and temperature-dependence of mantle viscosity, and ocean-continent and age-dependent variations in lithospheric thickness. Our results show that a flow model that incorporates lateral variations in viscosity provides an excellent fit to the splitting data in western and easternmost North America. In contrast, splitting observations in central North America remain poorly fit by our global flow model suggesting the presence of a fossil lithospheric component of anisotropy.



Comparison of the predicted and observed anisotropy across continental North America. Black symbols illustrate existing shear wave splitting measurements. Colored bars show the direction of maximum shear at the center of the asthenosphere for plate+density-driven mantle flow assuming a layered (blue) and laterally variable (red) viscosity structure. Density-driven flow is derived from the tomography model of Ritsema et al. [1999] and a velocity-to-density scaling of 0.15 g/cm^3 / km/s. Global mantle flow is calculated using CitComS [Moresi et al., 1996; Zhong et al., 2000].

SCEC Communication, Education, and Outreach "Frameworks"

Mark Benthien
University of Southern California

As EarthScope develops its Education and Outreach program, it may be useful to consider existing comprehensive programs of large Earth science research organizations. The Southern California Earthquake Center (SCEC) is one example, as is a community of over 500 scientists, students, and staff from over 50 academic institutions across the United States, in partnership with many other science, engineering, education, and government organizations worldwide. To develop applications of the knowledge and scientific products developed by this community, SCEC maintains a Communication, Education, and Outreach (CEO) program with four long-term goals:

- Coordinate productive interactions among a diverse community of SCEC scientists and with partners in science, engineering, risk management, government, business, and education.
- Increase earthquake knowledge and science literacy at all educational levels, including students and the general public.
- Improve earthquake hazard and risk assessments
- Promote earthquake preparedness, mitigation, and planning for response and recovery.

CEO is well integrated within the SCEC science planning process. This includes participation of CEO staff in the development of short-term research objectives and evaluation of proposals received each year in order to develop products and services needed by our various audiences. SCEC scientists in turn are involved in developing and fulfilling CEO short-term objectives, which are organized within four CEO focus areas: education programs and resources for students, educators, and learners of all ages; public outreach activities and products for the general public, civic and preparedness groups, and the news media; knowledge transfer activities with practicing professionals, government officials, scientists and engineers (with research partnerships coordinated within the SCEC implementation interface); and SCEC Community development activities and resources for SCEC scientists and students.

In recent years, several CEO activities in each of these focus areas have been developed into sustainable and transportable frameworks (organizing structures and systems) for conveying earthquake information to broader and more diverse audiences. These framework activities may serve as prototypes for some EarthScope education and outreach activities and are highlighted on this poster.

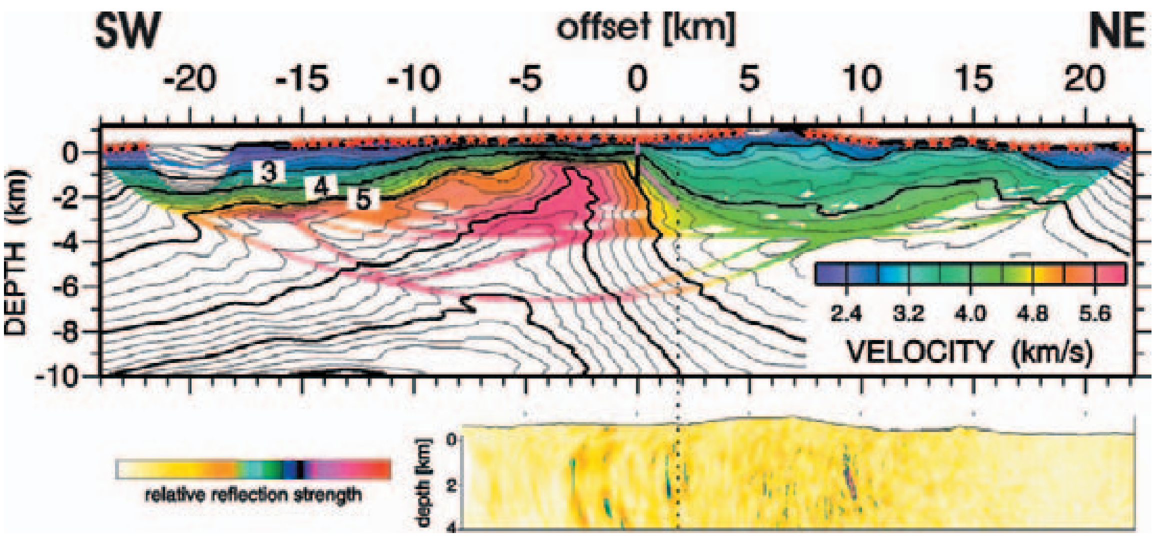
Seismic Reflection/Refraction-imaging at the San Andreas Fault

Florian Bleibinhaus
Virginia Tech

John Hole
Virginia Tech

Trond Ryberg
GeoForschungsZentrum Potsdam

A refraction/reflection seismic survey at the SAFOD drill site near Parkfield carried out in 2003 provides a detailed characterization of the subsurface structures. Three-component stations at a spacing of 50m were deployed on a 46 km long line perpendicular to the surface trace of the SAF. From the first arrival times of 62 explosive shots, a refraction p-wave velocity model was obtained. The most prominent feature of the model is a strong lateral contrast near SAF between Salinian granitic rocks and the Franciscan sedimentary melange. This model was used to perform a prestack migration of the reflected wavefield focusing on steep dips. The resulting images show a bright reflector down to at least 2 km depth near the position of the Coast Range Fault (CRF), which separates the Great Valley sequence from the Franciscan. Its steep dip suggests a strike slip rather than a thrust contact. The reflection is interpreted to arise from fault-zone structure rather than from an impedance contrast across the fault. Neither p- nor s-wave velocities indicate a significant contrast at that position. The high reflection strength may indicate the presence of fluids. The SAF, which was previously imaged at the same location by a shallower survey at a few hundred meters depth, is not a strong feature in the prestack migration result. This finding may be related to some extent to image quality, which is affected by large shot spacing, rugged topography and statics, and a complex direct arrival wavefield over shallow basement. We are currently working on a full-wavefield inversion to improve the velocity model, and thereby the migration image.



Velocity model from first-break tomography (top) and partial reflection image (bottom). Shotpoints are indicated by stars. The offset axis refers to the SAFOD borehole. The surface trace of the SAF is marked with a dotted line. The reflection image was obtained by stacking prestack-migrated sections of the nine northernmost shots.

Workshops for Establishing a Stable North American Reference Frame (SNARF) to Enable Geophysical and Geodetic Studies with EarthScope: Annual Report 2004-2005

Geoffrey Blewitt
University of Nevada Reno

SNARF Working Group
G. Blewitt (Chair)
K. Larson (PI)
J. Davis (Co-PI)
D. Argus
R. Bennett
Y. Bock
E. Calais
M. Craymer (NRCan Rep.)
T. Dixon
J. Freymueller
T. Herring
D. Johnson
M. Miller
G. Sella
R. Snay (NGS Rep.)
M. Tamisiea

The goal of this NSF EarthScope project (funded Feb 2004 - Jan 2006) is to coordinate the development of a new standard 'Stable North American Reference Frame' (SNARF) that would be suitable for scientific investigations of the North American plate and its boundary with the Pacific Plate. This is being achieved by a small working group who meet in a series of 3 - 4 workshops. An associated objective is to educate the scientific community on the use of reference frames and their limitations as to the interpretation of station coordinate time series.

YEAR 1 SUMMARY OF ACTIVITIES

1. The SNARF Working Group was established jointly by (1) UNAVCO Inc, in preparation for EarthScope, and (2) the International Association of Geodesy, under the committee 'NAREF' (North American Reference Frame), which has organizational links to the governments of both the USA (NGS) and Canada (NRCan).

2. A group of 16 expert participants were selected by an open invitation. These experts covers a broad range of expertise in problems relating to reference frames, ranging from mathamatical geodesy and reference frames, to physical Earth models, tectonophysics, and GPS observation modeling.

3. Two workshops were held: (1) at the UNAVCO Inc. headquarters, January 27, 2004; and (2) at Montreal, during the week of the Joint Assembly of the AGU and CGU, 17-21 May, 2004. A special session on SNARF convened at the Joint Assembly constituted an integral part of the Montreal workshop.

4. Educational activities on SNARF were directed toward the broader scientific community included web publication at unavco.org, conference and presentations (e.g. at AGU), and journal articles.

5. Scientific activities on SNARF have so far addressed:

a. Reference frame theory and practice;

b. Geodetic analysis for reference frame realization, including optimal analysis, station motion model, validation studies, software intercomparisons, and error analysis;

c. Earth models, especially GIA (glacial isostatic adjustment) and secular loading associated with current climate change, and an assessment of whether such effects can be accurately included in the SNARF reference system definition;

d. Tectonic considerations regarding proximity to plate boundary effects;

e. Quality-affecting issues, such as data quality, multipath, monument stability, local- to broad-scale subsidence, hardware configuration, and site selection.

YEAR 1 SUMMARY OF FINDINGS

The SNARF WG found that geodetic precision appears to have reached the level that the development of a reference frame with sub-mm consistency is not limited by geodetic observations; rather it is limited by our ability to model the observations in a predictive way. Our research on Earth models concluded that inconsistencies between various GIA models is currently the most limiting factor toward defining SNARF with sufficient accuracy. It is therefore clear that much research (which we estimate would take many years) will be required to resolve this issue. Nevertheless, numerous examples of poor quality data indicate that careful quality assessment and judicious selection of stations representing 'stable North America' will be important if a sub-mm frame is to be realized, and therefore continuing research into appropriate station selection is vital.

Therefore, in the interim (until an accurate GIA model can be adopted) a phased-in approach to SNARF would be appropriate. This implies that incremental improvements would continue to be made to some initial version of SNARF for many years to come, but that the initial version will not be as accurate as the GPS observations would otherwise appear to allow. An initial version of SNARF would help to define a standard so that GPS time series could then themselves be used to help improve the GIA models. In this feedback model toward an improved SNARF, the adoption of interim frames allows for consistent GPS software intercomparisons and consistent GIA model intercomparisons. It would also significantly improve consistency when comparing GIA models with GPS time series.

In summary, the focus of further research should be on (a) specific site selection to define SNARF, and (b) improved GIA models. Both of these problems will be better addressed if we adopt an incremental approach to SNARF (say, with annual updates), which can then itself be used (as in a feedback loop) to help resolve site selection and GIA modeling issues.

More details on the research leading to these findings can be found on-line at:
http://www.unavco.org/resarch_science/workinggroups_projects/snarf/snarf.html

PBO Nucleus: Support for an Integrated Existing Geodetic Network in the Western U.S.

Frederick Blume
UNAVCO

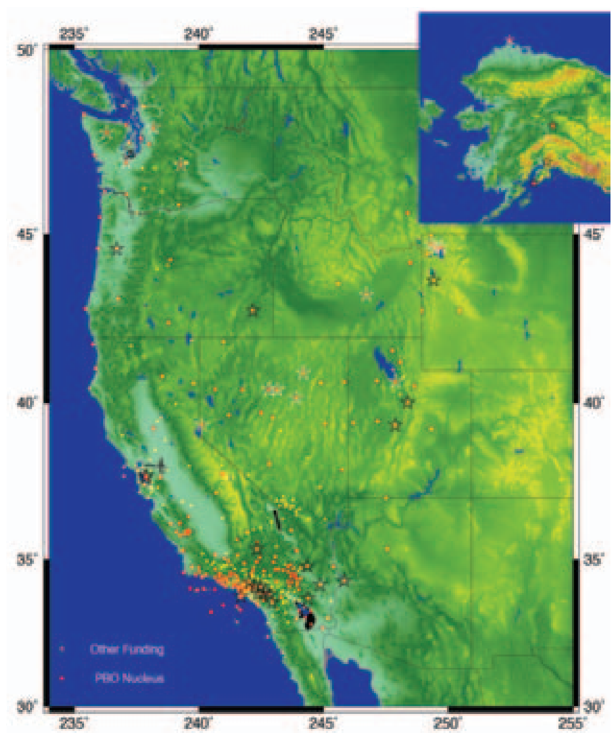
William Prescott
UNAVCO

Tectonic and earthquake research in the US has experienced a quiet revolution over the last decade precipitated by the recognition that slow-motion faulting events can both trigger and be triggered by regular earthquakes. Transient motion has now been found in essentially all tectonic environments, and the detection and analysis of such events is the first-order science target of the EarthScope Project. Because of this and a host of other fundamental tectonics questions that can be answered only with long-duration geodetic time series, the incipient 1400-station EarthScope Plate Boundary Observatory (PBO) network has been designed to leverage 432 existing continuous GPS stations whose measurements extend back over a decade. The irreplaceable recording history of these stations is accelerating EarthScope scientific return by providing the highest possible resolution. This resolution will be used to detect and understand transients, to determine the three-dimensional velocity field (particularly vertical motion), and to improve measurement precision by understanding the complex noise sources inherent in GPS.

The PBO Nucleus project supports the operation, maintenance and hardware upgrades of a subset of the six western U.S. geodetic networks until they are subsumed by PBO. Uninterrupted data flow from these stations will effectively double the time-series length of PBO over the expected life of EarthScope, and has created, for the first time, a single GPS-based geodetic network in the US. The other existing sites remain in operation under support from non-NSF sources (e.g. the USGS), and EarthScope continues to benefit from their continued operation.

On the grounds of relevance to EarthScope science goals, geographic distribution and data quality, 209 of the 432 existing stations were selected as the nucleus upon which to build PBO. Conversion of these stations to a PBO-compatible mode of operation was begun under previous funding, and as a result data now flow directly to PBO archives and processing centers while maintenance, operations, and meta-data requirements are continue to be upgraded to PBO standards. At the end of this project all 209 stations will be fully incorporated into PBO, meeting all standards for new PBO construction including data communications and land use permits. Funds for operation of these stations have been included in planned budgets for PBO after the construction phase ends and PBO begins an operational phase in 2008.

The research community has only begun to understand the pervasive effects of transient creep, and its societal consequences remained largely unexplored. For example, one open question is whether slow faulting pervasively moderates earthquake nucleation. The existence of slow earthquakes will impact seismic hazards estimation, since these transients are now known to 'absorb' a significant component of total slip in some regions and trigger earthquakes in others. The data from these stations serve a much larger audience than just the few people who work to keep them operating. This project is now collecting the data that will be used by the next generation of solid-earth researchers for at least two decades. Educational modules are being developed by a team of researchers, educators, and curriculum development professionals, and are being disseminated through regional and national workshops. An interactive website provides the newest developments in tectonics research to K-16 classrooms.



Stations comprising the PBO Nucleus network, in red, were selected from the AKDA, BARD, BARGEN, EBRY, PANGA, and SCIGN networks. Stations in yellow will be supported by other funding. PBO specification upgrade status is indicated by white stars (complete) and black (imminent).

Why Very High Rate (10-50 Hz) GPS Data is Useful for EarthScope

Yehuda Bock
Scripps Institution of Oceanography

Jeff Genrich
Scripps Institution of Oceanography

The Southern California Integrated GPS Network (SCIGN) is in the process of upgrading its stations to high-rate (1 Hz) sampling, and analyzing data in real-time (<1s) with instantaneous positioning to increase the temporal resolution and latency of measurements of seismic motion and transient deformation. Recent earthquake recordings indicate that there are significant benefits to the collection of even higher rate data available with modern GPS receivers. Our tests over short distances (meters) to typical SCIGN medium-scale station spacing (10's of km) show that instantaneous 10-20 Hz station positions exhibit white noise characteristics above 0.5 Hz, and have the same single-epoch precision level as reported previously for 1 Hz positions. Furthermore, because the instantaneous positions are essentially uncorrelated, "square-root-of-n" averaging can increase the detection threshold of short-term (up to several minutes) transient signals by nearly an order of magnitude. Averaging 20 Hz measurements to 1 Hz samples, for example, yields horizontal resolution of about 1 mm and vertical resolution of about 5 mm over medium-scale networks; for small aperture networks, horizontal resolution is about 0.2 mm in the horizontal and 0.5 mm in the vertical.

What are the implications of our study of 10-20 Hz data for the design, operations, and analysis of regional-scale GPS networks such as the 1200-station Japan GEONET and the in-construction 1100-station EarthScope Plate Boundary Observatory (PBO)? We have determined that the real-time continuous flow and analysis of very high rate data (20 Hz or even greater) is supportable through existing SCIGN radio communications infrastructure and instantaneous positioning software. These data are useful for directly measuring displacements from strong motion seismic events at the sampling rates (50-100 Hz) of modern seismic instrumentation (accelerometers and seismometers). We are also testing\ new GPS receivers that sample at 50 Hz, and expect that these data will also exhibit white noise characteristics at the higher frequencies. We can, therefore, envisage GPS seismic networks with output displacement channels at various frequencies (e.g., 50 Hz, 20 Hz, 10 Hz, 1 Hz). However, these data are useful not only for seismic motions but for the detection of possible aseismic transient deformation at frequencies of 1/several minutes, and possibly improved resolution of aseismic slow earthquakes short-term postseismic deformation. GEONET is already streaming 1 Hz data from all 1200 stations and will be upgradeable to very high rate observations with the introduction of IP version 6 communications in Japan. The current model of PBO data retrieval over commercial cellular providers is more problematic since there is no possibility of the continuous reliable collection of 10-20 Hz or even 1 Hz data. There are plans to store high-rate (5 Hz) data in a rotating buffer in the NetRS receivers for retrieval after significant seismic events. This approach, however, may not best accomplish the stated goal of PBO of detecting aseismic deformation transients, since valuable data are not being collected. On the other hand, SCIGN is continuing to upgrade its stations to continuous high-rate (1 Hz) real-time operations, and is building a prototype 2-20 Hz sub-network in San Diego County.

EarthScope Science for Mid-America: Onward!

Paul Bodin
University of Memphis

Mitchell Withers
University of Memphis

Joan Gomberg
U.S. Geographic Survey

Charles Langston
University of Memphis

Christine Powell
University of Memphis

Gary Patterson
University of Memphis

In mid-America (roughly the region between the Rocky and Appalachian mountains, and between the US/Canadian border and the Gulf of Mexico) the EarthScope program presents important opportunities to advance the understanding of the evolution, composition, and hazards of the North American heartland. On August 18-21, 2004, a diverse group of fifty Earth scientists representing academic institutions, state agencies, and seismic engineering professionals, gathered in Memphis, Tennessee, to define and discuss fundamental scientific issues central to the success of the EarthScope program. EarthScope projects that help to define the geometry of plate margins through time and the internal fabrics, compositions, and mechanical properties of the regions terranes will be key to understanding the evolution of what is now “stable” continental North America. Emphasis will need to be on the construction and deformational significance of intracratonic basins, rifts, and geophysical anomalies. We must also illuminate the relationship, if any, between shallow crustal and deeper lithosphere structures in the context of plate tectonics. While the region has been remote from plate boundaries for millions of years it is still seismically active, with areas that may be deforming rapidly, and it has also been the site of mysterious epeirogenic vertical motions. What is the best physical model to understand ongoing mid-plate earthquake occurrence? How do stress and strain vary temporally and spatially? To what extent do inherited lithospheric structures influence modern seismogenesis? What role in deformation and seismicity do fluids play? What are the physical properties of active fault zones? Answers to these basic questions require collaboratively facing two major scientific challenges. First, we need to define scientific ontologies and to construct regional databases, and address how the community will provide quality control for data, analysis methods and data products. Second we must define regionally meaningful strategies to nurture the development of scientifically literate consumers of EarthScope knowledge products. Among the many ideas discussed were building partnerships between research institutions and minority schools, providing support for a US educational seismology network, deploying EarthScope sensors at educational institutions, developing classroom materials that can be easily used by teachers, and promoting participation of researchers in local K-16 education.

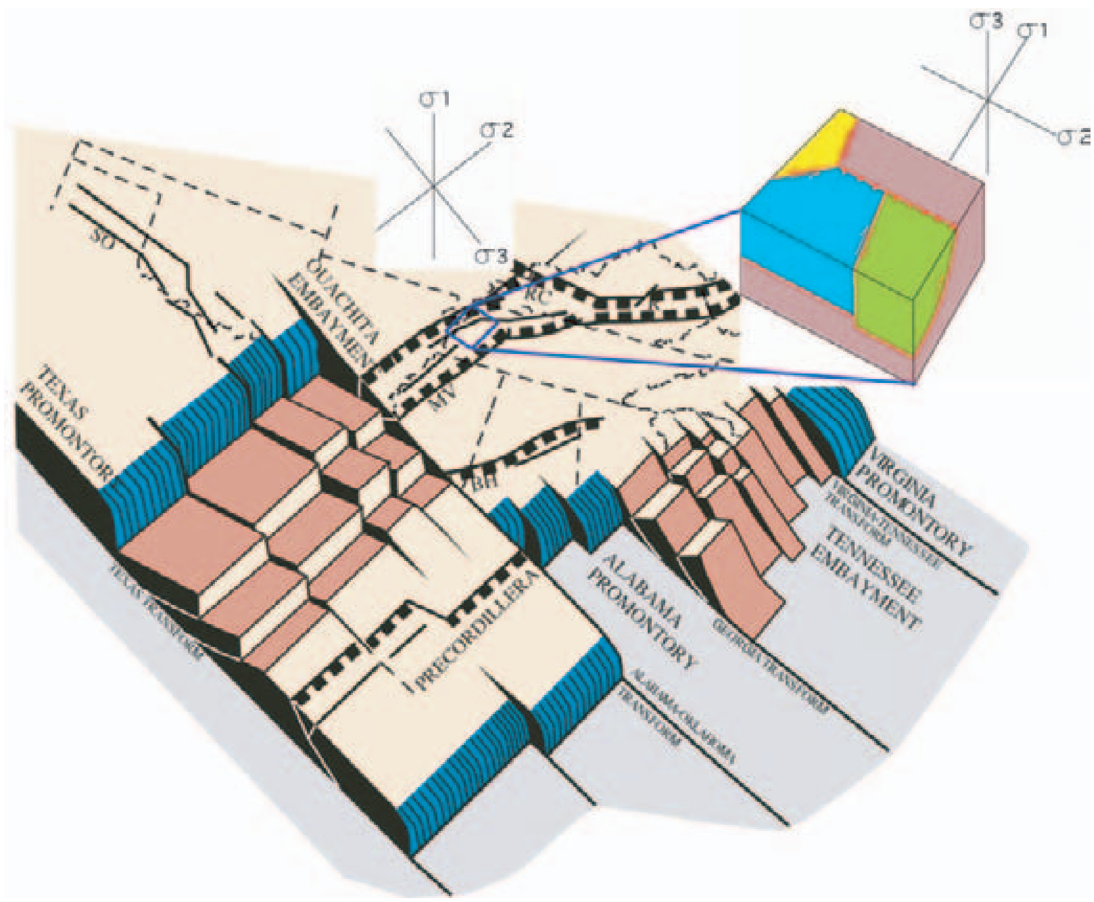
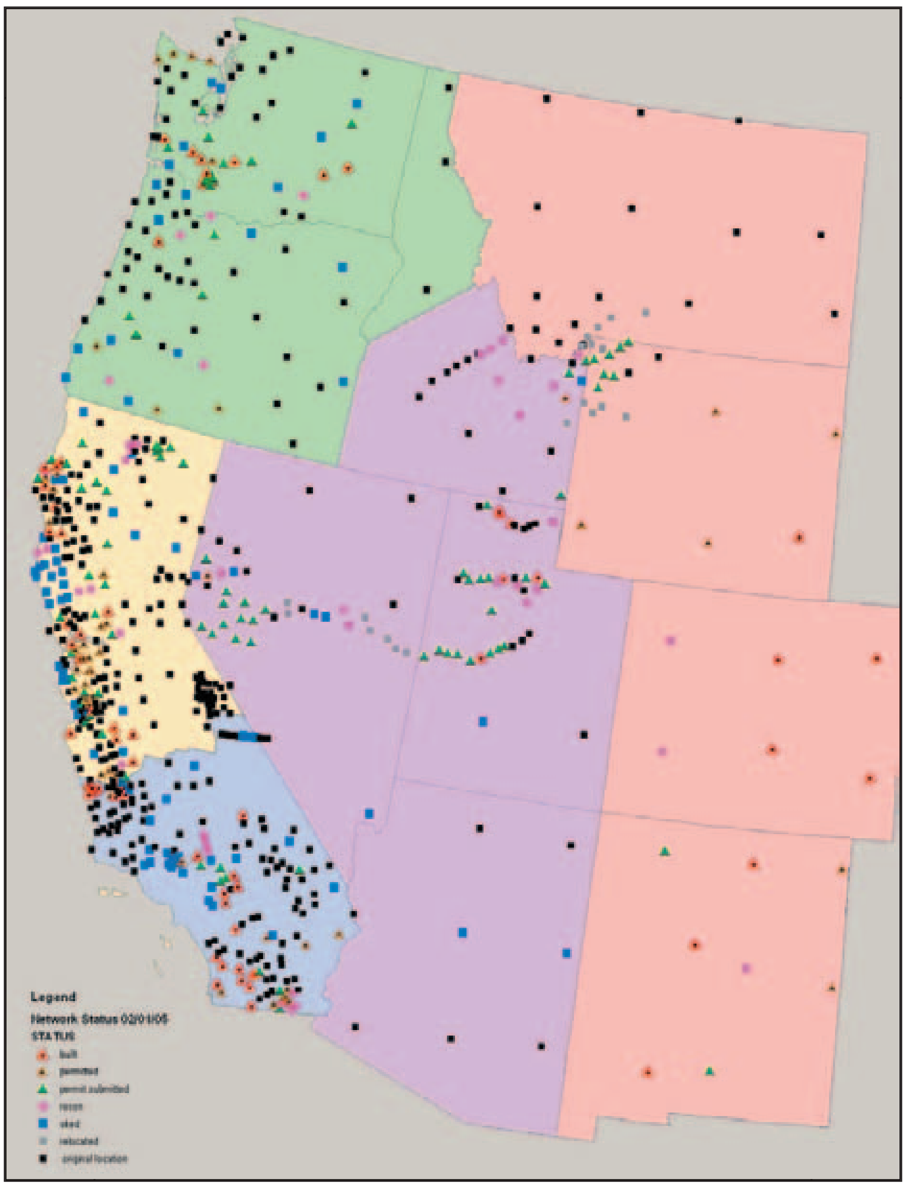


Figure modified from William Thomas (U. Kentucky, Lexington) illustrating the imprint of inherited structures and their role in current processes. The block model shows idealized rock packages associated with accreted-then-rifted crust, the insets show one possible geometry of faults in the seismically active New Madrid seismic zone, and implied stress field orientations.

Plate Boundary Observatory GPS and Strainmeter Site Permitting Update, Obstacles, and Plans for Years 2-5 of Network Buildout

Kyle Bohnenstiehl
UNAVCO

Permitting of GPS and strainmeter sites is a critical path to the construction of the Plate Boundary Observatory. Costs, schedule, and long term occupancy are all variables that must be managed to keep the network operating and producing scientific data. Of all of the variables in the network construction and long term maintenance, permitting poses some of the greatest risks that are difficult to manage. This talk looks at the current status of the permitting of GPS and strainmeter sites, the hurdles that have been encountered, and the corrective actions that have been taken to date. In addition, the talk will look ahead at permitting priorities in years 3-5 of network construction. Cooperation from Federal agencies, state, county, and local government will be addressed and cost and timing issues will be analyzed for each landowner category. NEPA process requirements as they apply to EarthScope facilities will be discussed and the relevance of this process to other large physical science facilities will be presented. Finally, an analysis of critical path risks will be presented with ways that the EarthScope community may be able to help overcome them. In light of the current regulatory climate that exists with public land owners, the lessons learned in permitting PBO are directly applicable to other large, geographically dispersed science projects seeking NSF funds.



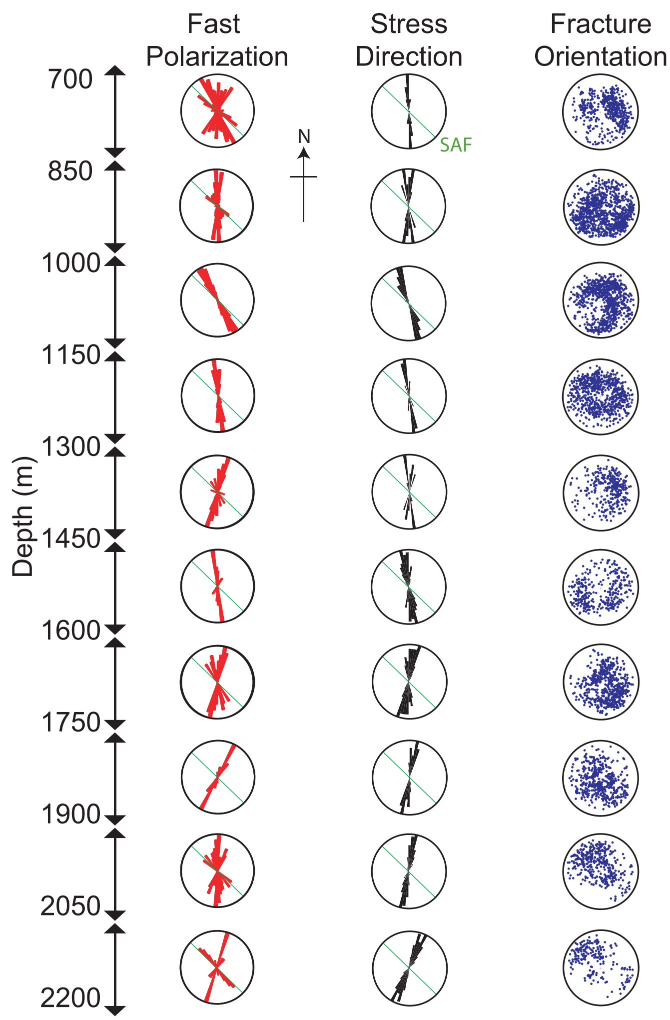
Current PBO GPS Network status on 2/01/2005.

Understanding Physical Properties and Seismic Anisotropy in the Crust Adjacent to the San Andreas Fault Using Observations from SAFOD

Naomi Boness
Stanford University

Mark Zoback
Stanford University

The region surrounding the San Andreas Fault Observatory at Depth (SAFOD) near Parkfield, CA is an ideal location to study the effect of crustal structure and the state of stress on seismic velocity anisotropy because the direction of maximum horizontal compression is at a high angle to the predominantly northwest-southeast structural trend. To study seismic anisotropy in the crust at multiple scales we utilize a suite of geophysical logs from the SAFOD boreholes, earthquake data recorded on the Pilot Hole array and the High Resolution Seismic Network (HRSN) operated by U.C. Berkeley. At the smallest spatial scale, data from the 2.2-km-deep pilot hole and upper section of the main SAFOD borehole provides a unique opportunity for studying the in-situ physical properties of the granitic crust adjacent to the San Andreas Fault Zone. Dipole sonic logs in the SAFOD boreholes indicate that the shear-wave velocity anisotropy of the rocks surrounding the wellbore is on the order of 3 to 10% and controlled by the tectonic stress field. An analysis of earthquake seismograms shows that ray paths through the Salinian granite adjacent to the fault exhibit fast shear wave polarizations aligned with the direction of maximum horizontal compression, in agreement with the SAFOD measurements. In contrast, ray paths along the San Andreas fault and through fault-parallel sedimentary structures yield fast directions consistent with the northwest-southeast structural trend. We observe both structural and stress-induced anisotropy at a variety of scales and direct measurements of the physical properties of the crust collected in the SAFOD boreholes allows us to discriminate between these mechanisms.



Comparison of the fast shear polarization direction with SHmax determined from borehole breakouts and tensile cracks [Hickman and Zoback, 2004] and fracture orientations as observed on the FMI log. The strike of the San Andreas Fault (SAF) is shown for reference. The direction of the fast shear direction correlates very well with the orientation of SHmax whereas the distribution of fracture orientations is seemingly random.

New Insights Into Lithospheric Evolution by Linking Lower Crustal and Mantle Xenolith Records with Surface Exposures

Samuel Bowring
Massachusetts Institute of Technology

Rebecca Flowers
Massachusetts Institute of Technology

James Crowley
Massachusetts Institute of Technology

Blair Schoene
Massachusetts Institute of Technology

Michael Williams
University of Massachusetts

Karl Karlstrom
University of New Mexico

The Precambrian lithosphere exposed in the western U.S. reflects a protracted history from ca. > 3.5-1.0 Ga which involved accretion of a collage of early Proterozoic rocks, including the enigmatic Mojave Province and island arcs, from 1.8-1.6 Ga followed by a major period of dominantly granitic magmatism and associated deformation ca. 1.45-1.35 Ga. Present day exposures in Arizona, New Mexico, and Colorado reveal a laterally segmented orogen that has experienced differential exhumation and has been strongly overprinted by Laramide- and Tertiary-aged tectonomagmatic processes. U-Pb and $^{40}Ar/^{39}Ar$ geo- and thermochronology of surface exposures combined with similar data from lower crustal xenoliths offer a direct look at the thermal structure through time at various depths in the lithosphere and hence offers a unique view of the temperature-time evolution of the orogen. These data are essential complements to seismic data in understanding the structure and evolution of the continental lithosphere.

In Colorado, Wyoming, New Mexico and Arizona, different crustal domains that expose sharply contrasting histories depending on the amount of exhumation characterize the Proterozoic orogen. In particular, some crustal blocks show long residence times in the middle-lower crust with very slow cooling rates (<1 °C Ma) from ca. 1.7 to 1.1 Ga while others show a strong overprint by ca. 1.4 Ga metamorphism and deformation followed by slow cooling. Comparison of a wide variety of areas allows us to piece together both vertical and lateral gradients in metamorphism and deformation and to gain insight into the maturation of continental lithosphere. Numerical thermal modeling is consistent with lateral variation in exposure levels being in part due to distribution of heat producing elements.

As an example, our work on the Four Corners region demonstrates a complex diachronous origin for the lower crust, and documents important mass transfers between asthenosphere, lithospheric mantle, and crust. Work on lower crustal xenoliths confirms a link between ca. 1.4 Ga mafic magmatism and metamorphism in the lower crust and tectonothermal events in the middle crust. These studies show that portions of the lower crust formed and accreted at 1.8-1.6 Ga, and were substantially modified ca. 1.4 Ga by mafic underplating that produced voluminous granitic magmatism and associated low P – high T metamorphism (0.35-0.6 GPa, 500-700°C) preserved in exposures of middle and upper crustal rocks. A regionally extensive high-velocity (7.xx) lower crust has been widely interpreted as evidence of underplated magmas ca. 1.4 Ga, and this has recently been substantiated by xenoliths studies that also indicate that the underplate is complex and intruded during at least several episodes (1.68 and 1.46, 1.42, 1.36 Ga). The presence of garnet granulites developed ca. 1.7 Ga also suggests a complex origin of the high-velocity layer.

For EarthScope to succeed in understanding the structure and evolution of the continental lithosphere, we need a systematic program to integrate geochronological, thermochronological, and petrological records of lower crustal xenoliths with those from surface exposures to map out the large-scale thermal history of the lithosphere in the western U.S. The ages, thermal history, geochemistry, and in some cases physical property measurements for the abundant and diverse lower crustal xenolith suites in the western U.S. will provide essential data for interpreting the seismic structure of the lower crust and upper mantle determined by EarthScope.

Signals from the Earth's Deep Plumbing

Kevin Brown
Scripps Institution of Oceanography

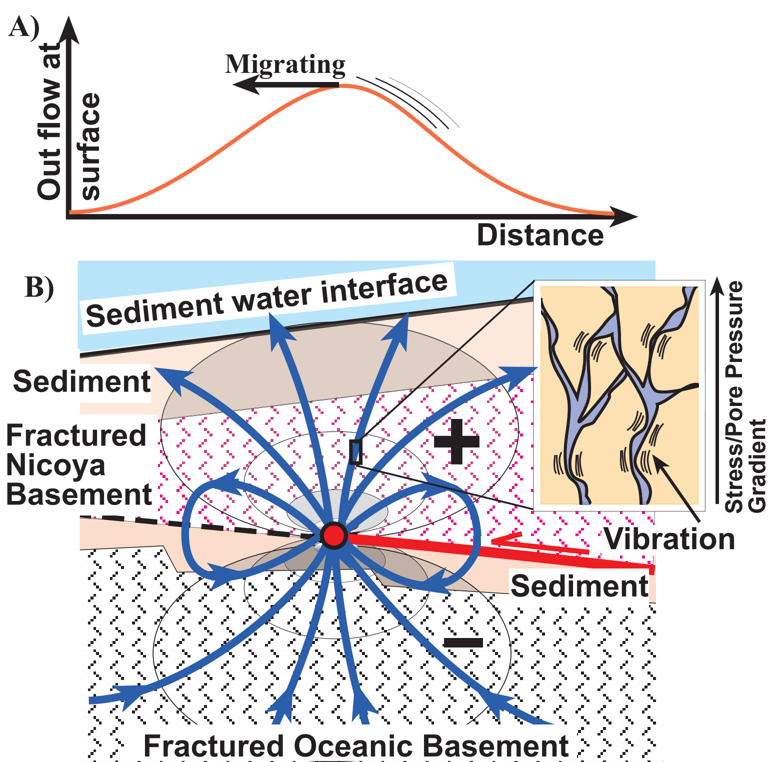
Michael Tryon
Scripps Institution of Oceanography

Susan Schwartz
UCSC

Dorman LeRoy
Scripps Institution of Oceanography

Slow, slip events at convergent margin plate boundaries increasingly appear to be associated with prolonged periods of elevated seismic signal, termed seismic tremor. This seismic signal has now been linked to pulses of fluid expelled through the surface of the Costa Rica subduction forearc. During a six month combined deployment of Ocean Bottom Seismometers (OBSs) and fluid flow meters, three correlated pulses of fluid and episodes of elevated seismic noise are seen over lateral distances of 30 km or more. Individual flow events displace between ±3 mm to 5 mm through the seabed and initiate and terminate generally within a few days of each other. The noise and flow events last a few weeks and start and stop within days of each other at adjacent stations. The occurrence of three flow events coincident with three periods of elevated seismic "noise" argues strongly that these phenomena share the same fundamental driving force. The simplest interpretation is that the flow and seismic noise result from progressive and slow (perhaps several 100s m/day) passage of an aseismic rupture dislocation and associated poro-elastic stress field. The propagating rupture dislocations generate intense stress/pore pressure gradients around the rupture tip. These gradients intensify and accelerate fracture flow as the dislocation approaches. We hypothesize the seismic tremor like noise is associated with momentum and fluid velocity changes generated at fracture constriction points similar to the "knocking of pipes" as faucets are turned on. Similar processes may be associated with volcanic tremor. Flow rate (forcing), fracture geometry, and wall elasticity and damping, all affect the onset and resultant resonant frequency so there should be an expectation of differences in source characteristics between different tectonic environments and structural settings.

Our data suggest three discreet creep episodes lasting several weeks occured in six month period. Geodetic data indicate that the Nicoya Peninsula section of the Middle America subduction zone is partially coupled with up to 50% of the plate convergence rate being accommodated by aseismic processes. It is likely that a portion is occurring as episodic creep, potentially resulting in 10-100s of unrecorded slip events over several decades. In summary, the earth's plumbing is signaling near-silent rupture migrations within coupled seismogenic faults and we predict that fluid flow/stress related effects will provide a new means to detect plate boundary creep events and instability and prerupture fault breakdown in both oceanic subduction systems and terrestrial environments such as the San Andreas.



A conceptual model that relates, a) the flow at the surface, and seismic noise, to the passage of a rupture dislocation along the decollement. The stress field around the rupture tip generates both net increases or decreases in total stress that intensify it approaches. These stresses impose a related pressure field on fluids within fracture systems in the crystalline Nicoya and subducting oceanic basement and within the pores of the sediments. This causes flow though the porous networks and, depending on the sign of the stress changes, in and outflow at the surface. The increasing stress/pressure in the fracture networks ultimately accelerate flow within the fracture systems to initiate sustained vibration of the fracture walls. It is this vibration that causes the seismic noise. This mechanism may explain the nearly silent earthquakes that are increasing been observed within subduction zones and suggests we can see deeper into the earthquake process by remote observation than we could ever have imagined previously.

Seismic Bright Spots, Magmatism and Fluids in the Deep Crust

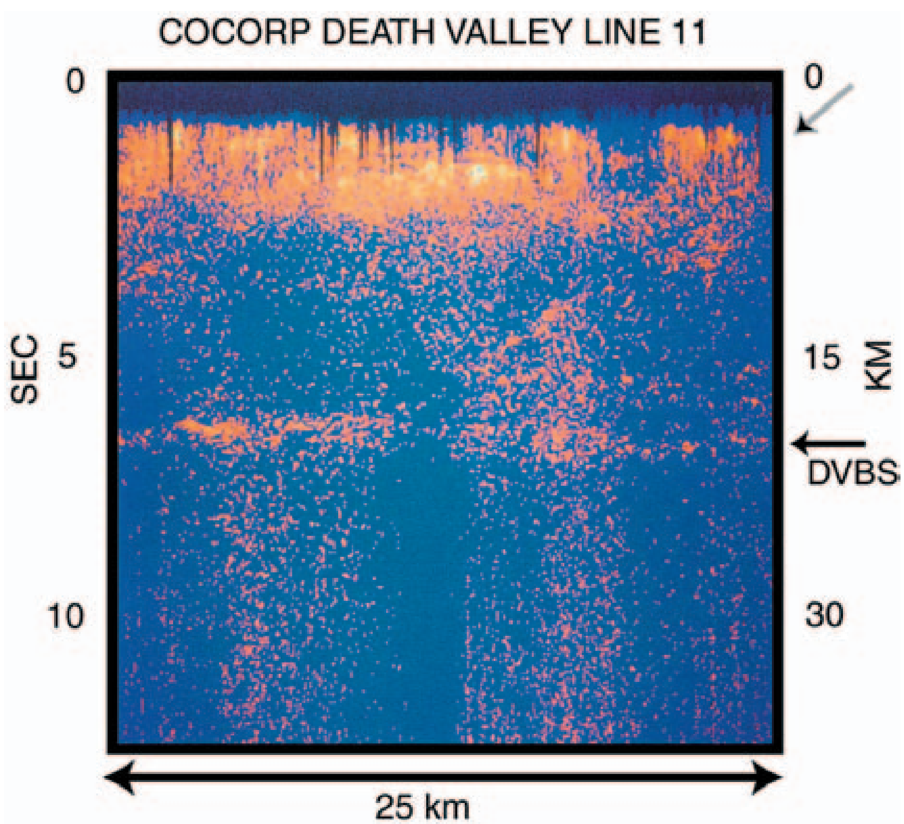
Larry Brown
Cornell University

Larry Cathles
Cornell University

One of the most dramatic observations in seismic exploration of the continental lithosphere over the last 25 years has been the discovery of seismic reflection "bright spots" in the middle to deep crust. Most have been interpreted as large magma sills, the "brightest" being still molten ("hot") while others have long since frozen ("cold"). These seismically mapped sills can have lateral dimensions of over 100 km, and range in thickness from tens of meters to possibly several kilometers. The brightest (presumably fluid) are most commonly observed near the brittle-ductile transition (~350°C isotherm) at midcrustal depths (15-20 km). Whether they consist of water or molten rock, these features can profoundly impact crustal rheology, metamorphism, igneous evolution, seismic and volcanic risk assessment, and mineral resources.

EarthScope, particularly USArray, offers and unparalleled opportunity to systematically identify and map seismic bright spots beneath the western U.S., to discriminate "hot" (magma) from "cold" (solidified) sills, and to evaluate their physical and chemical implications for crustal evolution. "Bigfoot" is an obvious reconnaissance tool for searching for such bright spots, with the flexible array providing the means to subsequently map their extent, physical properties (e.g. fluid), and tectonic relationships (feeders to surface volcanics). The geodetic tools of the PBO and INSAR offer complementary means of searching for surface deformation that may be associated with deep bright spots, either those identified by seismic studies or those, which should be targeted for seismic surveys. The Socorro bright spot in particular is the archetype of such features and the obvious choice for a calibration program of seismic, geodetic and magnetotelluric studies.

The results of this program should impact virtually all aspects of lithospheric evolution and thus constitute a valuable general resource for EarthScope. Sills serve as primary evidence (past and present) of thermal modification of the lithosphere, as markers for unraveling subsequent tectonic deformation and as guides to stress and rheological conditions at depth. Understanding the links between sills as ore deposits could lead to new approaches to mineral exploration, and a basic explanation for the very different regional abundances of environmentally sensitive elements.The techniques developed to detect and evaluate intracrustal bright spots should hone USArray's general capabilities to resolve more subtle intra-lithospheric complexity.



Deep reflection profile over Death Valley Bright Spot at ca 18 km depth. Dipping event may be feeder dike. After DeVoogd et al., 1986.

The Continental U.S., Secular Variation in Metamorphic Regimes and EarthScope

Michael Brown
University of Maryland

The core of the continental US comprises the southern extension of the Canadian Shield (Wyoming and Superior cratons, and the Trans-Hudson orogen), whereas central and southern portions consist of juvenile terranes (Mojave, Yavapai, Mazatzal), which represent accreted arcs, with cross-cutting collisional orogens (Grenville, Appalachian) in the east. To the west, the geology records deformation associated with the Rocky Mountains, Mesozoic and Cenozoic extension and a succession of oblique collisions involving terrane migration along the continental margin. Integrated studies of metamorphic evolution in different settings in concert with seismic reflection-refraction experiments to determine high resolution 3-D crustal and lithosphere structure will yield insight into thermal regimes and tectonic processes to complement studies of modern orogens (Andes, Himalayas).

The pressure (P) – temperature (T) – time (t) evolution of rocks reflects the thermal regime(s) of equilibration, whereas the distribution of peak P-T conditions records spatial variation in thermal regime(s). P-T conditions for metamorphic facies are well established, but new techniques have revealed more extreme conditions of crustal metamorphism (Figure). Thus, the eclogite facies extends to pressures >6 GPa (ultrahigh pressure metamorphism - UHPM), the granulite facies extends to temperatures >1,000ºC (ultrahigh temperature metamorphism - UHTM), and there is a transition between the two called high-pressure granulite metamorphism (HPGM). These reflect different thermal regimes (high dP/dT to low dP/dT) and secular change (Figure), suggesting three global tectonic styles with punctuated occurrence of orogenesis. Systematic changes coincide with Archean to Proterozoic and Proterozoic to Phanerozoic transitions. Archean rocks record P-T conditions of moderate-P – high-T metamorphic facies, and there is no record of subduction of continental crust into the mantle before ca. 2.7 Ga, when the first type II eclogite occurs.

UHTM (>900ºC, ~0.5-1.5 GPa) is predominantly a Neoarchean-Proterozoic phenomenon that coincided with supercontinent cycles (Superior/Sclavia, Nuna, Rodinia and Gondwana), suggesting association with crustal aggregation and events in the mantle. In the continental US, UHTM granulites (some suspect) occur within basement uplifts west of the Appalachians and in the Blue Ridge terrane, and in once-contiguous basement of the Arica embayment.

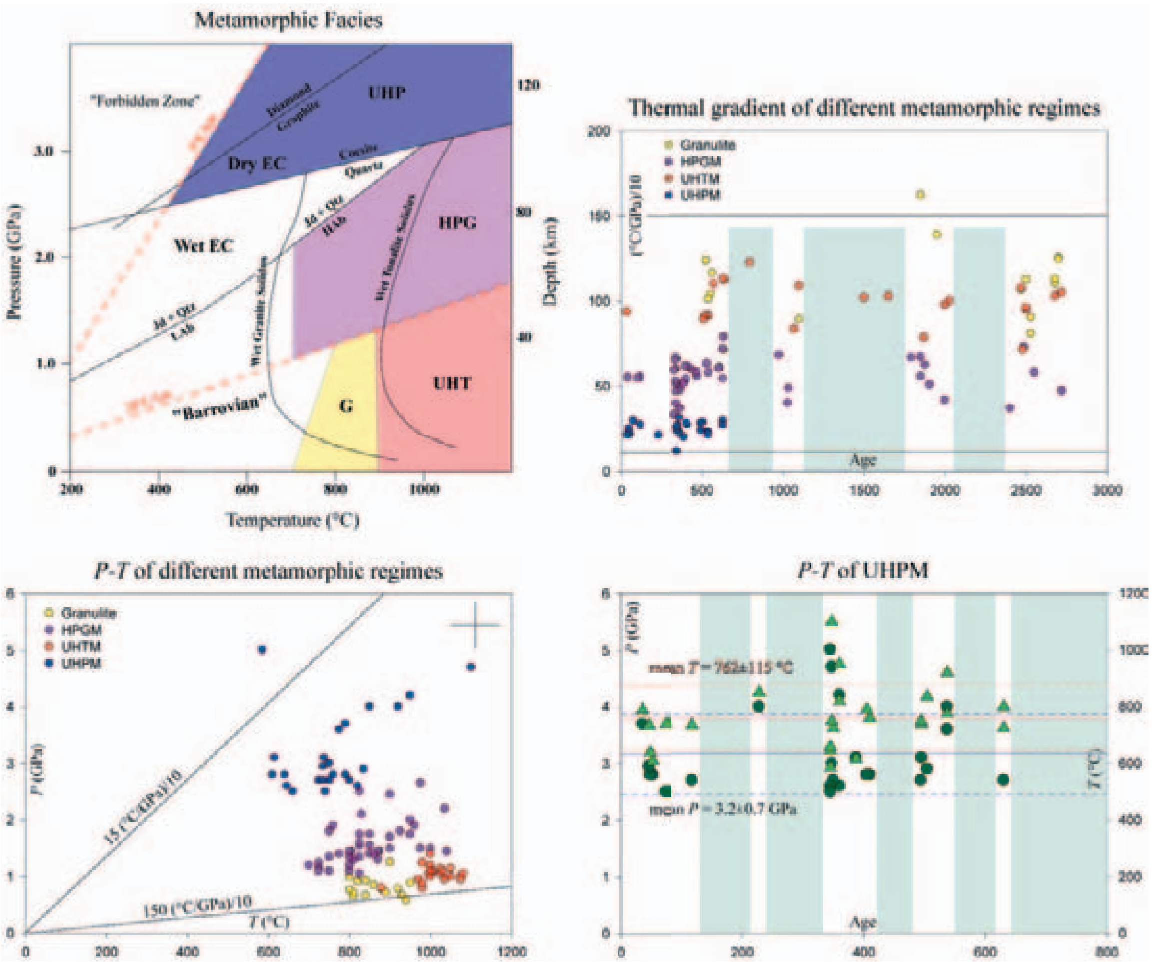
HPGM and medium-temperature (type II) eclogite metamorphism (~750->1000ºC, ~1.5->2.5 GPa) is predominantly a Proterozoic-Paleozoic phenomenon, for which the P-T regime suggests taking crust into the mantle, followed by thermal relaxation. This supports a transition to subduction during the Neoarchaean Era with some form of global 'plate' tectonics from the beginning of the Proterozoic Eon. In the continental US, eclogites occur with HPGM in the Charlotte belt of the Carolina terrane (Newbury eclogite, Silverstreet domain, Appalachians; age poorly constrained (550>HPGM>415 Ma), but likely Ediacaran-Lower Cambrian).

Blueschists and low-temperature (type I) eclogites (BS) first appear in the Neoproterozoic Era becoming common through the Phanerozoic Eon; they record low thermal gradients, probably associated with 'cold' subduction during the accretionary phase of the tectonic cycle. BS are common in the western continental US (Franciscan), but are rare in the collisional orogens of the east. UHPM (~700->900ºC, ~2.5->6.0 GPa) is predominantly a Phanerozoic phenomenon related to deep continental subduction, and is characteristic of the modern plate tectonics regime. UHPM rocks have not been reported from the continental US, but are possible within the Blue Ridge terrane (Lick Ridge eclogite, Appalachians, where suspect quartz/coesite occurs in zircon; the age of high-P metamorphism is ca. 460 Ma).

EarthScope data may be used to constrain crustal structure and relict lithosphere-scale features of orogens; for example, evidence of Proterozoic lithosphere subduction to depths >200km is increasingly common in high-resolution tomographic images, but it is unclear whether 'deep' subduction characteristic of the modern plate tectonics regime occurred before the Neoproterozoic Era. The challenge for us all in the EarthScope decade is to integrate studies of geological phenomena with results of geophysical experiments to resolve tectonic models and better understand processes in orogenesis. For example, a comparative study of deep structure in traversing the Adirondack Mts and the Northern Appalachians with that in traversing the Ozark Dome and the Southern Appalachians is likely to better constrain whether continental crust has been subducted to UHPM depths during the formation of the Appalachians and the Grenvillian orogen.

Figure on Page 91 >

Michael Brown
University of Maryland



P-T range of extreme metamorphic facies (Ultrahigh Pressure – UHP; Eclogite – EC; High Pressure Granulite – HPG; Granulite – G; and, Ultrahigh Temperature – UHT), plot of peak P-T for examples of crustal metamorphism under different metamorphic regimes (Granulite; High Pressure Granulite Metamorphism – HPGM; Ultrahigh Temperature Metamorphism – UHTM; and, Ultrahigh Pressure Metamorphism – UHPM), thermal gradient implied by peak P-T for examples of crustal metamorphism under different metamorphic regimes, and P-T at maximum P for examples of UHPM.

Investigation of Crustal Structures in the New Madrid Seismic Zone Using Industry Reflection Data

Sharon Browning
University of Memphis

Charles Langston
University of Memphis

Roy VanArsdale
University of Memphis

The New Madrid seismic zone (NMSZ), located in the central United States (Fig. 1), is the most seismically active zone east of the Rocky Mountains. It lies within the Reelfoot rift, a northeast-trending basement fault zone. Historical records and paleoseismic research indicate this region has experienced at least three major prehistoric events that occurred in approximately A.D. 900, and A.D. 490, in addition to the three large earthquakes estimated at M 7.8 to 8.1 in the winter of 1811-1812. A thorough understanding of the underlying structures and processes responsible for seismicity has not been determined. Recent studies suggest significant seismicity does not extend beyond a proposed eastern margin of the rift, leading to conjecture that the margin is accumulating strain, posing unknown seismic hazards for the central U.S. Seventeen seismic reflection lines are located adjacent to this margin and are being reprocessed to delineate crustal structure and provide information on fault geometry. Geologic interpretation of resulting structures will be constrained by available magnetic and gravity data, further defining the structure of the eastern margin and providing insight into seismic hazards for the central and eastern U.S. These reflection profiles complement data collected by USArray and add to the foundation of knowledge sought by EarthScope in integrating lithospheric studies.

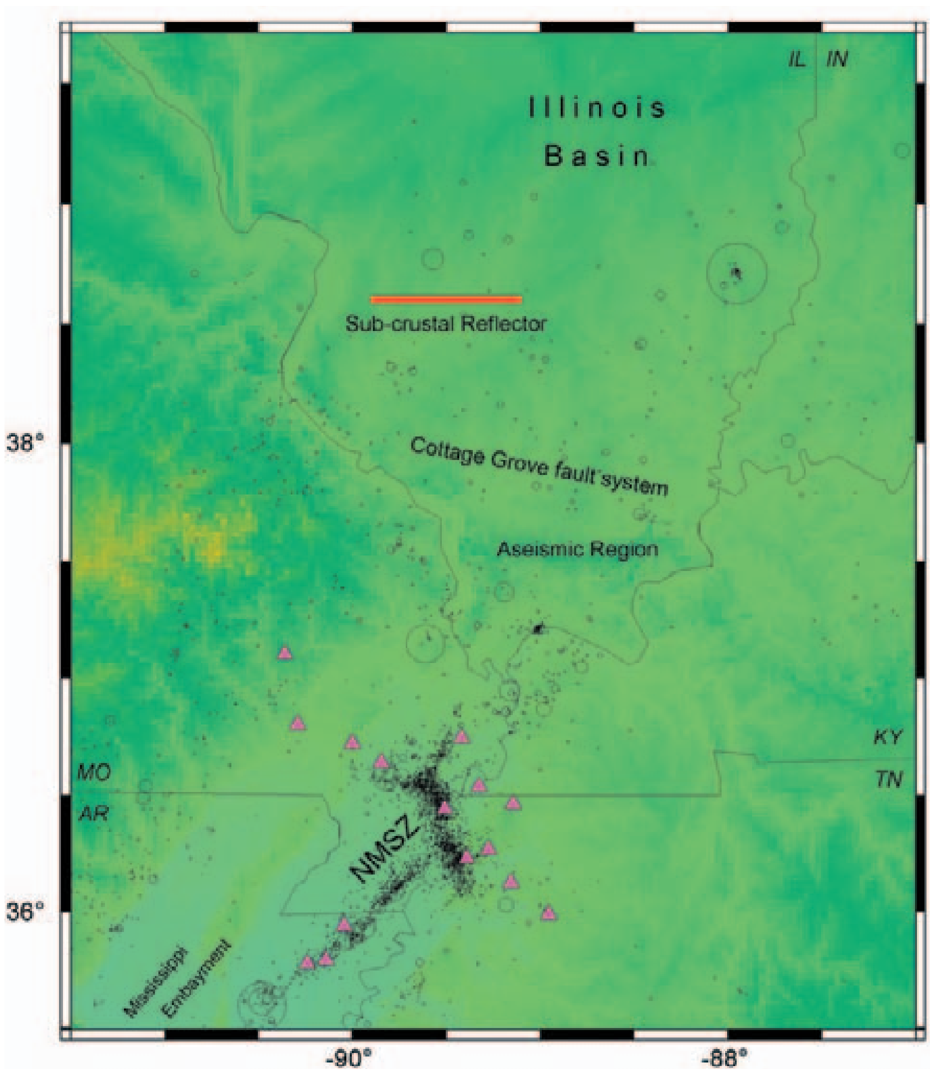
A Pilot Study of Continental Lithosphere Beneath the New Madrid Seismic Zone with a Broadband Seismic Array

Michael Brudzinski
University of Wisconsin-Madison/Miami University of Ohio

Wang-Ping Chen
University of Illinois

Cliff Thurber
University of Wisconsin

The New Madrid Seismic Zone (NMSZ) poses the greatest seismic risk in mid-America yet its tectonic origin and lack of appreciable current deformation remain a major enigma. With modest support from the College of Arts and Science at Miami University and the Research Board and the National Center for Supercomputing Applications (NCSA) at the University of Illinois, we will be undertaking a pilot study of the NMSZ with an array of about ten broadband seismographs, consisting of Guralp 3T sensors and Reftek 130 data acquisition systems. The deployment will begin in July of 2005 and can serve as a pilot study for future EarthScope/USArray projects in and around the New Madrid region. We aim to obtain new observations on deep-seated lithospheric structures in order to complement other results from seismicity, crustal imaging, geodesy, geopotential and geological mapping. To connect with short-term UW-Madison deployments over a decade ago (employing mid-period sensors), we plan to reoccupy some previous sites in the NMSZ. Furthermore, we will also focus on the northward extension of the NMSZ into the southern Illinois Basin, where 1) some of the largest earthquakes in mid-America occurred over the past 100 years, 2) an apparent aseismic zone exists south of the Cottage Grove fault system, and 3) a sub-crustal reflector has been identified from deep seismic reflection profiles. The broadband nature of our data will further constrain lithospheric structures by utilizing frequency-dependent properties of seismic reflections/conversions and anisotropy.

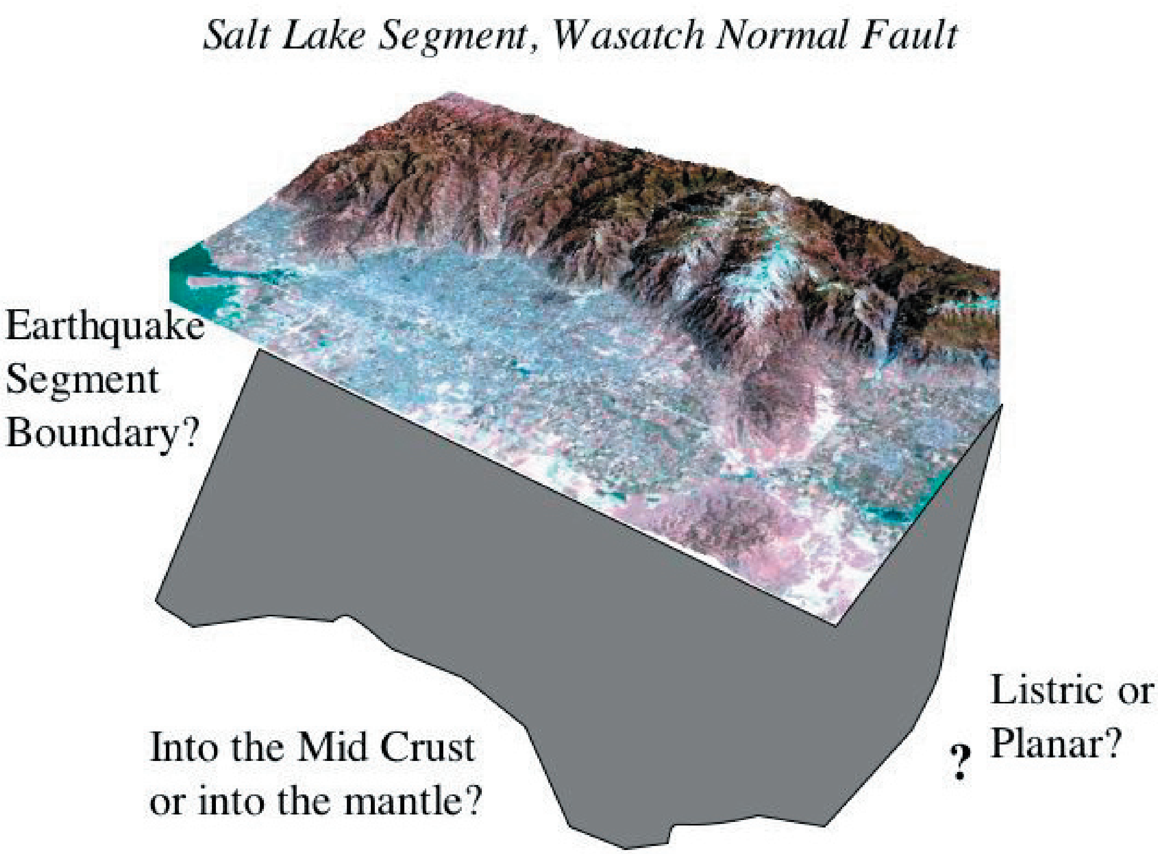


Map of region surrounding New Madrid Seismic Zone (NMSZ) showing topography, seismicity (circles proportional to fault rupture area [Brudzinski and Chen, SRL, 2003]), and seismic stations from previous short-term UW-Madison deployments (triangles). A new array of broadband seismometers will be deployed in July of 2005 for a pilot study of deep-seated lithospheric structures. We will reoccupy some previous sites as well as new ones in the southern Illinois basin, where a curious aseismic region and sub-crustal reflector have been identified.

Towards a Community Fault Model for the Great Basin

Ronald Bruhn
University of Utah

The three dimensional geometry of faulting in the subsurface of the Great Basin and its periphery presents one of the grand challenges for research during EarthScope. Despite years of research by earth scientists, we know relatively little about the subsurface geometry of faulting in many parts of the province. For example, there is little data concerning the dip -angle of the Wasatch fault in the subsurface, although this is one of the most studied normal faults in the world with respect to paleoseismology, thermochronology, and geodetics. Determining the subsurface geometry of faulting is fundamental to a wide range of topics including continental geodynamics, earthquake hazards, and the exploration and extraction of natural resources. A number of key questions of significance to EarthScope can be addressed with better knowledge of subsurface fault geometry: What are the relationships between brittle – frictional structures in the upper parts of the crust and more ductile structures in the deeper crust and mantle? Why is there a discrepancy between geological and geodetic determined rates of extension? What are the implications for strong ground motion in urban corridors surrounded and underlain by Great Basin faults? What are the major pathways for fluid transport in the crust, and between the mantle and crust? To answer these questions a group of scientists from the University of Utah, University of Nevada (both Reno and Las Vegas), University of Southern California and Harvard University are proposing to develop a community fault model that will be developed in conjunction with a related model of lithosphere seismic velocities. These models will be available to all scientists and the public. The modeling paradigm will be similar to that developed by SCEC for tectonics and seismic hazards research in southern California, The models will be constructed from a variety of sources including academic, government and industrial data, as well as by integrating new data acquired during EarthScope. Model development will require interdisciplinary collaboration and participation by a significant number of the scientific community, and provide an important resource for future studies of Great Basin structure, tectonics, and geodynamics.



The Wasatch normal fault at Salt Lake City, Utah. Despite the spectacular surface geology and excellent seismic and geodetic networks we know little about the subsurface geometry of the fault. G.K. Gilbert thought it dipped about 30 degrees, what do you think?

USArray: Preparing Arizona for Bigfoot's Deployment

Nievita Bueno
Arizona State University

Steven Semken
Arizona State University

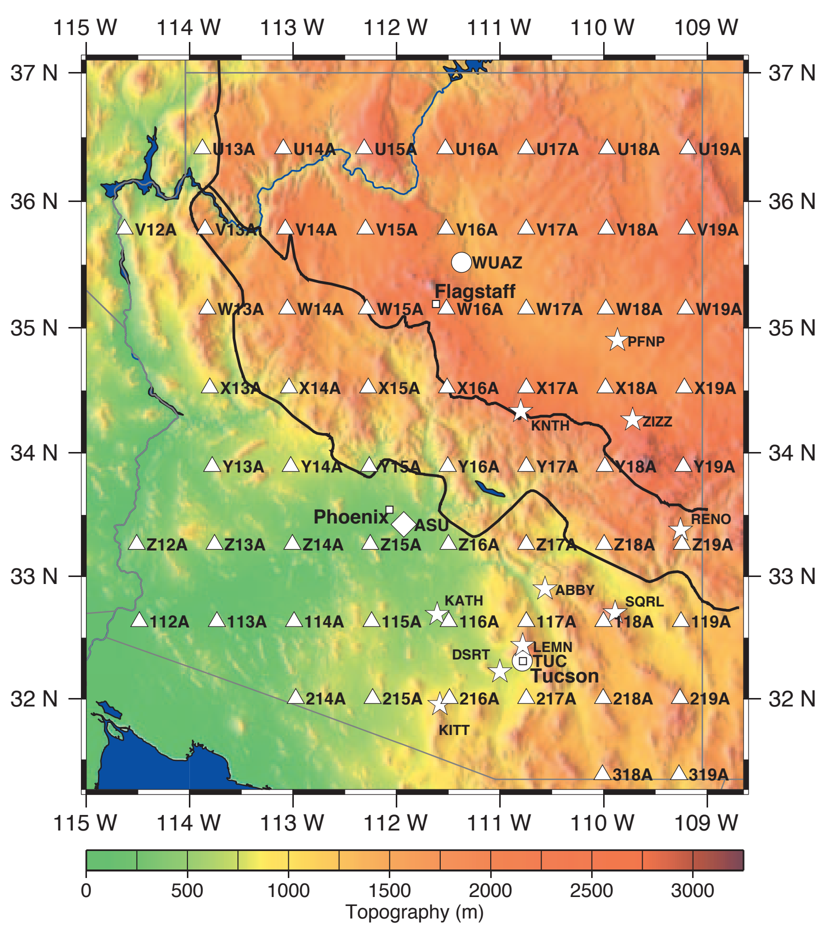
Matthew Fouch
Arizona State University

Prior to the deployment of the transportable component of USArray (Bigfoot), extensive preparations are necessary. In the state of Arizona, where the first deployments are expected in the fall of 2006, Arizona State University (ASU) is partnering with USArray and the IRIS Education and Outreach Program to develop a model strategy for streamlined siting and permitting. Arizona is a large state that encompasses significant expanses of Federal, State, Tribal, and private lands, each with unique requirements for access and use. We anticipate that the procedures developed and refined in Arizona will be applicable to deployments in other states and regions as Bigfoot moves on.

Our current progress entails the initial collection of specific physiographic, geologic, and jurisdictional data for a number of sites in the vicinity of the Phoenix area, which will then be integrated into a GIS database shared directly with USArray personnel via an ArcIMS server system. As this database comes online, we will move to outlying regions of the state, which are mostly rural. At all potential USArray sites, our goal is to engage local stakeholders at the level they prefer, while obtaining all clearances necessary to permit unimpeded collection of data in the time window of Bigfoot.

This project, in addition to its support of USArray deployment, also opens research opportunities related to geoscience education and outreach, given the cultural and ethnic diversity of the potential stakeholders across the state. A number of proposed station sites lie on the lands of seven different Native American nations, and our operations here will be informed by the results of a parallel ASU effort to work directly with Native leaders, communities, and schools on EarthScope research, education, and outreach. USArray will also impact other groups that have been historically resident in Arizona and underrepresented in the geosciences, such as Hispanics. We will survey preconceptions and attitudes toward geoscience in different communities, and work with cross-cultural and multilingual experts to determine how best to present and embed EarthScope research and outreach in these places.

We will present a flowchart indicating our working model for locating and permitting USArray sites, as well as preliminary findings and recommendations relevant to siting stations of lands of diverse use and jurisdiction.



USArray sites are indicated by triangles, and COARSE stations by stars.

Map of state of Arizona depicting locations of USArray sites and COARSE stations.

Tertiary to Quaternary History of the Central Sierran Frontal Fault System

Cathy Busby
University of California Santa Barbara

Dylan Rood
University of California Santa Barbara

Stephen DeOreo
University of California Santa Barbara

We document the Neogene to Recent evolution of the Sierra Nevada – Basin and Range transition in the central Sierra Nevada, with the goal of constraining the age and magnitude of deformation within the context of the evolving North America-Pacific transform boundary. This segment of the Sierran range front lies within the Walker Lane and consists of left stepping, en echelon escarpments. Geodetic GPS studies and focal plane mechanisms have been used to infer a major strike slip component on active normal faults along this segment of the range front. Field data from these faults are notably lacking, however, and very little is known of the short-term or long-term history of slip on them. We have established stratigraphies and ages for largely unfaulted Tertiary strata west of the modern range crest, and use these to characterize evolving paleo-relief on the Sierran block, as well as timing of “beheading” of Sierran paleocanyon systems from Nevadan source areas by faulting, and progressive offset of paleocanyons across Walker Lane faults. Previous studies of canyon-cutting suggest that the high topography of the range was inherited from the Cretaceous period, with an additional phase of Pliocene to Quaternary tectonically driven uplift; our work at Sonora Pass and Carson Pass, however, shows evidence for additional canyon cutting events during the Miocene. Our data also show that range-front faulting started earlier (about 10 Ma) in the central Sierra than is inferred for the southern Sierra (about 4Ma). These 10 Ma faults have kinematic indicators with a strike-slip component of deformation that predates migration of the triple junction northward to this latitude. This may indicate that Walker Lane microplate tectonics are not entirely related to the San Andreas fault.

Range-front faulting was initiated within the axis of the Ancestral Cascades arc, which our high resolution $^{40}Ar/^{39}Ar$ dates indicate was centered on the present-day central Sierran crest from 14 to 6 Ma. In the Sonora Pass area, initiation of transtensional deformation within the arc was accompanied by an episode of high-potassium volcanism at 10-9 Ma (Table Mountain Latite and Eureka Valley Tuff). Syndepositional faults 0 – 25 km east of the range crest form highly-tilted blocks with fanning dips and strata that thicken toward footwalls, and cross faults that likely accommodated vertical axis rotations (paleomagnetic studies in progress). Some of the same faults displace Quaternary strain markers. The Sonora Pass to Sonora Junction region thus forms a major right-stepping accommodation zone that has transferred slip to the Walker Lane, from 10 Ma to Quaternary time. In the Carson Pass – Kirkwood Valley area, six unconformity-bounded sequences are preserved within an up to 640 m deep, roughly NE-SW trending paleocanyon cut into Mesozoic granitic basement, with paleo-transport direction roughly parallel to the modern Mokelumne River drainage (toward the SW). Provenance studies in the paleocanyon fill indicate that it was cut off from rivers draining the Basin and Range province to the east sometime between about 14 and 10 Ma, and after that the paleocanyon fill was reincised to basement levels twice, suggesting the onset of range-front faulting by about 10 Ma. We are now mapping the Carson Pass-Kirkwood Valley paleocanyon across range front faults, including the Echo Lake fault zone, to get further geologic control on the tectonic evolution of the central Sierra Naevada and western Walker Lane.

Contemporary Tectonic Motion of the Eastern Snake River Plain, Idaho: A Campaign GPS Study, 1995-2004

John Chadwick
Idaho State University

Suzette Payne
Idaho National Laboratory

David Rodgers
Idaho State University

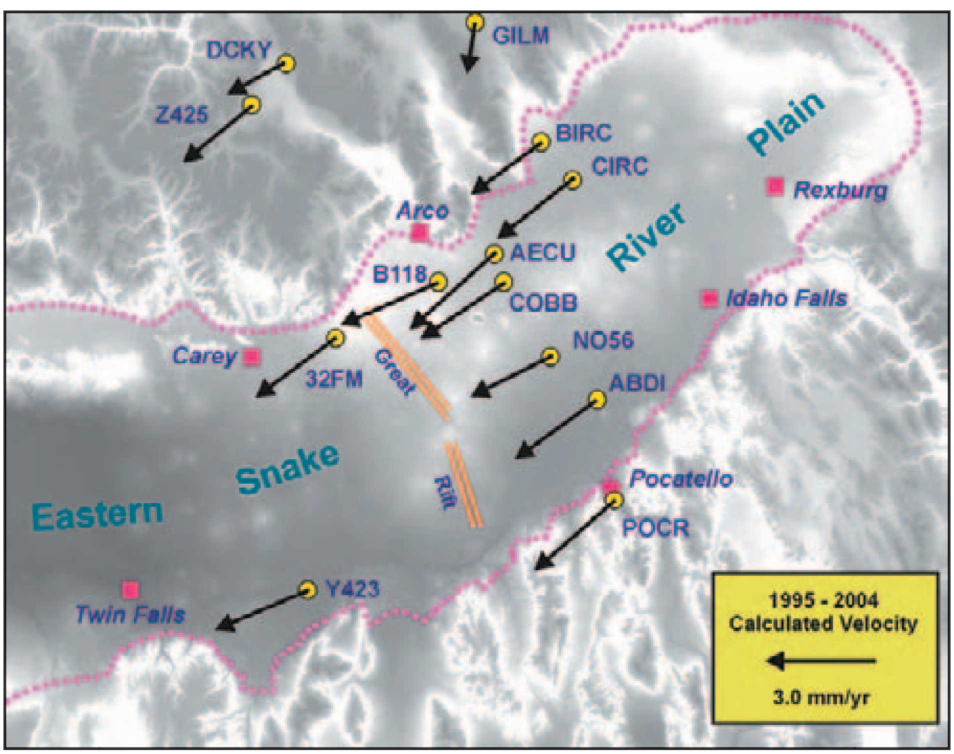
Teresa Van Hove
UCAR

The eastern Snake River Plain (ESRP) is a 100-km-wide, 400-km-long volcanic province bounded to the north and south by the actively-extending Basin & Range (B&R) province. The ESRP is virtually aseismic, leading some workers to propose it is a strong, rigid block, but numerous volcanic rift zones that cross the ESRP provide evidence of NE-SW extension as recently as 2,000 years ago via episodic dike injection. To address the nature of extension on the ESRP and its structural relationship with the B&R, we completed a campaign GPS study of 13 benchmarks in the central ESRP and adjacent B&R in April of 2004, using Trimble 4000 dual-frequency GPS receivers from UNAVCO. Stations were occupied for multiple GPS days, typically from 48 to 96 hours. These same stations were occupied in the summer of 1995 by the University of Utah, and the data from these two campaigns were processed using Bernese 4.2 software. A network of regional IGS stations (DRAO, PEI1 and NLIB) was used in a Helmert transformation to tie the campaign locations to a North American reference frame, and to obtain velocities relative to the stable North American continent.

The rates and directions of motion of ESRP stations were largely homogenous from 1995-2004. Displacement was consistently oriented SW (average 232.5 degrees), and rates were similarly consistent, ranging from 2.3 to 3.1 mm/yr. The spatial pattern of rate variations may indicate a subtle rate increase to the west, but it is clear that most of the measured displacement is the result of extension NE of the study area in the high-seismicity area of the Yellowstone Plateau. On the short time scale of this study, the ESRP study area essentially behaved as a rigid block.

Three B&R stations about 40 km to the north of the ESRP yielded displacement vectors that are similar to those observed on the ESRP. Displacement was oriented 188 to 241 degrees and rates varied from 1.3 to 2.3 mm/yr. Why the B&R rates are similar to, but slightly less than, the ESRP rates may be due to some combination of (1) post-seismic relaxation of the B&R stations associated with the nearby 1983 Borah Peak earthquake (2) rotation of the entire region about a pole to the north of the study area, leading to a progressive decrease in velocity from south to north, (3) the fact that B&R stations are located within the diffuse zone of seismicity that accommodates motion away from the stable craton, whereas the ESRP is SW of the zone of seismicity on the Yellowstone Plateau, or (4) inhomogeneous strain over a short time period that would not be observed over a much longer period.

Whatever explanation is valid, the GPS results support the interpretation that the two provinces are moving at comparable velocities relative to the stable North American continent, and that despite the dramatic differences in extensional tectonic style of the two provinces (half-graben faulting vs. fissuring), they are tectonically coupled and responding to similar regional stresses.



Velocities relative to the stable North American continent are shown for benchmarks on the eastern Snake River Plain and adjacent Basin and Range.

1.60 Ga Megashear and Remnant Ocean Basins: Redrawing the Basement Map of Western U.S.

Kevin Chamberlain
University of Wyoming

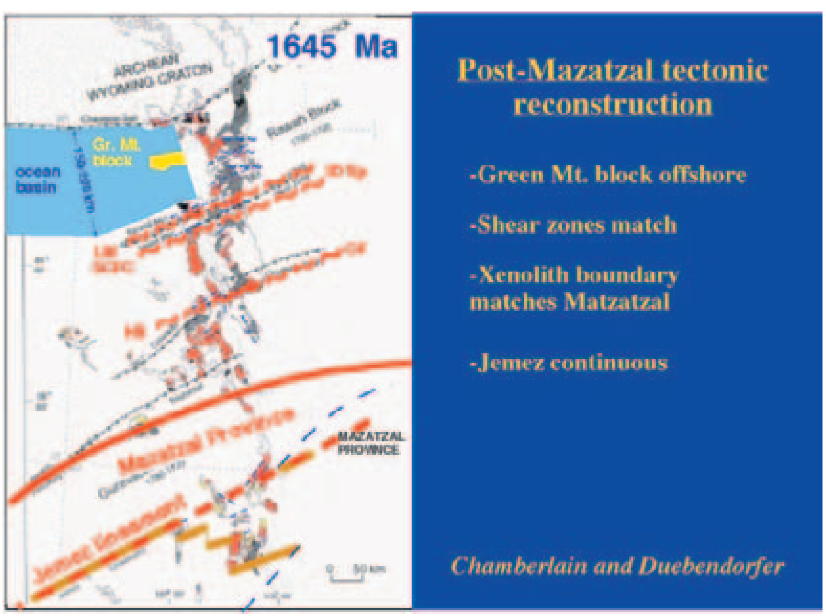
Ernest Duebendorfer
Northern Arizona University

Recent structural and geochronological results from the Cheyenne belt in the Sierra Madre, SE Wyoming, have established a thrust-tear fault system with a minimum of 30 km NNW displacement at 1.60 Ga. This event tectonically emplaced the Proterozoic Green Mountain block against passive margin sequences of the Archean Wyoming province. This event is 150 million years (myr) after the accretion of island arc rocks along the Cheyenne belt recorded in the Medicine Bow Mountains immediately to the east (Medicine Bow orogeny), and 30-50 myr after the Mazatzal orogeny, 500-1000 km to the south. Calc-alkaline magmatism and amphibolite facies metamorphism occurred in the Green Mountain block at 1.62 Ga (Premo and VanSchmus, 1989; Premo and Fanning, 2000), 20 myr before thrusting. The last stage of deformation in the Farwell Mountain zone, which marks the southern boundary of the Green Mountain block, is also 1.60 Ga in age.

To explain these observations, we propose that a 200-250 wide remnant ocean basin existed from 1.78 Ga to 1.62 Ga, south of present-day Sierra Madre, and that the basement rocks of central Colorado, Arizona and northwest New Mexico were 200+ km south of their present-day positions after the Mazatzal orogeny. North-dipping subduction of the remnant oceanic lithosphere, ca. 1.62 Ga, produced magmatism and high-grade metamorphism in the Green Mountain Block and ultimately led its to accretion to the Wyoming province, ca. 1.60 Ga. As the ocean basin closed, northward migration of the arc terranes of Arizona, western Colorado and western New Mexico were accomodated by a 1500 km-long, right-lateral megashear that stretched from the Sierra Madre to New Mexico. The topographic low between the Front Range and back ranges of Colorado is the present-day expression of this fault. Initiation of this subduction and megashear may have been triggered by accretion of a continent outboard of the Mazatzal province, perhaps Australia in the AUSMEX recontruction. The Cochise block of SE Arizona is the only other known region of the Proterozoic terranes of western US with deformation ca. 1.63-1.60 Ga.

This model rectifies and explains a number of enigmas in the Proterozoic evolution of western US: 1) the existence of a 200-250 km long, north-dipping mafic slab imaged beneath the Wyoming province by the CD-ROM experiment. A similar high velocity body was imaged to the west in the LODORE array. 2) North-dipping reflectors beneath the Farwell Mountain zone, imaged by the CD-ROM experiment. All of these features are interpreted as manifestations of 1.62-1.60 Ga subduction. The proposed megashear offset 4) explains the juvenile isotopic composition of the Green Mountain block, 5) improves the matches of shear zones and basement terranes between the Front and back ranges of Colorado, 6) reconciles the xenolith evidence for the Mazatzal-Yavapai boundary from the Four Corners region with its structural evidence to the east, and 7) restores the Jemez lineament in northern New Mexico. In our model, the megashear has been reactivated in the Mesoproterozoic, ca. 1.4 Ga, and the Laramide, at least.

The structural and geochronologic evidence for a 1.62-1.60 Ga thrust-tear fault system along the Cheyenne belt in SE Wyoming is robust and incontrovertible. Our large-scale tectonic model to explain this deformation is still being tested, however. Nevertheless, the recent discovery of intracratonic tectonism, ca. 1.6 Ga, and its potential broad tectonic implications underscore the need for ongoing structural, geochronologic and tectonic studies in the EarthScope program. Geophysical data must be combined with results from new, detailed geologic investigations to maximise the impact of the EarthScope effort.



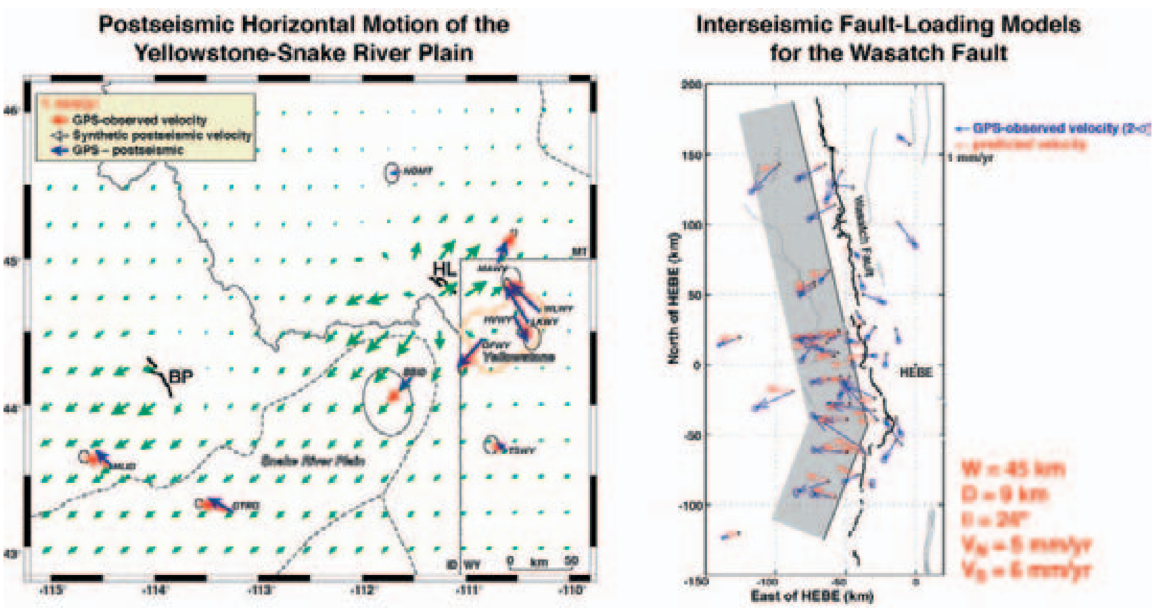
Proposed tectonic map for the western US for the period from 1.645 to 1.62 Ga. Incorporates new structural and geochronologic evidence for intracratonic tectonism along the Cheyenne belt 1.62-1.60 Ga. Ocean basin closes by northward subduction, and basement terranes migrate along megashear from Wyoming to New Mexico to restore present day configuration.

Postseismic and Interseismic Deformation of Large Normal-faulting Earthquakes in the Basin-Range

Wu-Lung Chang
University of Utah

Robert Smith
University of Utah

Time-dependent changes in crustal motion were determined by GPS and trilateration measurements from 1973 to 2000 following the 18 August 1959 M_s=7.5 Hebgen Lake, MT, earthquake. The data were used to assess intraplate post-seismic deformation and to model lithospheric rheology. This largest historic normal-faulting earthquake of the western U.S. interior occurred at the northwest edge of the Yellowstone volcanic field in the extensional-volcanic regime of the northern Basin-Range Province. Changes of baseline-length across the Hebgen Lake fault and its aftershock zone exhibited 4 to 6 mm/yr of extension up to 14 years following the earthquake. Rheological models derived by these data show that the lithosphere is stronger for the fault zone, but weaker in the vicinity of the Yellowstone caldera where much higher heat flow and thinner brittle crust are exhibited. Our models also imply a more viscous lower crust than the upper mantle, in agreement with a hypothesis that the continental mantle lithosphere is relatively weak. We then employed the derived Hebgen-Lake rheological model to evaluate the postseismic deformation of a much larger area of the Intermountain region produced by the Hebgen Lake and the 1983 M_s=7.3 Borah Peak, ID earthquakes. The results suggest that the postseismic relaxation of these earthquakes produced horizontal ground motions up to ~2 mm/yr that must be considered for intraplate kinematic models. Similarly, a viscosity model based on observations of the Late-Quaternary loading and vertical rebound of Lake Bonneville of the eastern Basin-Range Province was also used to evaluate postseismic ground motions associated with six most recent, <1.5 ka, Holocene paleoearthquakes and three large, M~5.6, historic earthquakes of the Wasatch fault zone, UT. These results demonstrate ~0.1 mm/yr of contemporary horizontal motions induced by these earthquakes, which are negligible compared to the ~1-3 mm/yr of E-W extension determined by GPS measurements. This study provides new insights into the widespread effects on regional deformation from postseismic relaxation of large earthquakes that should be considered in kinematic models and earthquake hazards of intraplate tectonic regions. Contemporary surface deformation of the Wasatch Front area, measured by campaign and continuous GPS, was then used to model the interseismic loading rate of the Wasatch fault, where paleoseismic data from trenching revealed long-term fault-slip rate. Combining these results provide important new insights on temporal variations of the seismic cycle and constraints on related earthquake hazards.



Left: Combined postseismic horizontal velocities (green arrows) produced by the M_s=7.5 1959 Hebgen Lake (HL) and M_s=7.3 1983 Borah Peak (BP) earthquakes. Corrected velocities (blue arrows) are obtained by subtracting postseismic motions from GPS-obsered velocities (red arrows). Right: Dislocation model for the interseismic loading of the Wasatch fault, UT that best fits the GPS-observed horizontal velocities. The loading parts of the fault are shown by gray patches with the same width and dip angle of W and D, respectively. D is the locking depth below that the fault is creeping interseismically. VN and VS are the loading rates of the northern and southern fault patches, respectively.

Looking Deeper Into the Landscape: Topography and Tectonic Inheritance in the Western U.S.

David Coblentz
Los Alamos National Laboratory

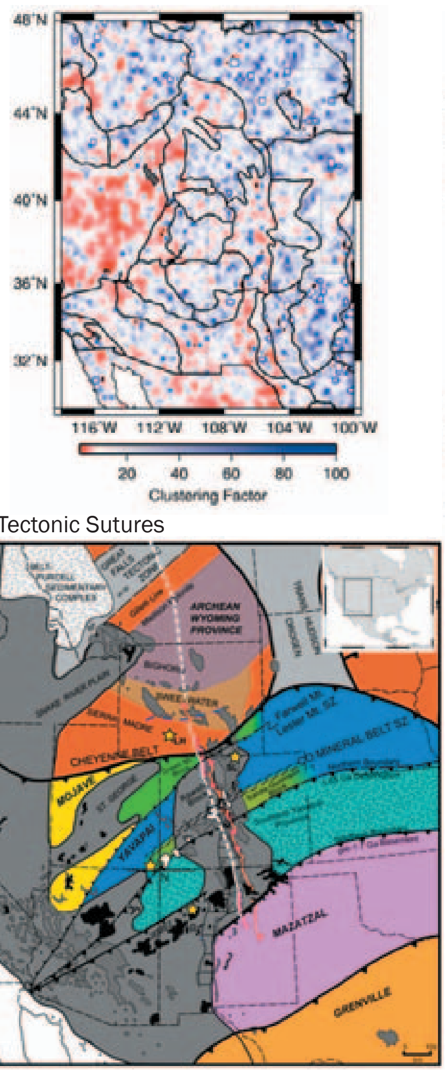
Aviva Sussman
Los Alamos National Laboratory

Detailed analysis of Earth's topography can provide important information about the geodynamic, geologic, and climatic history of a region. The relationship between landscapes and inherited tectonic features is complex and depends on a number of factors. Influential parameters that exert the greatest control on surface topography include the type, strength, and geometry of inherited tectonic boundaries, which in turn control observable topographic characteristics such as clustering, organization, flatness and grain orientation.

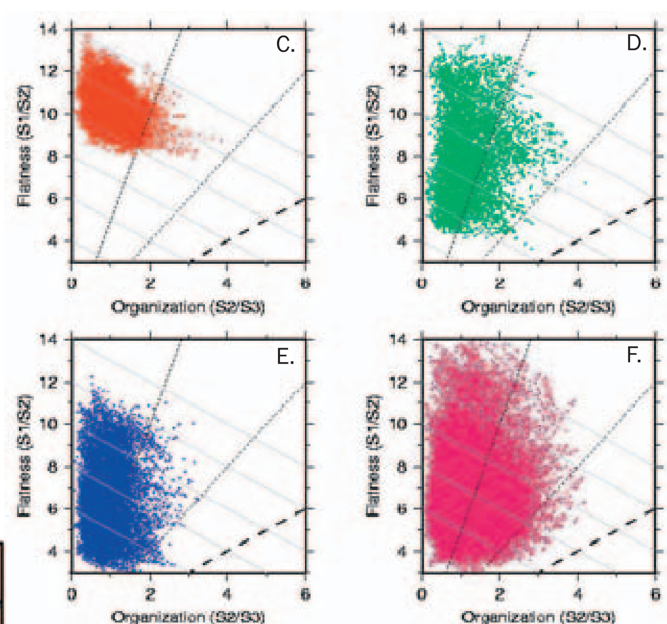
The western United States is an ideal place to evaluate these relationships due its long, yet relatively well understood tectonic history and mosaic of several crustal terranes. A number of recent studies have explored ways to extract tectonic information from topography and propose several provocative interpretations to explain Western U.S. landscapes, including: 1) a systematic decrease in topographic spectral power with increasing tectonic age of underlying crust, 2) a variation in local relief, mean elevation, and thermochronologically-determined exhumation history across major Paleozoic accretionary boundaries, 3) a relationship linking Neogene and ongoing rock- and surface-uplift with the creation of mantle buoyancy; and 4) a strong correlation between topography and lithospheric features such as mantle velocity structure, crustal thickness, and Precambrian crustal provinces.

Here we present results from a quantitative topographic analysis of the Western Cordillera of North America, motivated by the hypothesis that inherited tectonic features from the evolution of the Cordillera have been preserved in regional topographic characterstics. The analysis extracts information about clustering, roughness, organization, fabric orientation and spectral power from a 30-arc-second topographic DEM. While currently focused on identifying Precambrian crustal sutures, volcanic lineaments, and the Alvarado Ridge, our future work will exploit detailed information about the crustal and upper mantle structures from the USArray component of the EarthScope experiment to refine this approach and further quantify the influence of inherited tectonic structures on the landscape.

A.



B. Tectonic Sutures



The areal variation in the clustering factor (K-value of [Woodcock, 1977] - ratio of topographic flatness to organization) for the Western U.S. shown in comparison to the proposed pre-Cambrian sutures (Karlstrom and Humphreys, 1998.) While there is only a weak correlation between the suture boundaries and the K-values in (A), examination of the details in the distribution of the clustering factor (K-value) for C) Great Plains, D) Rio Grande Rift, E) Southern Rockies, and F) Northern Basin and Range indicate this to be a valuable tool for evaluating the presence of inherited tectonic features in the landscape.

The EarthScope Plate Boundary Observatory (PBO) Response to the September 28, 2004 Parkfield Earthquake

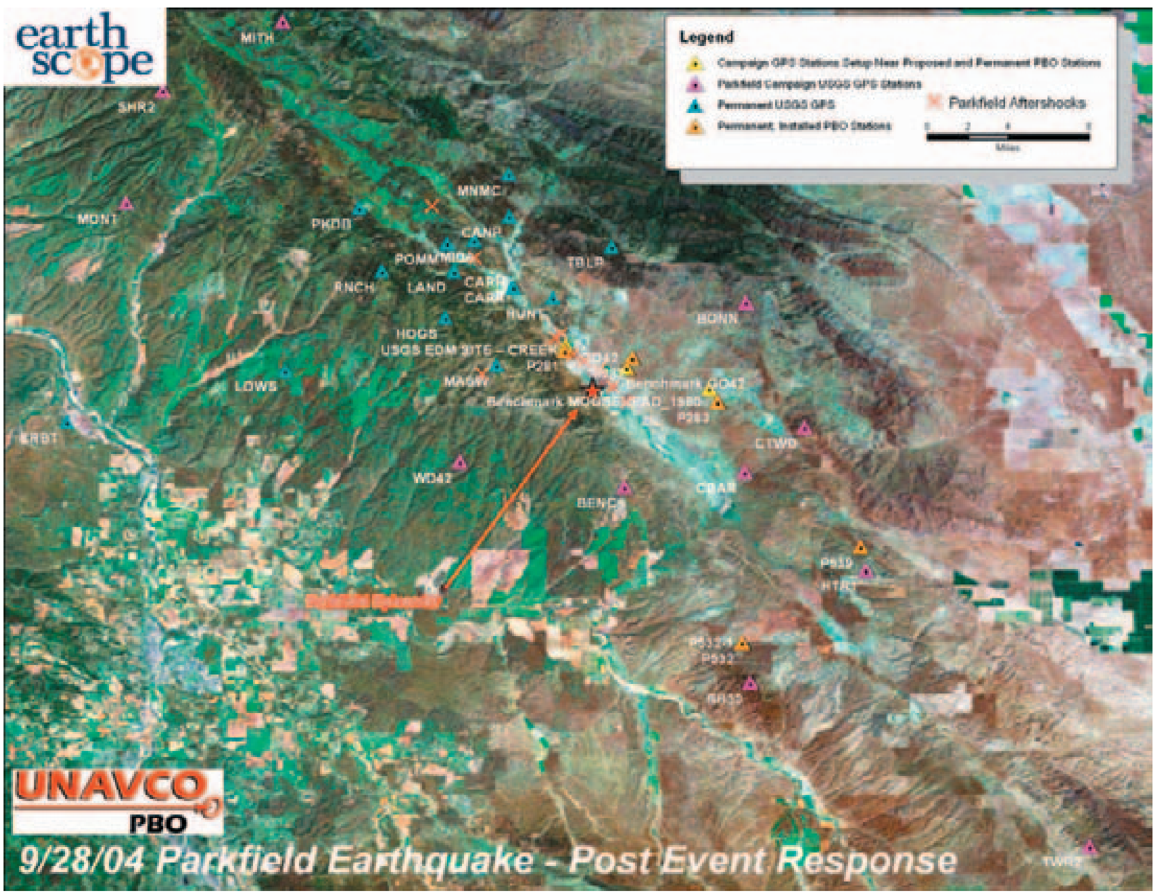
Brian Coyle
UNAVCO

Todd Williams
UNAVCO

Andre Basset
UNAVCO

Edward Arnitz
UNAVCO

On September 28, 2004 the M_w 6.0 Parkfield earthquake occurred on the San Andreas Fault seven miles southeast of the town of Parkfield. Within minutes of the earthquake, the PBO Transform Site Selection Working Group requested reprioritization and immediate installation of five PBO permanent GPS stations which had been scheduled for installation in Parkfield in 2005. Following the UNAVCO Event Response Plan, the UNAVCO President approved the rapid response and field crews were deployed from the PBO Northern and Southern California regional offices. In order to capture post-seismic deformation and any possible sympathetic rupture on fault segments south of the main shock, PBO targeted five stations for installation, focusing on the under-instrumented area south of the epicenter. Field crews began the reconnaissance and permitting process the day after the earthquake and within 72 hours the first station was installed. By the end of the week, they had also received a permit for one more station and submitted permit applications for three additional sites. By the end of the following week, the second permanent station was installed and three survey-mode GPS systems were deployed near to the proposed locations of the other three permanent sites, while permit approval was pending. PBO received permission to install the final three permanent stations on October 29, and completed these installations on November 10. Data from these and all other PBO stations are freely available through the UNAVCO Archive at ftp://data-out.unavco.org/pub/PBO_rinex.



EarthScope Plate Boundary Observatory (PBO) Response to the 9/28/2004 Parkfield Earthquake.

Quaternary Travertine-depositing Systems: A Geologic Record of Mantle Degassing

Laura Crossey
University of New Mexico

Karl Karlstrom
University of New Mexico

Dennis Newell
University of New Mexico

Tobias Fischer
University of New Mexico

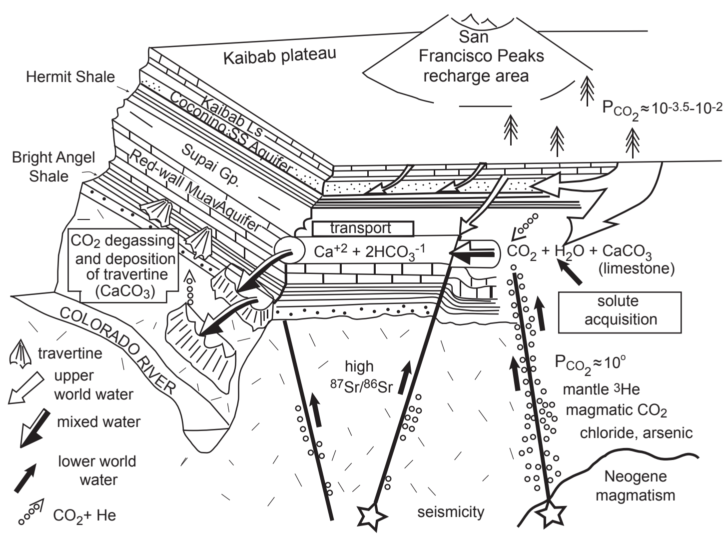
David Hilton
University of Arizona

P. Jonathan Patchett
Scripps Institution of Oceanography

Hot springs have long been of interest in terms of understanding magmatic systems and regional heat flow. Travertine-depositing cool springs in the western U.S. share many of the same geochemical characteristics and offer an important data set for examining connections between deeply sourced fluids, heat, and the groundwater system. A genetic model for the formation of travertine has emerged from study of the deeply-dissected hydrologic system of Grand Canyon of the southwestern U.S. Water and gas chemistry of active travertine-depositing springs provide evidence for the involvement of Cenozoic magmatism and mantle degassing in the genesis of vast quantities of Quaternary travertine, as well as adverse effects of deeply-sourced influences on water quality. Travertine formation is a three-stage process: acquisition of solute by a groundwater, transport of dissolved constituents, and deposition of travertine. The role of CO_2 degassing in the depositional phase of travertine formation is widely recognized. The amount of calcite dissolved from limestone aquifers (the calcite load of the ground waters) in the transport phase of the process depends critically on the amount of CO_2 input and the hydrologic pathway. Extensive travertine accumulations are a geologic record of high fluxes of CO_2. Travertines and travertine-depositing springs are preferentially located along basement-penetrating faults. Our model for solute acquisition focuses on the role of magmatism in active extensional tectonic settings as a source of excess CO_2.

Gas analyses from CO_2-rich springs record $^3He/^4He$ ratios up to 0.15 Ra, suggesting contributions of mantle-derived He, and its carrier gas CO_2, from nearby volcanic fields. $^{87}Sr/^{86}Sr$ in springs ranging from 0.710 to 0.735, as well as mixing relationships among other geochemical parameters, suggest mixing of deeply-derived waters within the aquifers. The radiogenic strontium isotope signal, contributed by waters that are deeply circulated through Precambrian basement, may account for the previously observed downstream increases in Colorado River $^{87}Sr/^{86}Sr$. Similarly, natural inputs from deeply sourced saline spring waters affect the Colorado River salinity as it crosses the western Colorado Plateau and enters the Basin and Range province.

Spring waters associated with active travertine accumulations are warmer, more saline (Na-Cl and $Na\text{-}HCO_3$), richer in CO_2, and elevated in $^{87}Sr/^{86}Sr$. In Grand Canyon, four distinct end members emerge based on major ion composition. Each mixes with the narrowly-defined $Ca\text{-}HCO_3$ Colorado Plateau end member ($Ca\text{-}Mg\text{-}HCO_3$ fresh waters). These trends seem to correspond to regional subprovinces and are identified as: 1) the northern part of the eastern Grand Canyon (NE; characterized by Blue Spring, BS), 2) the southern part of the eastern Grand Canyon (SE; characterized by Salt Creek, Travertine Canyon, and travertine-depositing waters of Havasu Creek, 3) springs of the western Grand Canyon (W), including springs near the Toroweap and Hurricane faults and the travertine-depositing waters of Travertine Grotto and the more saline Pumpkin Spring, and 4) springs of the far western Grand Canyon (FW), including waters of Travertine Slot near the Grand Wash cliffs. From a major ion chemistry standpoint, the NE trend is the most Na-Cl-rich, the W- trend is saline, but Ca-Mg dominated waters indicate reaction of the NaCl end member with carbonate strata; and the FW and SE trends are sulfate-rich. The identification of specific regional trends offers a possible avenue of tracing regional lithospheric heterogeneities though tracking of spring gas and water chemistry.



Model of the Grand Canyon hydrologic system showing interaction of lower and upper world water components during the acquisition, transport, and deposition phases of travertine genesis. Depicted are the major aquifer units of the plateau, and schematic flow lines indicating surface recharge and chemical evolution of upper world waters (open arrows) and input of lower world waters along faults (solid arrows). On left is a photo of Travertine Falls in Grand Canyon; an example of a travertine drape deposit.

Automated EarthScope Receiver Surveying (EARS): A Prototype for USArray Data Product Generation

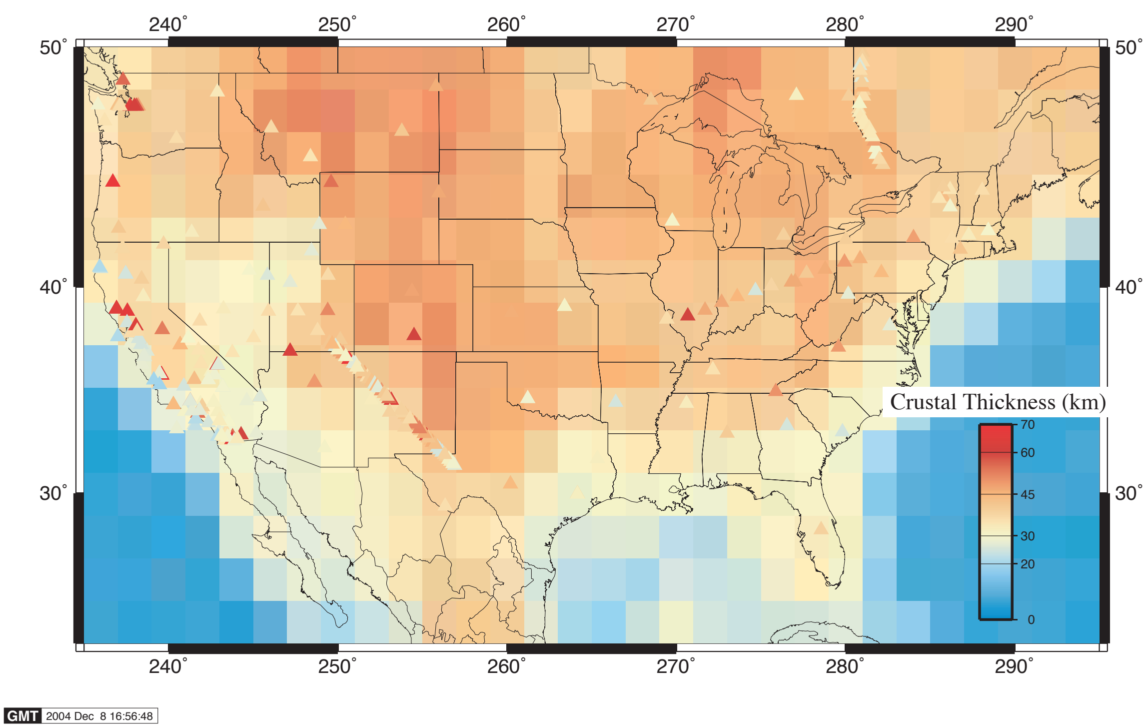
Philip Crotwell
University of South Carolina

Thomas Owens
University of South Carolina

Receiver functions are a well known, commonly used technique for estimating crustal and upper mantle structure. Because it is well known, relatively stable, and has been used frequently over the past 40 years, it is ripe for automated processing. We have developed an automated receiver function processing system that retrieves data from the IRIS DMC, preprocesses it, calculates receiver functions and saves the original data, the receiver functions and an estimate of the crustal thickness and V_p-V_s ratio. This system will form the basis of an ongoing, near real time, standard data product for the upcoming USArray component of EarthScope. We term this product the "Receiver Reference Model" (RRM). Generation of RRMs for all Earthscope stations provides for identification of anomalous regions for more detailed study as well as basic information about the subsurface for E&O applications. In preparation for the rollout of USArray, we have applied this system to historical earthquake data from the IRIS DMC to produce estimates of bulk crustal structure for all stations in the US for which there is usable data. We also apply it to GSN stations to form a global crustal survey. This process will continue for both USArray data as stations are deployed and for new earthquakes at existing stations. We present preliminary results of this receiver function survey including crustal thickness and V_p-V_s ratio estimates for the stations based on the iterative deconvolution technique of Ammon and the stacking technique of Zhu and Kanamori.

This project is supported by the EarthScope program at NSF through grant EAR-0346113.

The processing system is based on SOD (Standing Order for Data, http://www.seis.sc.edu/SOD), a Java-based Fissures/DHI client. SOD is a highly configurable automated processing system developed at South Carolina to aid in the analysis of large volumes of data and to ease the burden on the scientist by handling the routine tasks of selecting relevant seismograms, retrieving the data and applying preprocessing functions. In addition, we have assembled common seismological utilities into a basic analysis group, BAG, that SOD and other Java applications can use. Currently this framework includes mean removal, trend removal, tapering, filtering, cutting, travel time calculation, rotation and response gain. Other functions will be added over the course of time. The design of these tools are loosely based on the functions in the popular SAC seismic processing software package, which lowers the learning curve required to use and understand them. SOD and BAG are freely available from the University of South Carolina under the Gnu Public License, (http://www.seis.sc.edu/software).



Unreviewed RRM crustal thickness estimates for all broadband stations in North America in the IRIS DMC. Background image is the CRUST2.0 model. Triangles are the stations used. The color scale used for the triangles is the same as for the background image. Thus, stations where RRM results are identical to CRUST2.0 are nearly invisible whereas areas where RRM results deviate significantly from CRUST2.0 are very obvious. The next year of this EarthScope-funded project will be spent refining the method to deal with "problem" stations.

Frictional Strength Heterogeneity and Surface Heat Flow; Implications for the Strength of the Creeping San Andreas Fault

Matthew d'Alessio
U.S. Geological Survey

Colin Williams
U.S. Geological Survey

Roland Bürgmann
University of California Berkeley

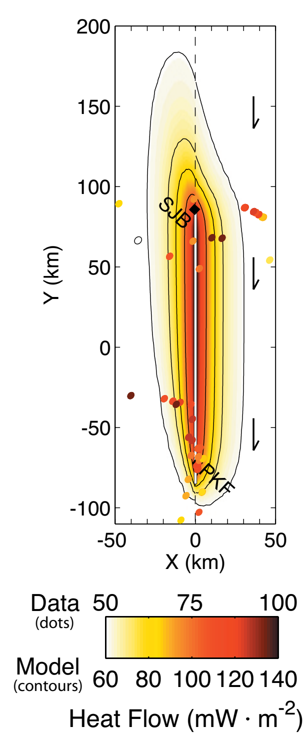
The magnitude of frictionally generated heat varies as a function of the frictional strength of a fault. Surface heat flow observations along much of the San Andreas fault (SAF) constrain the coefficient of friction of the fault to be < 0.2, much lower than laboratory derived friction values for most geologic materials. These observations launched a long-standing debate over the frictional strength of natural faults and physical mechanisms that control that strength.

While the heat flow data are generally robust and have good spatial distribution, there is a notable gap along the creeping section of the SAF where no heat flow measurements have been collected. This section of the fault has unique frictional properties that result in steady, aseismic creep rather than the earthquake-producing stick-slip behavior of the surrounding sections of the SAF. Brune (2000) suggested that the creeping section is a frictional asperity with a coefficient of friction much higher than the rest of the SAF, a scenario that might go undetected given the lack of data in the region. Here we test Brune's hypothesis by using numerical models to explore the effects of faults with spatially and temporally heterogeneous frictional strength on the spatial distribution of surface heat flow.

For stationary asperities, heat flow at the endpoints of the asperity is half the magnitude predicted by assuming an infinite fault. Over geologic time, the asperity and surrounding crustal blocks will be offset laterally by strike-slip faulting, transporting the heat and requiring a non-linear solution to the 3-D heat flow equations. Heat generation by asperities between laterally migrating crustal blocks produces heat flow patterns that are asymmetric across the fault and along-strike. Figure 1 shows an example of this pattern for a moving asperity given one of the many possible fault slip scenarios we explore.

We compare these complex spatial patterns with the available heat flow observations and show that heat flow anomalies from a frictional asperity with a high coefficient of friction should be detectable with the existing observations. The lack of a measurable anomaly implies that the creeping section has a coefficient of friction as low as the surrounding SAF. Based on our modeling, we make predictions about the heat flow that will be observed in strainmeter boreholes installed as part of the Plate Boundary Observatory (PBO).

Because the creeping section does not slip in large earthquakes, the mechanism controlling its weakness is not related to dynamic processes resulting from high slip rate earthquake ruptures. At least for the creeping section, this lack of heat flow anomaly in central California would rule out thermal pressurization of fault zone fluids, acoustic fluidization, wrinkle-like slip pulses, and other dynamic processes as the mechanisms that control frictional strength.



Predicted map-view heat flow for a frictionally strong asperity (?=0.8) surrounded by a weak fault (?=0) after 5 myr. The asperity (white bar, -85 < y < 85) is the length of the creeping section (170 km) and travels with the crustal block on the right side (x>0) at 3.4 cm/yr.

Transient Crustal Motion in the Northern Basin and Range from GPS

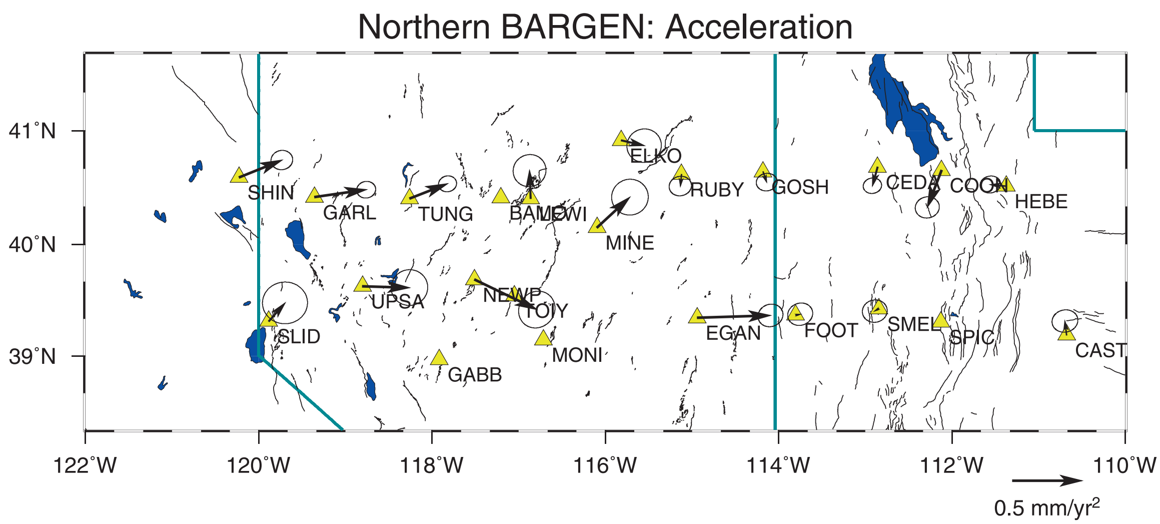
James Davis
Harvard-Smithsonian Center for Astrophysics

Brian Wernicke
California Institute of Technology

Sunil Bisnath
Harvard-Smithsonian Center for Astrophysics

Pedro Elosegui
Harvard-Smithsonian Center for Astrophysics

We have now observed with the northern transect of the Basin and Range Geodetic Network (BARGEN) for nearly nine years. Formal uncertainties for estimated horizontal site accelerations range from 0.03-0.06 mm/yr^2, implying a resolution (one formal sigma) of 0.3-0.6 mm/yr in the change of horizontal velocity over this time period. In the eastern part of the network, the accelerations are generally less than 0.1 mm/yr^2, except for site COON, whose south-southwesterly acceleration may be caused by crustal loading associated with Great Salt Lake water-level variation. The accelerations to the west are generally eastward, with typical values of 0.4-0.5 mm/yr^2. The largest accelerations are therefore at the 10-sigma level, if the formal standard deviations are correct. An analysis using the eastern-most sites yields a mean acceleration of -0.04 mm/yr^2, with a standard deviation of 0.09 mmyr^2, or about 3-sigma. At this level, a number of sites still yield statistically significant accelerations that are too large to be ongoing for very large, and hence must be transient. To ascribe the estimated accelerations to random site motion ignores the spatial coherence of the results. We will therefore examine the possibility that other GPS errors that could possibly account for the observed accelerations. We will also examine the possibility that such small transient motions may be associated with intraplate forces but have escaped prior detection. Either way, these results have important implications for the main goals of the geodetic component of EarthScope.



Horizontal acceleration vectors estimated from BARGEN GPS data, 1996-2004.

Scaling Properties and Mechanisms of Stress Heterogeneity in the San Andreas Fault Observatory at Depth (SAFOD), Parkfield, California

Amy Day-Lewis
Stanford University

Mark Zoback
Stanford University

Stephen Hickman
U.S. Geological Survey

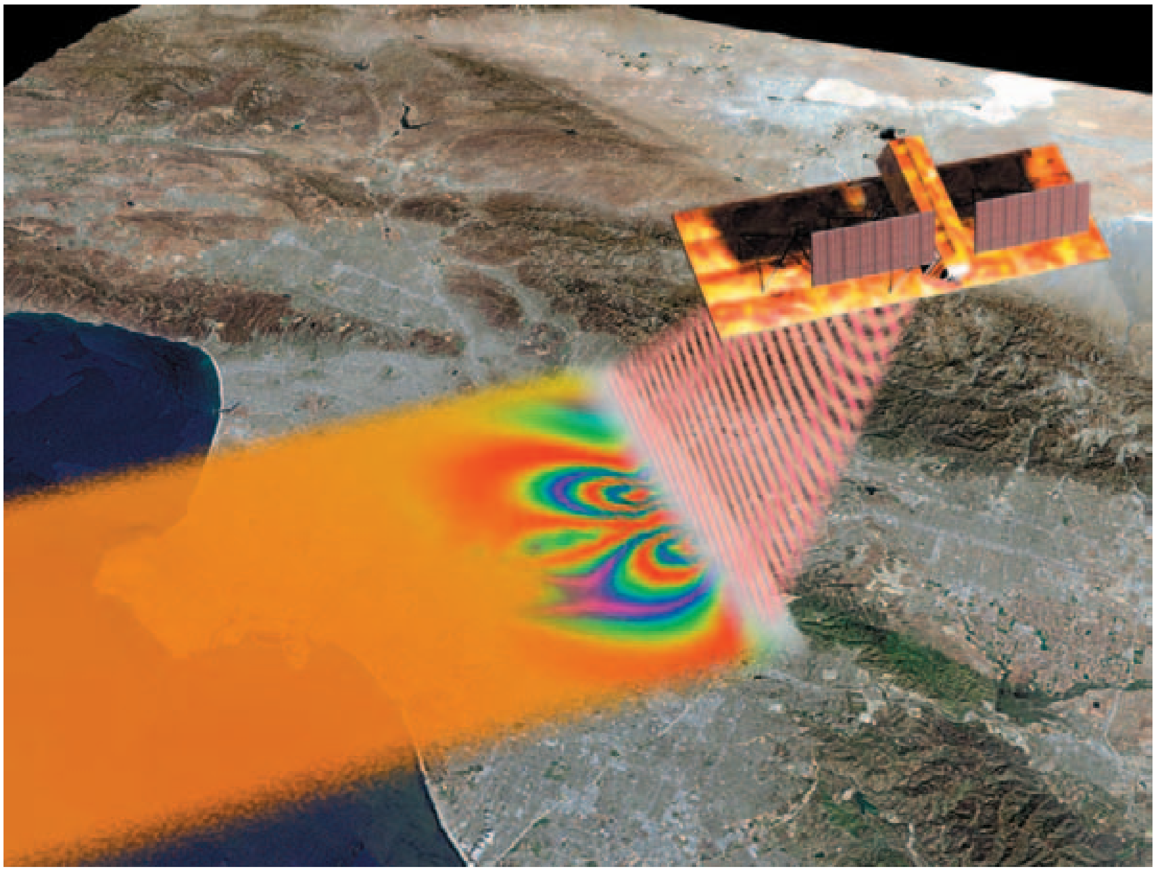
Statistical characterization of stress-induced wellbore failure and rock property heterogeneity from well logs collected in the San Andreas Fault Observatory at Depth (SAFOD) Pilot Hole and Main Hole offers potential insight into the scaling properties and mechanisms of observed stress heterogeneity. Wellbore breakouts identified in Ultrasonic Borehole Imager (UBI) and Formation MicroImager (FMI) data from the Pilot Hole show significant step-like rotations in the direction of maximum horizontal compressive stress (SH_{max}). We observe an overall eastward breakout rotation of approximately 25 degrees from 800 m to 2,200 m depth, creating an increasing angle between SHmax and the local strike of the San Andreas Fault. Within each depth interval exhibiting a fairly uniform breakout orientation, smaller scale fluctuations occur about the local mean. Preliminary analysis of more recent data from the SAFOD Main Hole indicates similar, multi-scale breakout azimuth rotations. Using classical spectral analysis methods (periodogram), we find that the overall variation of the breakout directions in the SAFOD Pilot Hole exhibits self-similar (1/f, or "flicker noise") behavior over depth scales from meters to kilometers. This result corroborates evidence for the fractal nature of stress rotations as observed previously in the Cajon Pass, California scientific wellbore.

Wellbore data commonly display some degree of variability in failure directions which, in most cases, reflects small variations in the directions and/or magnitudes of the in situ principal stresses. At SAFOD we are investigating the relationship between the observed breakout rotations and stress drops associated with slip at various scales on the numerous nearby faults, as well as the influence of variations in fault strength with depth on the San Andreas Fault. Previous theoretical modeling showed that the latter mechanism can explain the observed large-scale rotation of the stress field as a function of depth in the SAFOD Pilot Hole. In addition, slip on smaller faults intersecting boreholes has been shown elsewhere to cause localized stress perturbations with a wavelength only a few times longer than the width of the slipped patch. We also consider the possible role of rock property variability in controlling heterogeneity; rock properties measured in well logs display self-similar behavior in a wide variety of lithologies and geologic environments including Cajon Pass and the KTB borehole in Germany. We employ both spectral and statistical methods to look at several SAFOD well logs including sonic velocities, bulk density, neutron porosity, gamma-ray, and resistivity, taking into account both drilling and data acquisition artifacts. Our results on stress heterogeneity induced by both fault slip and physical property variations reveal 1) important details about the state of stress in the crust adjacent to the San Andreas Fault in the SAFOD area, and 2) increased knowledge of how crustal stress heterogeneity affects earthquake generation and faulting behavior.

Observational Strategies Related to EarthScope for an InSAR Mission

Andrea Donnellan
Jet Propulsion Laboratory

Interferometric Synthetic Apertur Radar (InSAR) is the fourth component of EarthScope, complementing SAFOD, PBO, and USArray. A community InSAR workshop held in the fall of 2004 brought together researchers in a variety of EarthScope related fields including crustal deformation, information technology, and education and outreach. Workshop attendees recommended a comprehensive InSAR program consisting of InSAR satellites; access to foreign SAR data, significant research, analysis, and modeling activities; and technology development for future applications. Breakout groups discussed scientific problems and observational strategies related to their discipline. This talk will discuss observational strategies for an InSAR mission as they relate to EarthScope.



Concept for an InSAR satellite showing an interferogram that might be observed following an earthquake.

Recent Observations of Episodic Tremor and Slip Along the Northern Cascadia Margin

Herb Dragert
Geological Survey of Canada

Honn Kao
Geological Survey of Canada

Garry Rogers
Geological Survey of Canada

The motions of continuous GPS stations located along the northern Cascadia Margin are characterized by saw-tooth functions consisting of accelerated northeastward displacements for periods of 13 to 16 months, followed by transient southwestward displacements over periods of one to two weeks, superimposed on steady, linear northeastward trends over the past decade. These motions have been modelled by a combination of long-term locking on the shallow subduction interface and temporary locking and repeated slip of a few centimetres on the deeper plate interface between the Juan de Fuca and North America plates. The episodes of slip are accompanied by distinct low-frequency tremors which led to the naming of the phenomena as "Episodic Tremor and Slip" (ETS). Although the processes involved in ETS are not fully understood, the most recent observations indicate that the generation and migration of fluids are the likely root cause of this dynamic behaviour. Evidence is accumulating that tremors occur over a wide depth range and tremor source regions may coincide with layers of strong seismic reflectors resolved in previous structural studies. This opens the question of whether the stress relaxation interpreted as slip occurs on a single fault plane or as distributed shear.

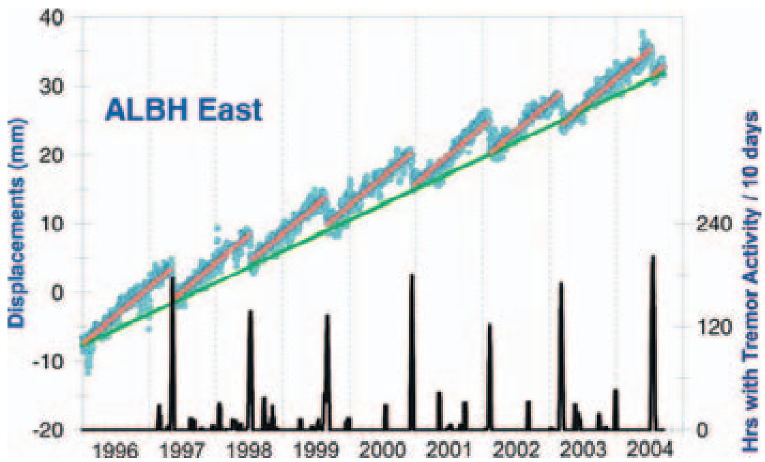


Figure 1. GPS and seismic data showing the occurrence of episodic tremor and slip (ETS) at Victoria, British Columbia. The blue circles show daily changes in the east component of position of the continuous GPS site ALBH relative to Penticton which is considered fixed on the North America plate. The green line represents long-term eastward motion due to steady deformation caused by the locked portion of the plate interface on the Cascadia subduction zone. The red line segments show distinct periods of 14 to 15 months with elevated eastward trends, each punctuated by a 1 to 2-week reversal of motion that has been modelled by slow slip on the deeper plate interface. The black graph at the bottom shows the number of hours within a sliding 10-day window that show distinct, low-frequency, non-impulsive seismic activity that has been called "tremor". The correlation of the periods of slow slip with periods of extended tremor prompted the naming of this phenomena as Episodic Tremor and Slip.

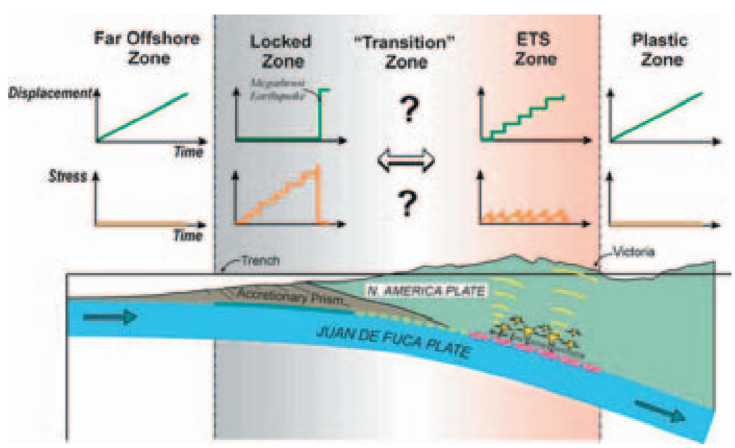


Figure 2. Conceptual model for plate motions and stress accumulation across the Cascadia subduction interface. The permanent relative displacements and changes in shear stress across the interface are sketched as functions of time in each zone. The transition of the displacement/stress behaviour from that in the locked zone to that in the ETS zone is not well defined but may provide a new basis for defining the "transition zone". Stars represent sources of tremors that accompany slip events.

Filling the North American Proterozoic Tectonic Gap: Structural and Thermochronological Evidence for ca. 1.6 Ga Deformation and Orogenesis in Southern Wyoming, USA

Ernest Duebendorfer
Northern Arizona University

Kevin Chamberlain
University of Wyoming

Matthew Heizler
New Mexico Institute of Mining and Technology

Kathleen Harper
University of Wyoming

Structural and thermochronologic studies in the Sierra Madre, southern Wyoming, indicate that parts of the 1.78-1.75 Ga Cheyenne belt, an Archean-Proterozoic suture zone, were reactivated at ca 1.6 Ga. One significant result of this study is that the Cheyenne belt in the Sierra Madre, as typically portrayed on maps, is not the 1.78-1.75 Ga arc-continent suture documented in the Medicine Bow Mountains to the east. In the Sierra Madre, a brittle thrust-tear fault system, the Battle Lake thrust-tear fault zone (BLFZ) truncated and overrode mylonites of the Cheyenne belt and transported remnants of these mylonites at least 30 km to the north-northwest. This interpretation of north-northwest tectonic transport direction is supported by kinematic analysis of more than 225 fault surfaces.

The Battle Lake fault zone has been traced for more than 45 km from the westernmost Sierra Madre eastward and southeastward toward the Wyoming-Colorado border where it is buried beneath Quaternary alluvium. The 30 km estimate of tectonic transport is consistent with Nd isotope data from the Laramie Range, the Medicine Bow Mountains, and the Sierra Madre that indicate that Archean crustal material was incorporated into the Paleoproterozoic accreted terranes as far as 30 km south of the Cheyenne belt in the former ranges, but that an abrupt transition in Nd values exists across the BLFZ in the Sierra Madre. Regional seismic reflection profiles across the Sierra Madre (CD-ROM) identified a strong south-dipping reflector that projects toward the surface of the BLFZ in the Sierra Madre. We interpret this reflector to be the BLFZ, and if our interpretation is correct, it originally penetrated to midcrustal depths and may have had a downdip length of as much as 45 km. Thus, we interpret the BLFZ to be a major crustal structure, $^{40}Ar/^{39}Ar$ and U-Pb thermochronology defines broad age patterns in the Sierra Madre that are delineated by discrete deformation zones. North of the amphibolite-grade, 1.78 Ga, Divide Peak mylonite zone, a foreland structure associated with the Medicine Bow orogeny, $^{40}Ar/^{39}Ar$ hornblende and biotite and U-Pb apatite dates suggest cooling below 300°C by 2.0 Ga. South of the Divide Peak mylonite zone but north of the BLFZ, hornblendes yield apparent $^{40}Ar/^{39}Ar$ ages of ca. 1.80-1.78 Ga that may record tectonic burial and cooling associated with Cheyenne-belt tectonism. South of the BLFZ, a hornblende sample has a well-defined, weighted mean $^{40}Ar/^{39}Ar$ age of 1618±3 Ma. Replicate analysis of a synkinematic muscovite from the Battle Lake fault zone yielded three $^{40}Ar/^{39}Ar$ dates between 1597 Ma and 1579 Ma with a preferred crystal growth age of 1590±10 Ma. We interpret the young ages to record a thermal and deformational event in the southern Sierra Madre between 1.62 and 1.59 Ga. Similar ages for deformation have been documented in the Medicine Bow Mountains to the east. The proximity of samples (in some cases less than 1 km across discrete structures) with different $^{40}Ar/^{39}Ar$ hornblende and U-Pb ages argues against either partial resetting during protracted cooling or partial resetting during ca. 1.4 Ga magmatic and thermal events.

We suggest that this 1.6 Ga event represents a previously unrecognized period of contractional deformation in southwestern Laurentia. The time interval between 1.62 and 1.59 Ga is not widely represented in the geologic record worldwide. Of the proposed conjugate margins of western Laurentia, only Australia records significant tectonism at this time. A more thorough understanding of the timing and extent of this deformation may have implications for Rodinia configurations, particularly with regard to the AUSWUS and AUSMEX reconstructions.

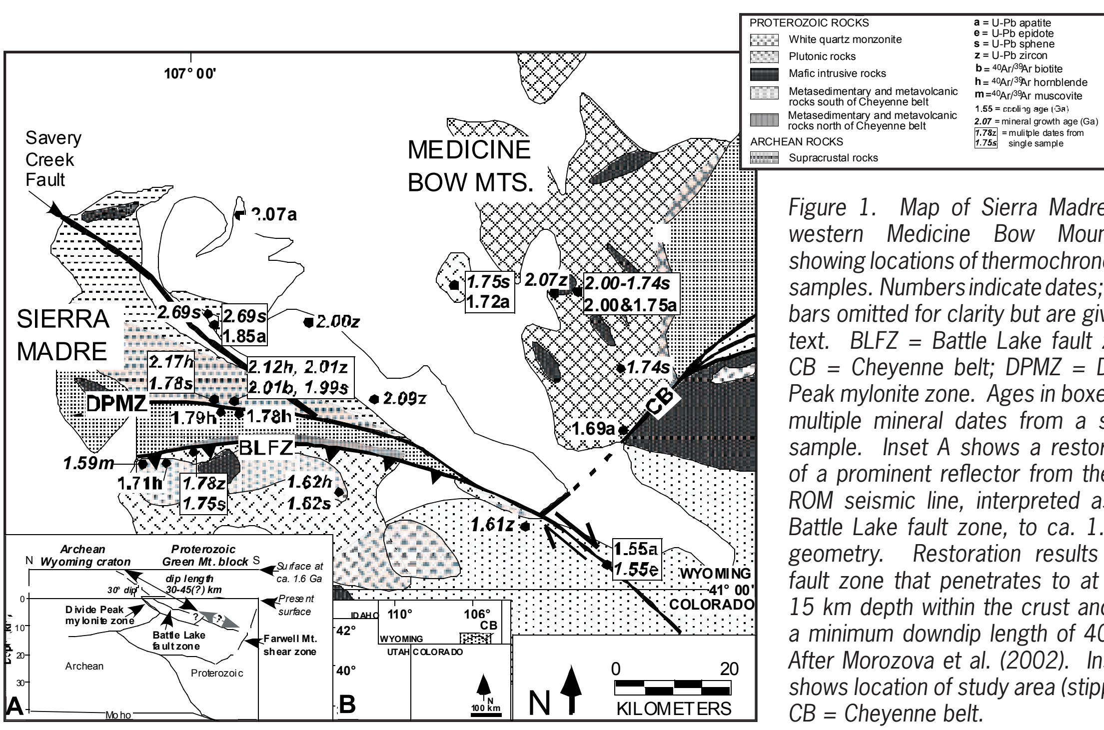


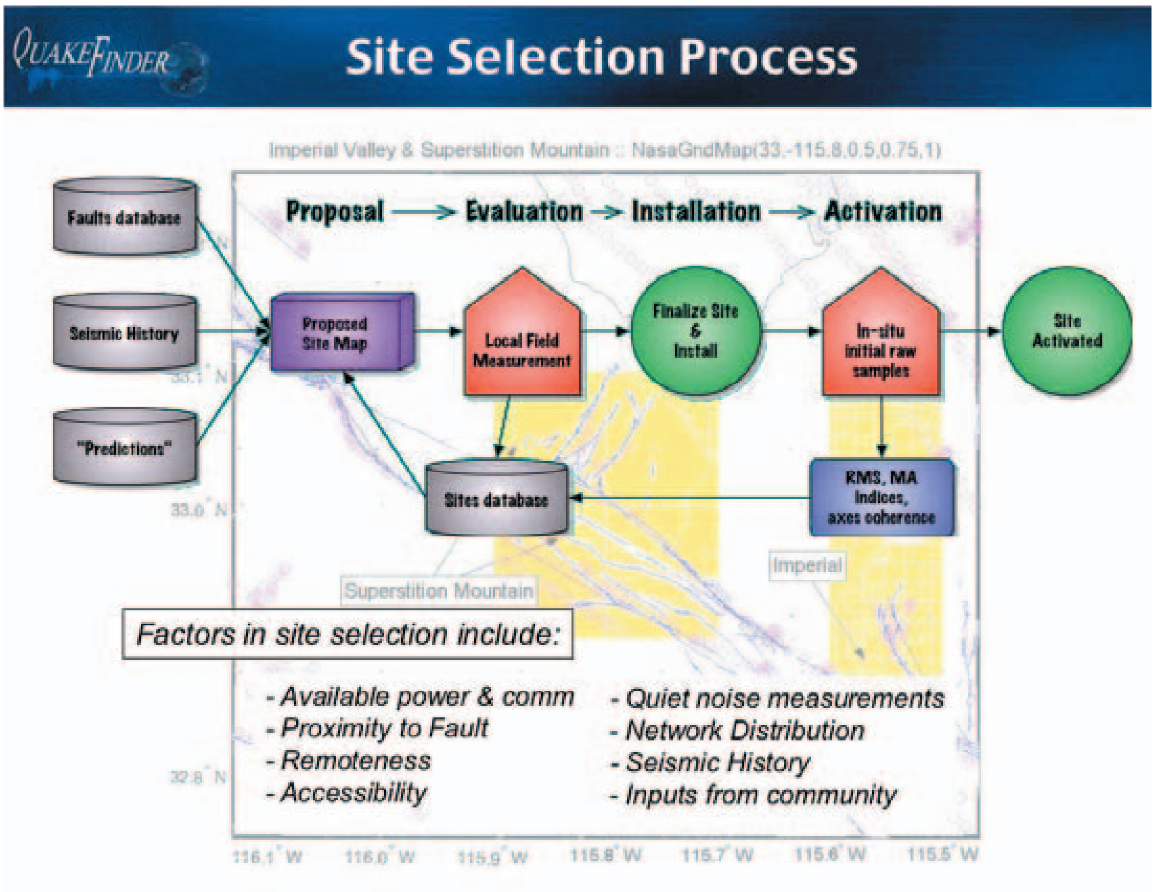
Figure 1. Map of Sierra Madre and western Medicine Bow Mountains showing locations of thermochronology samples. Numbers indicate dates; error bars omitted for clarity but are given in text. BLFZ = Battle Lake fault zone, CB = Cheyenne belt; DPMZ = Divide Peak mylonite zone. Ages in boxes are multiple mineral dates from a single sample. Inset A shows a restoration of a prominent reflector from the CD-ROM seismic line, interpreted as the Battle Lake fault zone, to ca. 1.6 Ga geometry. Restoration results in a fault zone that penetrates to at least 15 km depth within the crust and has a minimum downdip length of 40 km. After Morozova et al. (2002). Inset B shows location of study area (stippled); CB = Cheyenne belt.

ELF/ULF Magnetic Field Monitoring of the California Fault System

Clark Dunson
Quakefinder, LLC

At 17:15 UTC, (just after 10AM in the morning), a 6.0 temblor shook the Parkfield, California area. Unlike a number of quakes of magnitude 5.0 or greater that have been studied in detail over the last decade, the hypocenter of this quake was proximate to a number of geo-magnetic monitoring stations and instruments. The results of intensive study of the ULF emissions from this region are presented in this poster.

Quakefinder, LLC. operates a network of monitoring sites in the vicinity of Parkfield and throughout California which work in concert with the UC Berkeley network to form the existing network of sensors. Additionally, Quakefinder will be deploying a new series of research-quality three axis magnetometers which will be closely calibrated to give high coherence between each of the 10-15 new observatories. This poster also presents details of these new systems. Plans for locating the new observatories, and for upgrading processing of the signals are also discussed.



Incorporating Plate Boundary Observatory and Other EarthScope Data Products in Broader Objectives for Geoscience Education and Outreach: 2005 Activities

Susan Eriksson
UNAVCO

Greg Anderson
UNAVCO

A community-based EarthScope Education and Outreach (E&O) Program Plan (2002) includes fostering the use of EarthScope data products, discoveries, and new technology to address societal needs. Collecting, manipulating and aggregating real scientific data for classroom use is also a current priority in science education. Educators particularly want their students to use these data to make conclusions, following the logical processes characteristic of the scientific endeavor. The education programs of the NSF-funded EarthScope will be designed to make data products available to a variety of audiences in formal education (students and instructors in middle/high school, community colleges, undergraduate science majors and students in general science education, graduate students) and in informal education (museums, park information centers, science centers, and media).

Part of PBO's mission is to generate, archive, and distribute a variety of high-quality geodetic data products to support EarthScope scientific research in atmospheric, space physics, and crustal deformation processes. These products will include raw and quality-checked data from 891 continuous GPS stations, up to 174 borehole strainmeters and seismometers, and five long-baseline strainmeters. While these raw data will be used directly by some researchers, PBO is also committed to produce higher-level products such as station velocities, strain time series, and the like for a user community with a wide range of technical expertise and data product requirements. Scientific applications of these higher-level products will include improved finite-fault earthquake source models, regional and local strain fields, and high-level integrated crustal deformation models.

Generating and using these higher level data products will be the responsibility of the EarthScope E&O program, EarthScope facilities (PBO, USArray, SAFOD), and the broader science and education communities. Many existing organizations, networks, and programs will help provide the synergy needed to accomplish this important task and avoid duplication of efforts. Some examples include the Digital Library for Earth System Education (DLESE), particularly the Data Services Working Group which sponsors workshops in curriculum development. Resources such as "Using Data in Undergraduate Science Classrooms (Manduca and Mogk, 2003) and other resources from Science Education Resource Center at Carleton College will help in the design of EarthScope data products in undergraduate classes. PBO is already working on a chapter for the Earth Exploration Toolbox (http://serc.carleton.edu/eet/) for a general undergraduate audience.

More challenging is the use of similar data products in middle and high schools. A well established and full curriculum, high stakes testing, and a general population of science teachers with little knowledge of geoscience are factors to overcome in taking EarthScope data products into secondary education. However, teachers' desire for using real data, the excitement of the EarthScope project, compelling tools for data visualization, and 'teachable moments' related to natural events are positive factors. In development are tools such as the EarthScope Voyager, interpretation in parks based on local geoscience and geological hazards (East Bay Parks, San Francisco area and Johnston Ridge Observatory, Mount St. Helens National Volcanic Monument), and workshops in which teachers will help set priorities for using PBO data products and incorporating data products into lesson plans for the 2005-2006 school year.

Lastly, providing education at the graduate and upper undergraduate levels and including diversity as a core value will ensure a robust scientific community using PBO and other EarthScope facilities. UNAVCO has scheduled two workshops for 2005, one on strainmeter data processing and the other on use of GLOBK/QOCA, to address this goal.

Computer science undergraduates at the University of Colorado work with geology students to test the EarthScope Voyager.

Composition of Rocks Near and Within the San Andreas Fault Zone as Determined From SAFOD Pilot Hole Mineralogy and Analysis of Exhumed Parts of the San Andreas Fault

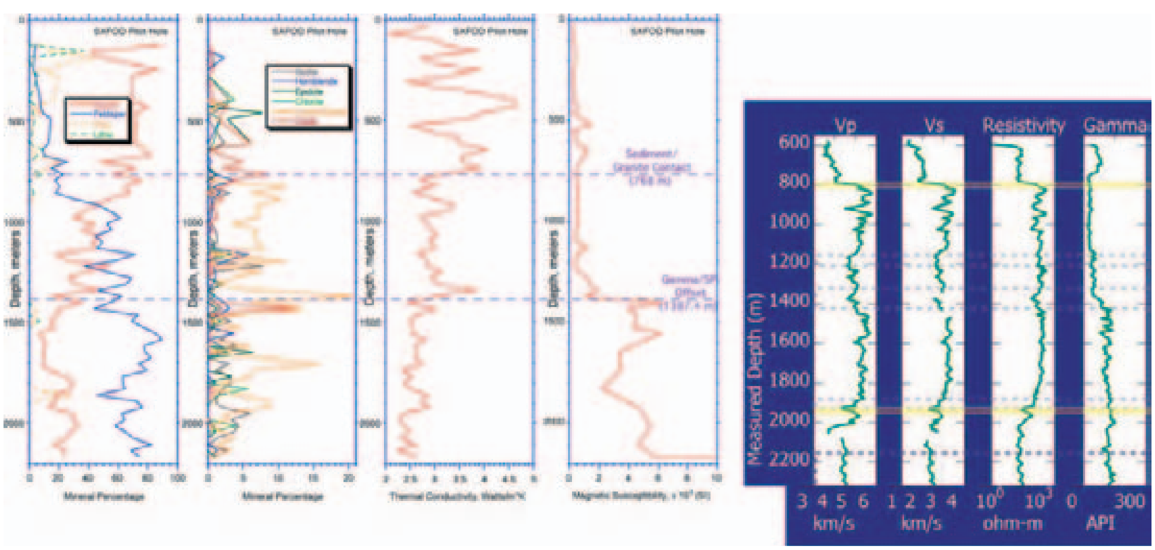
James Evans
Utah State University

Michael Rymer
U.S. Geological Survey

Diane Moore
U.S. Geological Survey

Stephen Hickman
U.S. Geological Survey

We characterize the mineralogy of cuttings from the SAFOD pilot hole drilled in 2002, as well as examine the microstructures and textures of a suite of samples from outcrops of the main trace of the San Andreas fault ~2.4 km north of the SAFOD drill site. We examine the location, composition, and deformation mechanisms of subsidiary faults encountered in the pilot hole to help us determine the nature of the San Andreas and subsidiary faults to be penetrated by the main SAFOD hole in 2005. Point-counts of cuttings from the SAFOD pilot hole indicate several zones of alteration as marked by increases in calcite, zeolites, and Fe-oxides. The main zone of alteration occurs at ~ 1400 m measured depth in the pilot hole, and corresponds with an offset in the SP/gamma ray signature, decreases in V_p and V_s, and a slight decrease in the resistivity of the rocks as measured with wireline geophysical logs [Boness and Zoback, 2004]. We suggest that the pilot hole intersects a subsidiary fault zone at this depth that consists of altered granitic protolith. This is consistent with other geologic investigations of exhumed faults of the San Andreas system [Chester et al., 1993, 2004] in which fluid-rock alteration occurs in a damage zone and slip is localized along narrow slip surfaces. The SAF at the SAFOD site may consist of several strands, each with a damage zone associated with it. We also examine the main trace of the SAF in exposures where the fault juxtaposes highly sheared Jurassic to Cretaceous serpentinite, consisting of altered peridotite and tectonized antigorite within the fault, against Pliocene (?) brecciated sedimentary deposits on both sides of the fault. Serpentinite samples within 20 cm of the fault contact exhibit two subvertical foliations superposed on an earlier metamorphic foliation. Foliated zones 1–5 mm wide are subparallel to the SAF contact, and wavy to folded antigorite grains are cut by thin faults that consist of ultracataclasite. Foliation orientations are consistent with a right-side-up sense of shear. Samples from the sedimentary deposit exhibit Fe-filled brittle fractures and calcite veins in a random cataclastic texture within 50 cm of the fault. Within 10 cm of the fault the sedimentary rocks have a moderate foliation, and ultracataclasite fragments lie in a matrix of sheared sandstone. Beyond 50 cm of the fault the sedimentary rocks exhibit variable amounts of deformation, ranging from regions of intense intragranular fracturing to nearly undeformed grains. These observations suggest that at this site the SAF consists of a narrow zone of highly localized shear within the foliated host rock, Further analyses of the creeping and locked sections of the fault near SAFOD, as well as further study of the composition of the rocks encountered both in the pilot hole and in the main SAFOD hole [Solum et al., this meeting], will provide constraints on the nature and distribution of faulting associated with San Andreas Fault Zone at Parkfield.



Mineralogy of the cuttings from the SAFOD pilot hole plotted as a function of depth, along with the thermal conductivity data of C. Williams, magneticsusceptibility data, and wirelone log dat of Boness and Zoback [2004 AGU]. Major compoent compositions show an increase in feldspar content with depth, and a decreasing quartz content. Minor mineral compositionstrack the variations in alteration-related assembleges, and suggests the presence of alteration at ~ 1400 m and ~1750 m. The upper alteration zone coincices with changes is seismic velocity, thermal conductivity, and resistivity determined from borehole geophysical data of Boness and Zoback, 2004 [GRL and AGU abstract].

Imaging the b-Value Distribution Beneath the Yellowstone Hydrothermal System

Jamie Farrell
University of Utah

Stephan Husen
Swiss Seismological Society

Robert Smith
University of Utah

The Yellowstone region is one of the most seismically active areas in the U.S. Cordillera. There are 26,404 earthquakes in the catalog for the years of 1973 - 2003. Recently, the earthquake catalog has been relocated using 3-d velocity models and non-linear, probabilistic earthquake locations. During relocation, coda magnitudes, Mc, were recomputed using a newly derived magnitude equation including newly available instrument calibrations. The relocated earthquake catalog encompasses 20,245 earthquakes between 1984 and 2003 with consistent magnitudes throughout the entire time period. Reliable information on location uncertainties, included in the probabilistic solution to the earthquake location problem, allowed us to select only well-constrained earthquake locations, leaving 19,741 events to map the b-value distribution. Seismicity in the Yellowstone National Park region is characterized by extensive swarms. In order to accurately map b-values in the area, the catalog has to be deswarmed. An algorithm was used that categorized earthquake swarms based solely on interevent times and distances. Using the above algorithm, a total of 204 swarms were identified from 1984 – 2003. After deswarming the catalog, 9,377 events remained. There is no need to additionally decluster the catalog because the mainshock/aftershock pattern of seismicity is not observed in the Yellowstone National Park region. The 597 events triggered by the 2002 Denali Fault earthquake were then removed giving a total of 9,110 independent events in the catalog. Using the deswarmed catalog, we will image the b-values distribution for the Yellowstone National Park region using ZMAP. B-values will be also evaluated using the original – clustered and not relocated – catalog and compared to the results obtained with the selected catalog. This will help us to better understand the effects of dependent events and earthquake locations on the b-value distribution. Variations in b-values can be indicative of material heterogeneity, the applied shear stress, the effective stress, and/or the thermal gradient of an area. In order to distinguish between the different causes, we will compare the b-value distribution with existing crustal tomography results, which will help us to better understand crustral structure and ongoing tectonic processes beneath the Yellowstone National Park region.

PBO Facility Construction: GPS Network Status

Karl Feaux
UNAVCO

Mike Jackson
UNAVCO

Greg Anderson
UNAVCO

David Mencin
UNAVCO

The Plate Boundary Observatory (PBO), part of the larger NSF-funded EarthScope project, will study the three-dimensional strain field resulting from active plate boundary deformation across the Western United States. PBO is a large construction project involving the reconnaissance, permitting, installation, documentation, and maintenance of 875 permanent GPS stations and up to 175 strainmeter stations in five years. PBO has a demanding 5-year project installation schedule, for both GPS and strainmeter installations. During the first year of the project, PBO not only met the first year GPS production goals, but also completed various project startup activities, including developing and implementing policies and procedures to streamline the remote office operations. Operations are ongoing in the five PBO remote offices that were located, staffed, and setup in the first year of the project. The GPS station design was completed and procedures were developed to ensure consistent construction practices throughout the six PBO regions. The GPS driller selection and evaluation plan was developed to ensure a competitive subcontractor selection process. A PBO construction safety plan was developed and implemented to ensure safe PBO worksites. Also, PBO began the development of a robust database and other web-based tools to facilitate the data entry, documentation, and reporting of all the reconnaissance, permitting, and installation activities. The completion of these tasks was necessary in order to meet the even more demanding schedule for Year 2 and beyond. GPS construction highlights in Year 1 include the San Simeon earthquake response and the installations on Augustine volcano in Alaska. GPS construction highlights in Year 2 include installations on Mount St. Helens volcano and the Parkfield earthquake response. To date PBO has 115 operational GPS stations of the 250 installations planned by the end of Year 2.

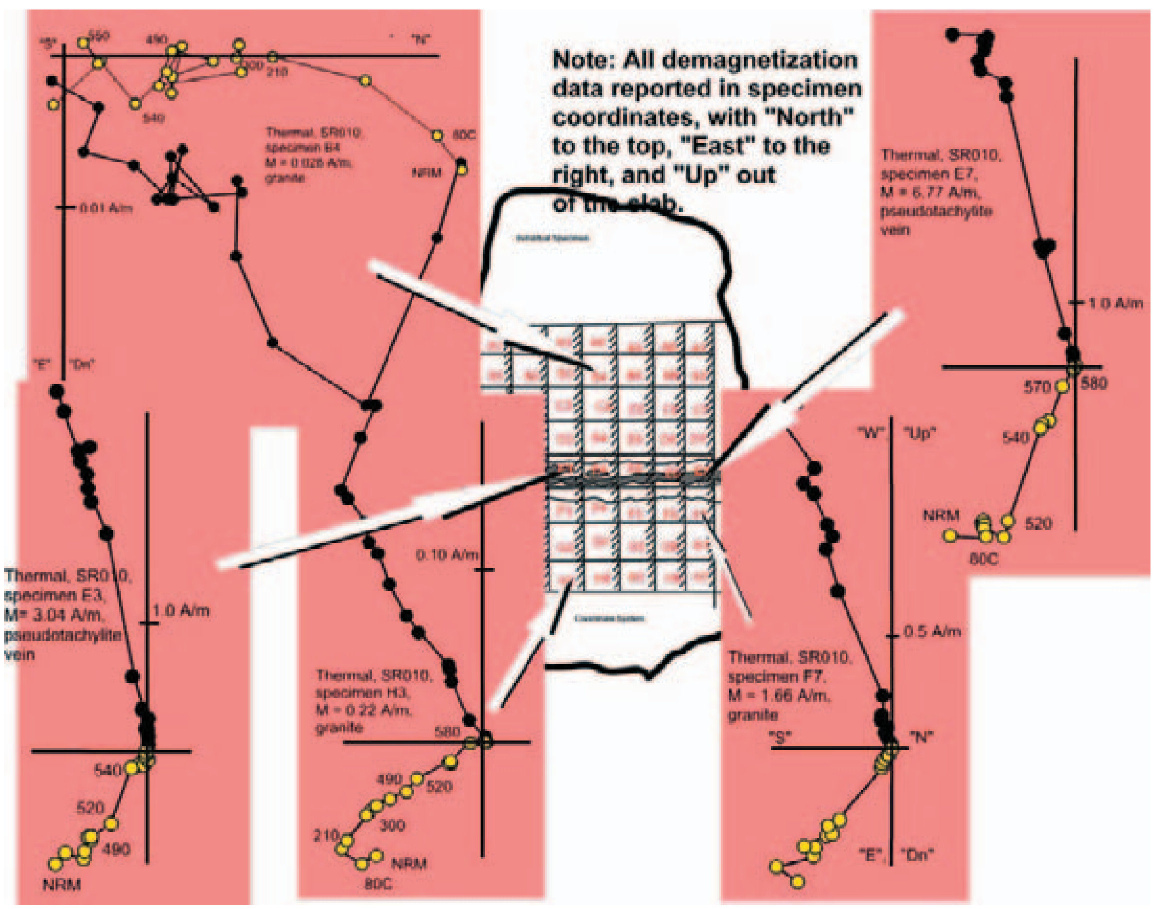
Slinging equipment from AC59 to base camp - Augustine Volcano, Alaska.

Paleomagnetic and Rock Magnetic Record of Transient Co-seismic Electric Currents in Fault-rocks

Eric Ferre
Southern Illinois University

John Geissman
University of New Mexico

A literature review of magnetic remanence in fault rocks deformed at seismic slip rates, such as the Nojima Fault rocks, suggests that they commonly exhibit anomalously high natural remanent magnetization (NRM). Several models have been proposed to explain such high NRMs, similar to those of lightning struck rocks, involving formation of abundant fine (single domain) magnetite grains during quenching of frictional melts, or large piezo-electric or tribo-electric pulses. We have analyzed young pseudotachylite (PST) veins and immediately adjacent host rocks from a seismically active fault zone (Eastern Peninsular Ranges [62-56 Ma tonalite host rock], California). Notably, magnetic properties of the PST veins differ considerably from host rock. Typical NRM intensities for PST range from 2.0 to 20.0 A/m, with the NRM of single component character (median destructive fields are typically about 40 mT and 80 percent of laboratory unblocking temperature spectra between 500 and 580ºC). Modified Lowrie-Fuller tests suggest that pseudotachylites at this locality locality contains abundant fine, single-domain magnetite particles. Our results are compared with those from artificially generated PST to obtain a better understanding of co-seismic electric phenomena. Models of electrical and magnetic properties of fault rocks suggest that anomalous NRM should be acquired by these materials along the fault plane even in the absence of melting. These results could be applied to the SAFOD core samples and would provide a unique opportunity to document the existence of co-seismic electric currents along the San Andreas Fault.



Zijderveld diagrams showing thermal demagnetization of fault-related pseudotachylite and host rock (Santa Rosa Mountains, CA).

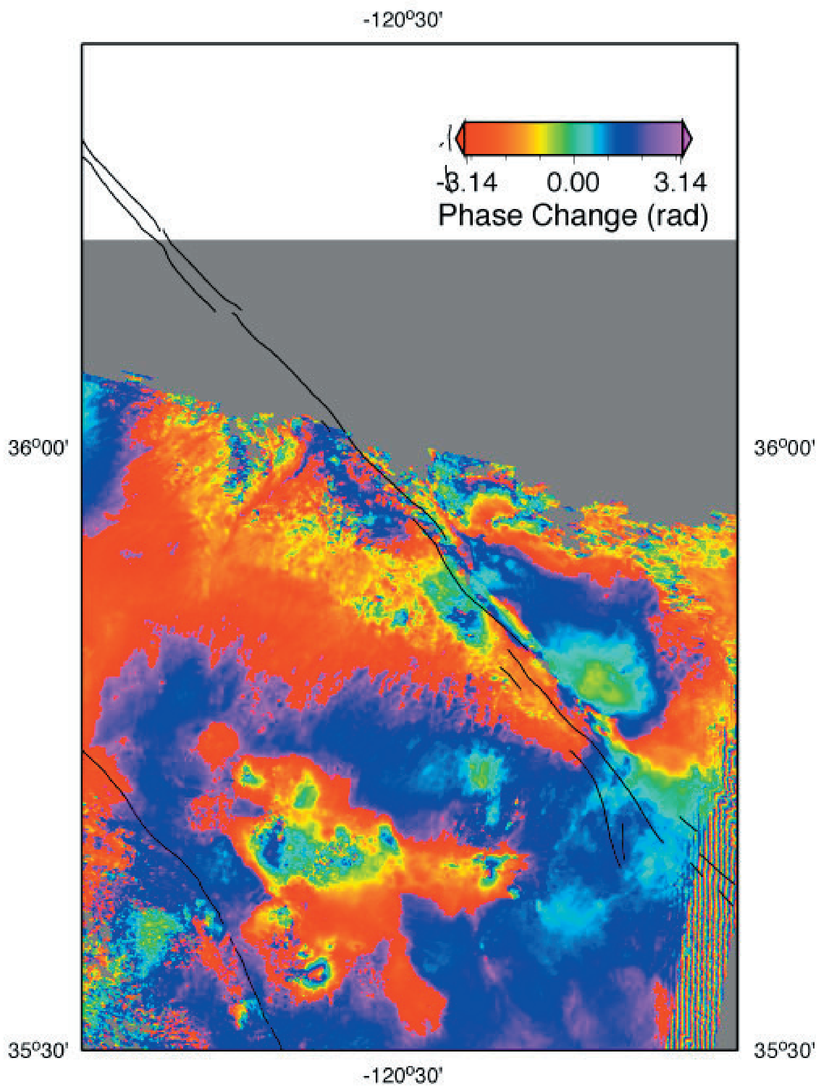
SAR Interferometry of the 2004 Parkfield Earthquake Zone: Using WInSAR Envisat and Radarsat Data to Measure Co-seismic and Post-seismic Deformation

Eric Fielding
Jet Propulsion Laboratory

Ingrid Johanson
University of California Berkeley

Roland Bürgmann
University of California Berkeley

Synthetic aperture radar (SAR) interferometry has proven valuable over the last decade for constraining the fault rupture locations and slip distributions for a number of earthquakes around the world. Preliminary analysis of SAR interferometry (InSAR) data for the Parkfield earthquake has been tantalizing, revealing some details of the surface deformation during and after the earthquake but not quite mapping the full rupture zone. The two SAR satellites in full operation at the time of the 2004 Parkfield earthquake were Envisat and Radarsat, both C-band (5.6 cm wavelength) radar systems that have been recently added to the WInSAR (Western North America Interferometric Synthetic Aperture Radar Consortium) archive. Parkfield is in a vegetation cover transition zone between the less vegetated southern California region and the more vegetated northern California region. The substantial vegetation cover to the north and west of Parkfield cause noise and low interferometric correlation in the C-band radar data, so far making it difficult to measure the surface deformation in that area. Southwest of Parkfield, the Envisat InSAR data maps surface ruptures on the main trace of the San Andreas and the southwest fracture zone strand, in the co-seismic and post-seismic phases. The combination of the spatially dense sampling of the InSAR with GPS and creep meter data that have greater temporal resolution at station locations improves our knowledge of the fault zone behavior.



Portion of Envisat interferogram spanning interval from 4/14/2004 to 10/6/2004 (eight days after the Parkfield earthquake). Thin black lines show previously mapped fault traces. Interferogram phase has been unwrapped and then rewrapped to the original fringe pattern after masking with gray the areas with high noise and low correlation. Sharp phase offsets due to surface deformation appear along the main San Andreas Fault trace and the "southwest fracture zone" strand southeast of Parkfield (near the top edge of the InSAR data).

EarthScope Possibilities for Understanding Lithospheric Processes in Eastern North America

Karen Fischer
Brown University

Aibing Li
University of Houston

Michael Wysession
Washington University

Krishna Sinha
Virginia Tech

When the EarthScope transportable array arrives in eastern North America and is combined with the flexible array and the permanent backbone stations, it will provide resolution of crust and mantle structure at a scale that is capable of constraining how the Archean to Phanerozoic lithospheres assembled and were subsequently modified by post-orogenic processes and ongoing mantle flow. Results from existing IRIS/PASSCAL broadband seismometer arrays and permanent stations provide hints of models likely to emerge. For example, the Missouri to Massachusetts (MOMA) and Florida to Edmonton (FLED) Broadband Seismometer Experiments reached from the continental margin deep into the cratonic interior on roughly orthogonal profiles. Analyses of these data have provided constraints on the morphology of the lithosphere-asthenosphere boundary, the distribution of anisotropy and strain between the lithosphere and and asthenosphere, and how lithospheric support of collisional mountain belts evolves over time.

What is the shape of the lithosphere-asthenosphere boundary? What anisotropies exist in the lithosphere versus the asthenosphere? Are lithospheric and asthenospheric strain coupled? What is the pattern of asthenospheric flow? Surface wave inversions and migration of teleseismic scattered waves define a decrease in lithospheric thickness from 200-250 km beneath the craton to less than 100 km at the continental margin. Shear-wave splitting in SKS phases indicates significant anisotropy beneath the region, but alone these data cannot constrain the depth at which the anisotropy occurs. Love and Rayleigh surface wave inversions beneath the MOMA (Gaherty, 2004) and FLED arrays show that Love wave velocities are fast relative to Rayleigh. In combination with the SKS splitting, the surface waves indicate that the upper 200 km of the mantle beneath the eastern U.S. contains radial anisotropy, and that much of the SKS splitting is due to azimuthal anisotropy in the sub-lithospheric mantle. These results suggest that deformation fabrics in the lithosphere and asthenosphere are fundamentally different. The orientations of the SKS fast directions are in general consistent with asthenospheric flow around the base of the lithosphere dominated by plate motion. With the 70 km station spacing of the transportable array, Rayleigh wave resolution tests show that azimuthal anisotropy of more than a percent should be distinguishable from isotropic anomalies at lateral length scales as small as 200-300 km in the shallow upper mantle.

How does lithospheric support of collisional mountain belts evolve over time? What are the roles of crustal root buoyancy and lithospheric strength? Crustal properties were determined using Ps phases scattered from the Moho and, where possible, crustal reverberations. Significant roots of thickened crust exist beneath the Appalachians along both the MOMA and FLED arrays, and yield similar ratios of surface topography to excess crustal thickness. However, both are small when compared to topography/crustal root ratios in young orogens. These results are consistent with global trends in orogenic crustal thickness, mountain topography and gravity anomalies that suggest a systematic decrease with age in the buoyancy of crustal roots relative to the mantle. Such an increase in crustal root density can be explained by progressive metamorphic reactions. In most regions, the average crustal root densities that best fit the gravity data isostatically compensate surface relief, suggesting that the continental lithosphere remains weak enough to permit exhumation of crustal roots in response to erosion over hundreds of millions of years. Petrological constraints on the temporal evolution of the Appalachian lithospheric geotherm would provide a key test of this hypothesis, reinforcing the need for integration of geological and geophysical information in EarthScope science.

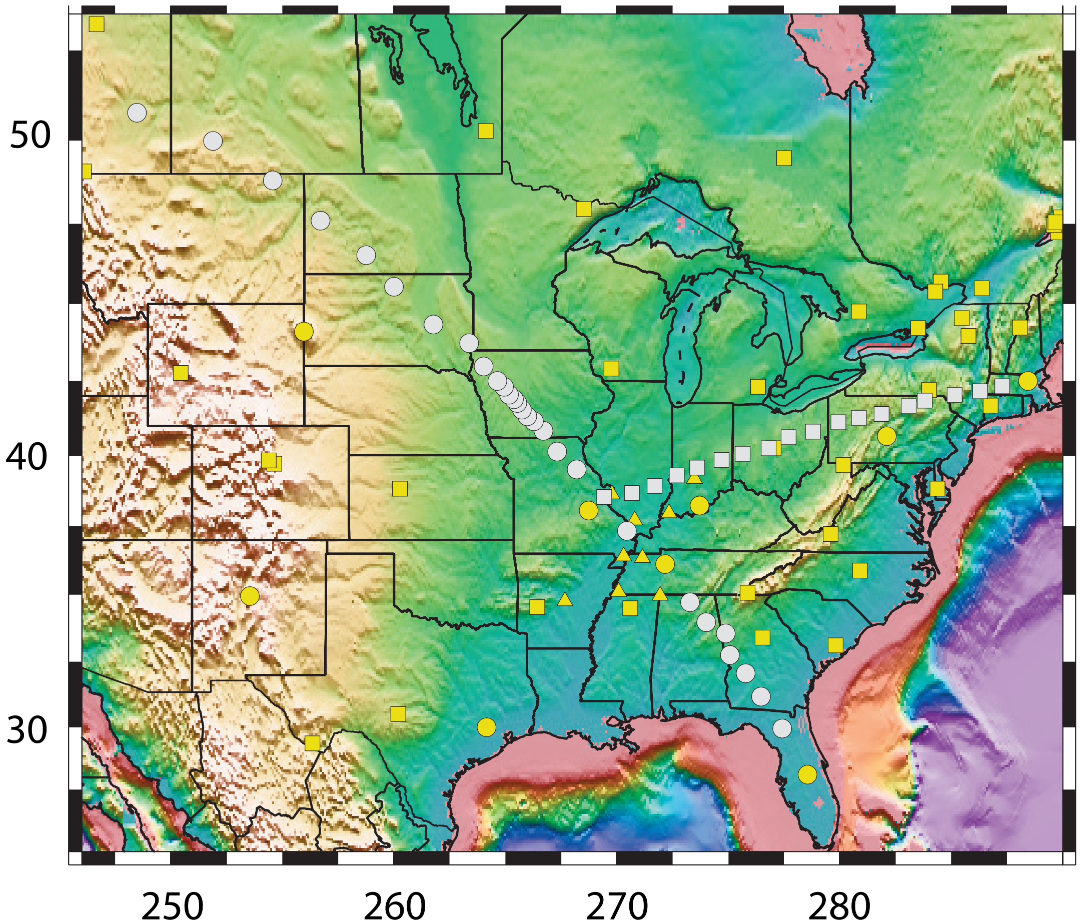
Figure on Page 118 >

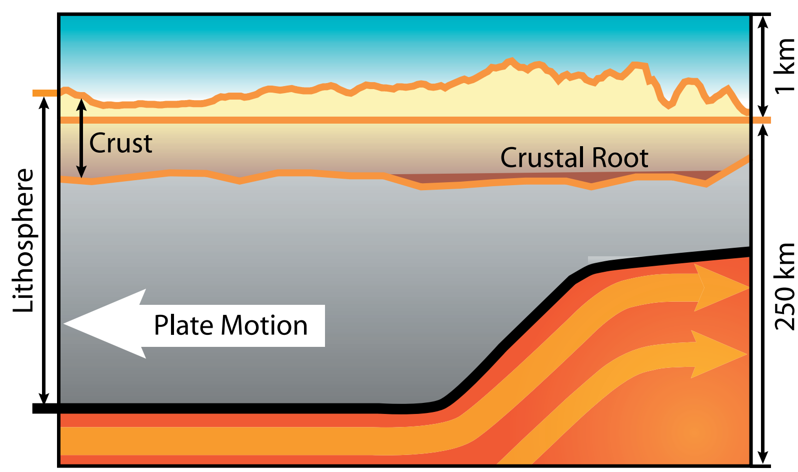
Karen Fischer
Brown University

Aibing Li
University of Houston

Michael Wysession
Washington University

Krishna Sinha
Virginia Tech





Top: Map showing the locations of stations in the 1995-1996 Missouri to Massachusetts Broadband Seismometer Experiment (MOMA, white squares) and the 2001-2002 Florida to Edmonton Broadband Seismometer Experiment (FLED, white circles). Permanent stations that are part of the IRIS Global Seismic Network (yellow circles), the U.S. National Seismic Network and the Canadian National Seismic Network (yellow squares), and the New Madrid Seismic Network (yellow triangles) are also shown. Surface elevation is given by colored shading. Bottom: Profile along the MOMA array showing crustal thickness constrained by PS phases and a schematic view of lithospheric thickness from surface wave inversions and PS phases. Arrows indicate flow in the asthenosphere which is interpreted as the source of splitting in SKS phases.

EarthScope Workshop for the Northern Rocky Mountains

David Foster
University of Florida

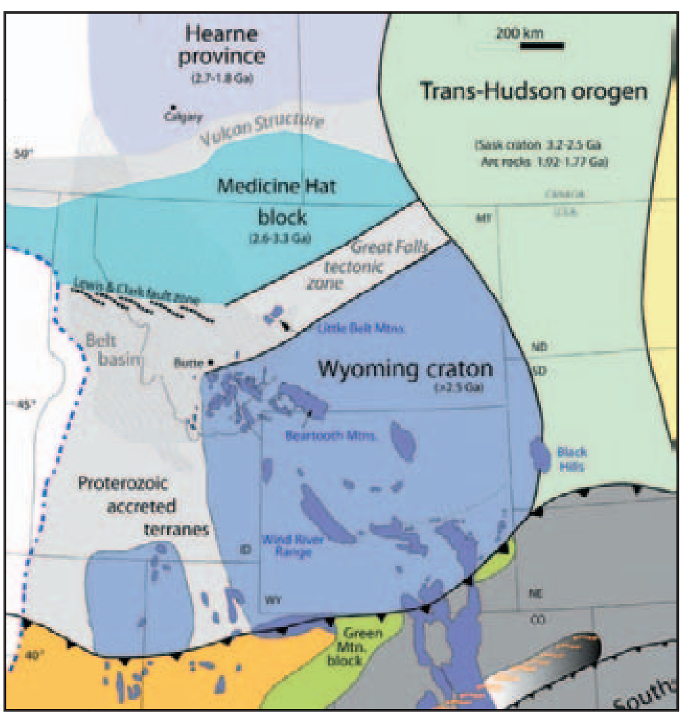
Paul Mueller
University of Florida

David Mogk
Montana State University

An EarthScope workshop for the Northern Rocky Mountains will be held in September 2005. The workshop will provide an opportunity for a diverse array of earth scientists to meet and discuss the opportunities that EarthScope will provide for utilizing the northern Rocky Mountains as a natural laboratory for enhancing our understanding of continental evolution. Geographically, the workshop will focus on the area generally within northern Wyoming, SW Montana, and eastern Idaho. This region has an incredibly diverse and extensive geologic history that is recorded in rocks that range from ancient (>3.5 Ga) gneisses to the Yellowstone hotspot/Snake River Plain. This portion of the North American continent provides an ideal environment for studying the physical and chemical evolution of the crust-mantle system because it records multiple generations of crustal evolution involving a variety of tectonic environments (e.g., continent-continent collisions, rifting, the formation of a major sedimentary basin (Belt basin), and impingement of a modern mantle plume). The region provides an opportunity, therefore, to examine two of the most challenging problems in the study of the formation and evolution of continental crust: 1) how newly segregated, low-density crust and lithosphere (most commonly formed in island arcs and along continental margins) is integrated into compositionally and structurally mature continents and 2) how this newly formed crust and lithosphere evolves within the continental environment and how its structure and composition influence the subsequent evolution of the continent itself. These are two of the most basic questions in continental crustal evolution because modern continents are clearly not the geochemical or structural equivalent of modern island arcs. In addition, it is clear that Precambrian structural features do influence Phanerozoic continental evolution, particularly in western North America. To understand the processes by which this combined crust-lithosphere system forms and evolves requires the application of many disciplines (geochemistry, petrology, geophysics, etc.). In particular, EarthScope resources can play a pivotal role in elucidating the complex history of the northern Rocky Mountains, and thereby add significantly to our understanding of both crustal genesis and continental evolution.

The workshop will consist of an approximately 2-day meeting, which will begin with a general session followed by breakout of smaller working groups. A concluding session will include presentations from the individual working groups. Appropriate and timely announcements will allow ample opportunity for all interested parties to apply for inclusion. If sufficient interest exists, the PIs will also conduct a self-funded pre-meeting field trip to highlight major geologic features of the region.

The broader impacts of the proposed activity will be in accordance with the Education and Outreach (E&O) objectives delineated in the EarthScope plan, and will be integrated with related research activity from the beginning by establishing an E&O working group in parallel with the research-oriented working groups. The workshop will also serve to identify colleagues who are interested in contributing to EarthScope E&O in the northern Rocky Mountains and to lay the foundation for future work in this area through the establishment of local alliances, providing content to the EarthScope E&O webpage, developing supplemental curricular materials in anticipation of EarthScope deployment, and related activities as defined in the E&O plan.



Map showing the major basement provinces in the northern Rocky Mountains. Most of the basement elements are covered and obscured by Phanerozoic strata and plutons. These basement provinces, however, imparted a strong control on the nature and style of Phanerozoic structures in the northern Rocky Mountains. The accurate identification of crustal age-provinces in this region is also critical to testing extant models for Proterozoic tectonic reconstructions.

Crust and Uppermost Mantle Structure Beneath the Southern Basin and Range/Colorado Plateau: Results from the COARSE Broadband Seismometer Array and Goals for Regional USArray Studies

Matthew Fouch
Arizona State University

Hersh Gilbert
University of Arizona

George Zandt
University of Arizona

Susan Beck
University of Arizona

Andrew Frassetto
University of Arizona

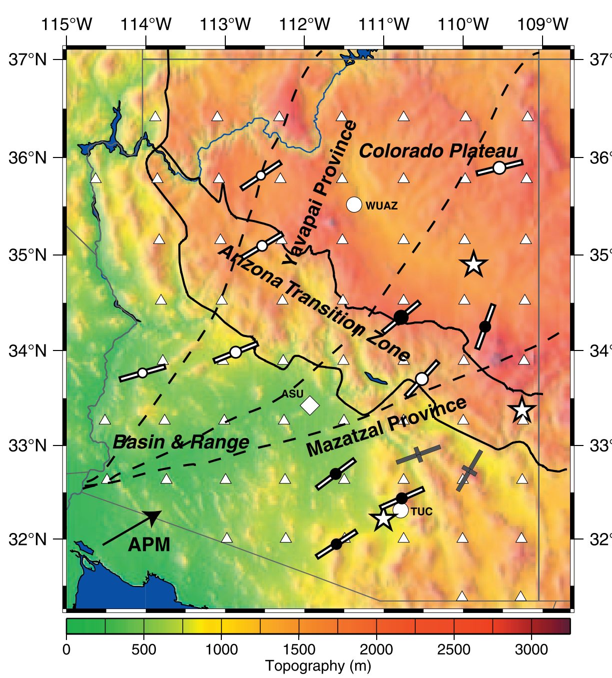
Jesse Yoburn
Arizona State University

Thomas Owens
University of South Carolina

Edward Garnero
Arizona State University

The transition between the southern Basin and Range (BR) and Colorado Plateau (CP) is an ideal tectonic setting to investigate processes of crust and mantle deformation away from plate boundaries. A key question is the distinct effect of the juxtaposition of vertical and horizontal tectonics as exhibited by uplift and lateral stability of the CP near significant rapid lateral extension in the BR. To help investigate the relative contributions of crust and upper mantle to these processes, we have been operating the broadly spaced, 10-station COARSE (COnsortium for Arizona Reconnaissance Seismic Experiment) seismic array in eastern Arizona, which traverses the southern BR and CP (Figure 1). We augment these data with three permanent broadband stations (ASU, TUC, and WUAZ). The primary goal of our work is to provide new constraints on regional seismic structure beneath the BR and CP using modern broadband seismic data and analysis techniques in a region of notable seismic undersampling of lithospheric-scale structure in the western United States.

Inspection of COARSE data reveals key differences in the seismic structure of the crust and upper mantle beneath this region: (1) Results from stacked receiver functions indicate that the crust underlying the multiple metamorphic core complexes occupied by COARSE stations exhibit a relative simple Moho signal correspond to a ~30 km thick crust. We also find clear evidence for first-order inter-crustal structures that may have resulted from faulting associated with Cenozoic extension. Stations within the core complexes also exhibit significant azimuthal variations in inter-crustal arrivals, which could be due to the presence of anisotropic material within the crust. (2) Beneath the CP, receiver function results change dramatically from the southern BR. For instance, crustal thickness values are significantly larger (~40 km) for stations on the CP. These stations, however, exhibit smaller amplitude multi-peaked Moho arrivals, suggesting that the velocity contrast between the crust and mantle may be significantly smaller than in the BR, that velocity variations occur over a large depth interval, and/or that the Moho beneath this portion of the CP is uneven, rather than a flat, simple seismic velocity discontinuity. Additionally, stations on the CP exhibit large negative arrivals, which generally result from a layer of low seismic velocities located beneath layers of higher seismic velocities. These low velocity zones at depths of ~15 and 60 km are associated with young volcanic fields and may help explain the source of uplift and support of the Arizona Transition Zone. (3) Shear wave splitting measurements for stations indicates the distinct presence of mantle seismic anisotropy (Figure 1). Fast directions are aligned ~NE-SW, while splitting times range from 0.8 to 1.4 seconds across the array. Fast directions are parallel both to present-data absolute plate motion and regional Proterozoic terrane boundaries, but are not parallel to current Basin and Range extension. (4) Distinct pockets of local crustal seismicity with local magnitudes as large as 4.2 are organized into narrow areas within both the Arizona Transition Zone and on the southern margin of the CP. Many of these events fortuitously originated within the bounds of our array, enabling location of these otherwise undetected events. One zone of seismicity is located near Superior, AZ, and exhibits source depths between ~15 and ~20 km. Other pockets of seismicity also detected by the array include an earthquake swarm in December 2003 near the Springerville volcanic field with source depths ranging from ~30 to ~40 km. We are in the process of systematically cataloging these events, including focal mechanisms for the larger events. The newfound presence of many small earthquakes near the COARSE array suggests that the combination of USArray transportable and flexible array stations deployed in the region will detect local seismicity in a number of areas previously thought to be comparatively aseismic.



Preliminary shear wave splitting results for COARSE and other regional stations [Ruppert, 1992; Sandvol and Ni, 1994]. Fast polarization directions denoted by azimuth of white bars; splitting times denoted by scaled circles. COARSE results are shown with black circles; other studies are shown with white circles. Two stations in the BR exhibit null measurements (gray bars). Stars denote COARSE stations that have not yet been evaluated for shear wave splitting; circles and diamond represent permanent regional stations; triangles denote proposed USArray station locations in Arizona. Solid lines denote present-day terrane boundaries; dashed lines show (very) approximate Proterozoic terrane boundaries [Karlstrom and Humphreys, 1998].

Fast directions are parallel both to present-data absolute plate motion (APM) and regional Proterozoic terrane boundaries while splitting times do not correlate with geologic terrane boundaries. The deployment of USArray stations in this region will vastly improve our understanding of the relationship between crust/upper mantle deformation and geologic terranes across this region.

Stratigraphy of the Arizona Lithosphere and Evidence of Remnant Partial Melt Beneath the Colorado Plateau: Project COARSE

Andrew Frassetto
University of Arizona

Hersh Gilbert
University of Arizona

George Zandt
University of Arizona

Matthew Fouch
Arizona State University

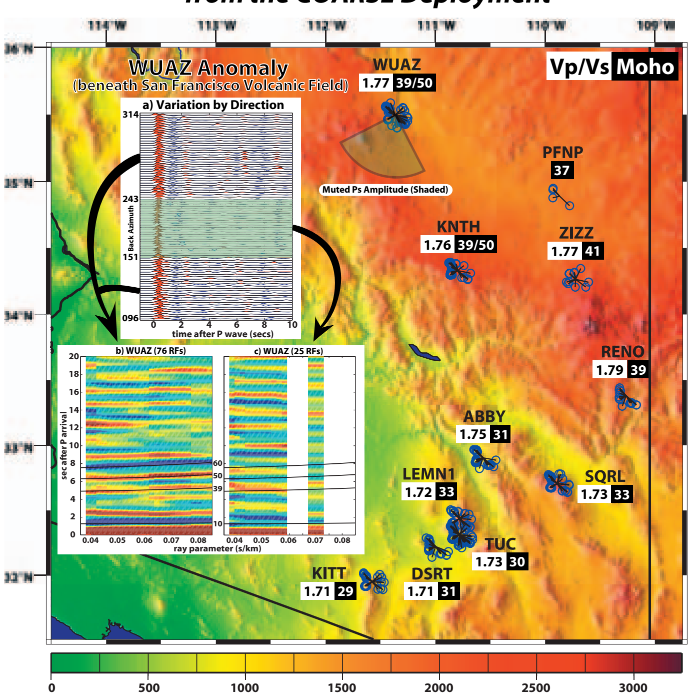
Project COARSE (COnsortium for Arizona Reconnaissance Seismic Experiment) has operated a temporary broadband seismic network across eastern Arizona for the past two years. The COARSE array samples lithosphere across the Southern Basin and Range (BR) and parts of the Arizona Transition Zone (ATZ) and Colorado Plateau (CP). Our observations aim to further distinguish the structural difference between the stable Colorado Plateau and highly deformed Basin and Range. Forces related to Laramide subhorizontal subduction of the Farallon plate beneath the North American plate followed by a slab steepening or detachment event in the mid-Cenozoic are common to geologic and tectonic models of the deformation and volcanism within the western United States. How these events modified the lithosphere remains unknown and is the subject of the study.

Receiver functions from COARSE stations display distinct differences between the CP-ATZ and BR stations including variations in crustal thickness, amplitude of the Moho arrival, low velocity zones within the crust and uppermost mantle, muted primary Ps phases, and crustal anisotropy. All BR stations possess a clear high amplitude Moho arrival corresponding to crustal thicknesses of ~30 km and show a V_p/V_s of 1.73. In contrast, receiver functions from CP and ATZ stations reveal a highly stratified mid to lower crust with a V_p/V_s of 1.77. At WUAZ and KNTH two prominent primary Ps phases of comparable amplitude occur at approximately 40 and 50 km. These results raise the possibility of a layered Moho boundary or mafic material near the base of the crust beneath the ATZ. Common to all stations sampling the CP and ATZ, a substantial low velocity layer appears to underlie the region at ~60 km depth.

In the CP, stations WUAZ and ZIZZ contain a shallow, high amplitude, negative polarity arrival at 1-2 s following the direct P wave. These stations are located near the San Francisco and Springerville Pliocene to Holocene age volcanic fields, respectively. This arrival could result from the top of an anomalously slow shear wave-speed layer. Amplitudes of receiver functions at WUAZ vary significantly with azimuth (Figure 1a). Receiver functions from southwestern azimuths are characterized by heavily muted converted phases that display very little moveout (Figure 1c). These data sample the crust beneath the ~1000 year old volcanic deposits near Sunset Crater. A preliminary forward model shows that shear wave-speeds reduced to ~2.25 km/s between ~9-15 km depth produce a receiver function that matches the observed negative arrival. We believe that this phenomenon may result from the presence of a broad partial melt body beneath the San Francisco volcanic field.

In order to complement these results, we have begun to augment these receiver function observations with teleseismic delay time estimates from the COARSE array combined with nearby regional stations. Delay time estimates will resolve velocity perturbations between CP and BR stations, as well as constrain delays within the zone of reduced receiver function amplitude at station WUAZ.

Receiver Function Results from the COARSE Deployment



Piercing points show the azimuthal coverage at 40 km depth beneath COARSE array and regional stations. From our teleseismic event database, we estimate V_p/V_s using moveout plots. These values, along with a previously determined bulk crustal velocity, allow for depth converted receiver function stacks to estimate the depth to the Moho and approximate depths to other layers in the crust and upper mantle.

The inset images focus on the high amplitude negative converted phase anomaly characteristic of receiver functions from WUAZ. The shaded green region on the map and back azimuth receiver function plot corresponds to a region of reduced receiver function amplitude at WUAZ (Figure 1a). The moveout plots are split between receiver functions that do show muted amplitude and those that do not (Figure 1b and 1c). Teleseismic waves that traverse the region of recent activity in the volcanic field show reduced amplitude and no moveout. The moveout of those that do not traverse the volcanic field show evidence of a direct arrival from the top of an upper crustal low velocity zone.

A Transect Across Alaska, from Pacific to Arctic Margins

Gary Fuis
U.S. Geological Survey

Thomas Brocher
U.S. Geological Survey

George Plafker
U.S. Geological Survey

Thomas Moore
U.S. Geological Survey

Michael Fischer
U.S. Geological Survey

Warren Nokleberg
U.S. Geological Survey

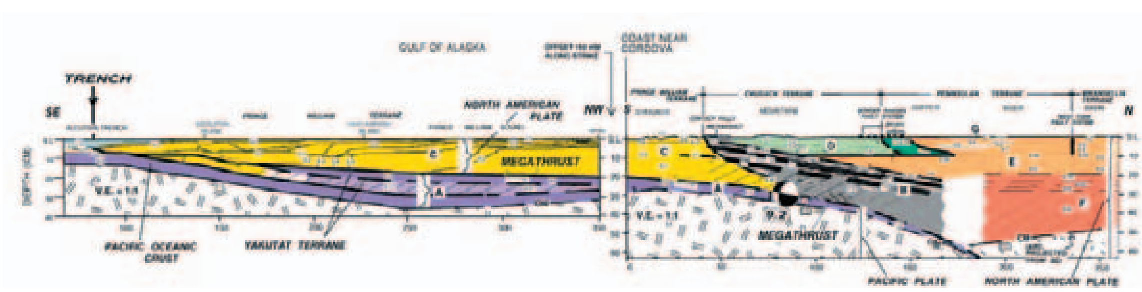
Robert Page
U.S. Geological Survey

Nikolas Christensen
U.S. Geological Survey

During the period 1984 to 1990, the U.S. Geological Survey, University collaborators, and the Alaska Division of Geological and Geophysical Surveys investigated the crust of Alaska along a ~1500-km-long, north-south corridor. The project, known as the Trans-Alaska Crustal Transect (TACT), extended from the trench in the Gulf of Alaska to the Arctic coast. The data collected included refraction/wide-angle reflection, vertical-incidence reflection, geologic, gravity, magnetic, magnetotelluric, earthquake, and petrophysical data. In most places onshore, the seismic data were collected along or near the Trans-Alaska Oil Pipeline. The transect crossed oceanic, oceanic-arc and platform, and continental-marginal terranes that have been variously subducted, subcreted, accreted, rotated, imbricated by thrust faults, translated by strike-slip faults, and intruded by numerous magmatic arcs. We use the data collectively to present an interpretation of the structure and tectonic history of Alaska. Currently in the Gulf of Alaska, the Pacific plate and the overlying Yakutat terrane are subducting beneath and colliding with the North American plate. (The Yakutat terrane includes fragments of an accretionary prism and of the Pacific plate.) Subduction is resisted by the buoyancy of this doubly thick oceanic crust. Currently on the Arctic margin of northeastern Alaska, there is compression that may be related to the ongoing subduction/collision of the Pacific plate/Yakutat terrane (PAC/YAK) in the south.

The most spectacular structures and the deepest Moho along the transect are located near the Pacific and Arctic margins. Near the Pacific margin, the Chugach Mountains are being uplifted by the subduction/collision of the PAC/YAK and are underlain by a stack of subcreted oceanic layers similar to the PAC/YAK. We interpret this stack as remnants of the extinct Kula (or Resurrection) plate that was converging rapidly on North America in the latest Cretaceous and early Cenozoic. Continental Moho just landward of this subcreted stack is more than 55 km deep, in an area of low-lying topography. Near the Arctic margin, the Brooks Range and southern part of the North Slope are underlain by striking duplex structures that extend ever deeper into the crust from north to south. We interpret these duplexes to overlie a crustal-scale wedge consisting of continental crust of the North Slope passive margin and an attached fragment of mantle that has moved southward with respect to the North American plate. Moho has been depressed to nearly 50-km depth beneath the crest of the Brooks Range. The tectonic history leading to the current structure of northeastern Alaska is complex, with several compressional episodes and at least one extensional episode occurring between Late Jurassic/Early Cretaceous and the present.

Central Alaska consists of continental-marginal terranes and at least one oceanic arc that collided with these terranes in the Late Jurassic/Early Cretaceous and was partially obducted. Some of these terranes were oroclinally folded in the Early Cretaceous, and many were extended and intruded in the mid-Cretaceous. Offset along major strike-slip faults (Tintina and Denali faults) followed. Moho is everywhere between 30 and 35 km deep in central Alaska.



Southern part of transect across Alaska. Colors are by tectonic kindred: A (purples), actively subducting oceanic crust (includes Yakutat terrane); B (grays), layers of Mesozoic (Mz) oceanic crust and mantle subcreted (underplated) in the late Mz or early Cenozoic (Cz); C (yellow), Cz accretionary prism; D (greens), Mz accretionary prism (dark green, ophiolite); E (orange), backstop to Mz accretionary prism (here, Peninsular/Wrangellia terrane); F (red-orange), lower continental crust; G (light yellow), other Cenozoic sedimentary rocks. CM, continental Moho; OM, oceanic Moho. Numbers are seismic P-wave velocities. Focal mechanism for 1964 M_w 9.2 Alaskan Earthquake is projected ~125 km onto transect from west. Entire transect across Alaska extends another 1000 km northward (to right).

Fluid Overpressures on the San Andreas Fault Following the Passage of the Mendocino Triple Junction

Patrick Fulton
Pennsylvania State University

Demian Saffer
Pennsylvania State University

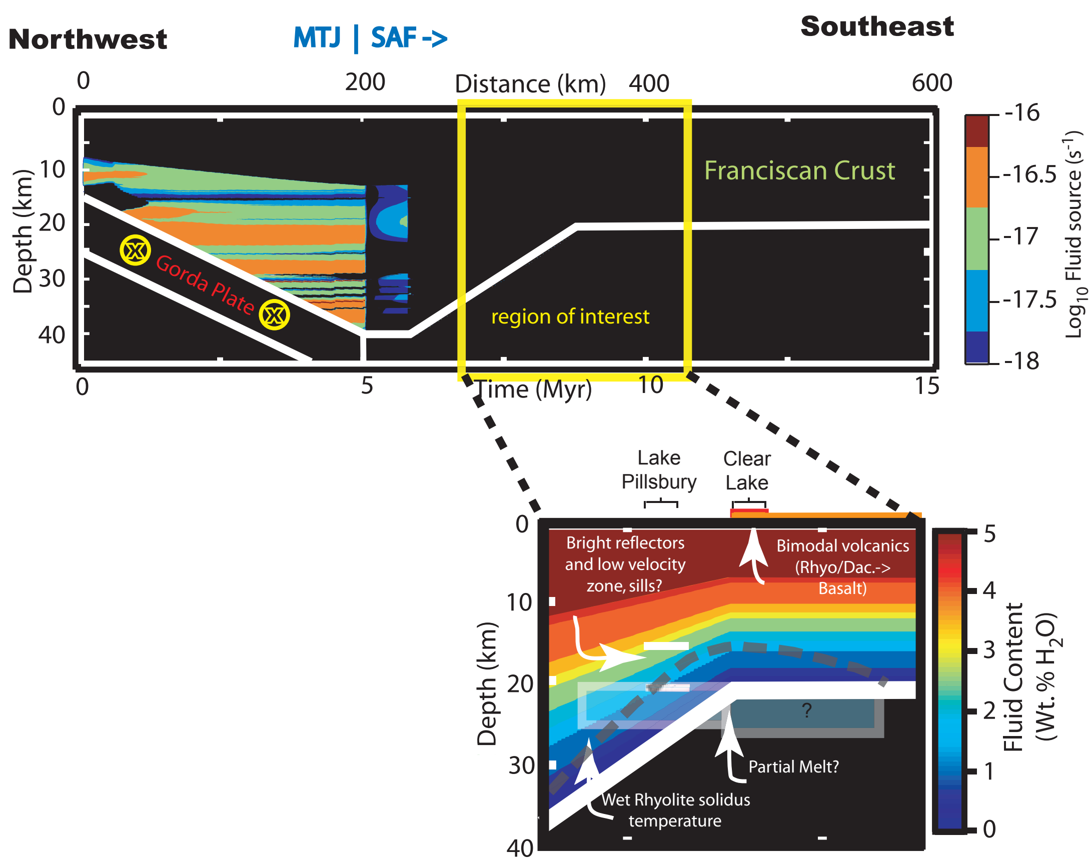
Barbara Bekins
U.S. Geological Survey

Fluid pressures significantly greater than hydrostatic have been hypothesized to account for the weak nature of many large plate-boundary faults. However, on the San Andreas Fault, the hypothesized subsurface processes which could create, sustain, and potentially localize such pressures over millions of years are not well understood. In this study, we use two-dimensional finite element models of coupled fluid flow and heat transport perpendicular to the fault to evaluate hypothesized mechanisms for generating elevated pore pressure. The models account for transient changes in crustal geotherm and thickness of the seismogenic crust in response to the passage of the Mendocino Triple Junction. Theoretical curves of whole-rock fluid content as functions of pressure and temperature allow us to calculate fluid sources due to metamorphic dehydration within the Franciscan mélange as a function of depth and thermal history. Fluid sources in the crust range from 10^{-18} to 10^{-16} s^{-1}, but are spatially limited after the passing of the Mendocino Triple Junction as the lower crust quickly dries out.

Results of our pore pressure modeling show that significant overpressures are generated over a wide extent north of the MTJ, where fluid sources are abundant, but quickly dissipate when sources cease. Models that include geologic structures such as serpentine sills and fault core and damage zones show only a very limited ability to sustain or localize overpressures.

Our results imply that metamorphic dehydration by itself is severely limited as a mechanism for weakening the San Andreas Fault. However, bright lower crustal reflectors interpreted as melt sills and volcanics of crustal origin following the MTJ where the lower crust is predicted to be free of hydrous minerals, suggest a substantial flux of additional fluids from the mantle. This may be a point of evidence for a dehydrating serpentinized mantle wedge. Resultant fluid pressures from such a model have not been evaluated, but would be expected to have a more prolonged effect along the SAF than crustal dehydration alone.

Dehydration of Franciscan Crust in Response to Mendocino Triple Junction



Fulton, Saffer, & Bekins, 2005

As the Mendocino Triple Junction migrates northward, the Franciscan crust is heated and deformed in its wake. Metamorphic dehydration in response is primarily north of where the SAF forms, as the lower crust quickly dries out. Bright reflectors interpreted as melt sills and volcanics of crustal origin from lower crust predicted to be free of hydrous minerals, suggest a substantial flux of additional fluids from the mantle - possibly a dehydrating serpentinized mantle wedge.

Mapping Upper-mantle Anisotropy in Western U.S.: Constraints on Crust-mantle Coupling

James Gaherty
Lamont-Doherty Earth Observatory

Li Zhao
University of Southern California

Mousumi Roy
University of New Mexico

A principal goal of the EarthScope program is to develop a better understanding of the processes that control the assembly and evolution of the continents. Many of these processes are associated with upper-mantle structure and dynamics. The character of continental tectonism depends not only on the nature of mantle buoyancy forces, but also on the strength of the crust and mantle lithosphere that must transmit those forces. In this presentation, we will discuss an integrated analysis we are developing to map seismic velocities and anisotropy beneath western North America at spatial scales of order 100 km, and to interpret this anisotropy in the context of regional flow models. The seismic analysis utilizes full-wave 3-D Frechet (sensitivity) kernels for generally anisotropic structure to invert phase delays of long-period surface and body waves recorded at USArray and existing broadband stations. The resulting high-resolution 3D upper-mantle model includes isotropic, radially anisotropic, and azimuthally anisotropic heterogeneity. The numerical flow models will utilize boundary conditions constrained by observations of surface kinematics, and material parameters estimated from geologic constraints. We plan to evaluate the degree of crust-mantle coupling across several focused study regions in the western US: the San Andreas fault and vicinity, the central Basin and Range, and variations in lithospheric fabric across smaller-scale regions such as the Coast Ranges, Cascadia Arc, and Sierra Nevada batholith.

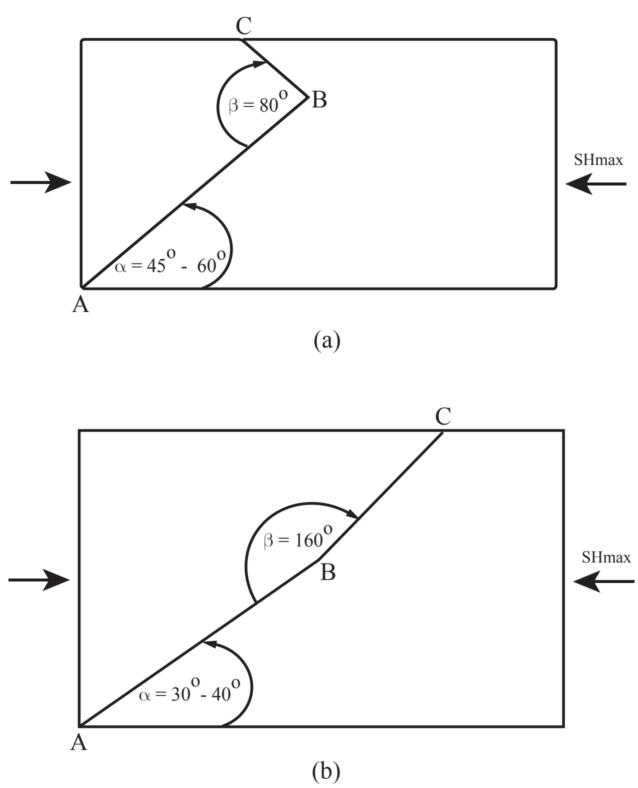
Two-dimensional Numerical Modeling Suggests That There is a Preferred Geometry of Intersecting Faults That Favors Intraplate Earthquakes

Abhijit Gangopadhyay
University of South Carolina

Pradeep Talwani
University of South Carolina

Synthesis of available geological, geophysical, and seismological data, and simple two-dimensional mechanical modeling showed that intersecting faults can act as stress concentrators and are spatially correlatable with the locations of observed intraplate seismicity in compressional stress regimes. However, intersecting faults are ubiquitous. Thus the obvious question is why are some intersecting faults the foci of intraplate seismicity while others are not. This research is directed towards answering this question by numerical modeling and carrying out a parametric study using a two-dimensional, commercially available Distinct Element Code (UDEC). The models include blocks of rocks containing a set of intersecting faults. The rocks and the faults were assigned suitable elastic properties that pertain to major intraplate regions in eastern U.S. We modeled two cases. The first case included two intersecting faults within the rock block, one of which was a relatively long or main fault AB, and the other a short or intersecting fault BC (Figure 1). The second case included three intersecting faults, one of which was the long or main fault, the second one was a shorter fault oriented parallel to the main fault, and the third one was the connecting intersecting fault or jog. In each case the models were tectonically loaded for the same amount of time (100,000 cycles) along the horizontal direction (assumed to be the direction of maximum horizontal compression SHmax) at a rate of 5 mm/year similar to the ambient plate velocity in intraplate regions of eastern U.S. The models were run by varying the angle between the main fault and the intersecting fault (Beta) for different orientations of the main fault with respect to SHmax (Alpha), and different lengths of the intersecting fault. The maximum shear stress at the intersection of the faults B when observed along each fault plane was tabulated for every run of the model. The magnitude of the maximum shear stress at the intersection increased linearly with increase of the length of the intersecting fault BC. These stress values were then plotted with respect to (Alpha) and (Beta). The relative stress values were examined.

In the case of two intersecting faults (Figure 1), the maximum shear stresses at the intersection B, observed along the main fault AB were larger when Alpha was between 45 to 60 degrees, and the angle Beta was 80 degrees. The maximum shear stress occurred when Alpha was 50 to 60 degrees. When observed along the intersecting fault BC, the maximum shear stresses at the intersection B were larger when Alpha was between 30 and 40 degrees, and Beta was 160 degrees. In this case, the maximum shear stress occurred when Alpha was 40 degrees. The results were similar in the case of three intersecting faults. The optimum orientation of Alpha is comparable with those observed in New Madrid and Charleston Seismic Zones. These results suggest that there is a preferred geometry of intersecting faults – an observation that can be used in identifying potentially seismogenic faults in eastern North America.



2-D block geometry showing optimum directions of intersecting faults for generating intraplate earthquakes.

Poroelastic Response in a Marine Sediment-hosted Fault Zone: Implications for Stress Change Detection Using Seismic Velocities

Glen Gettemy

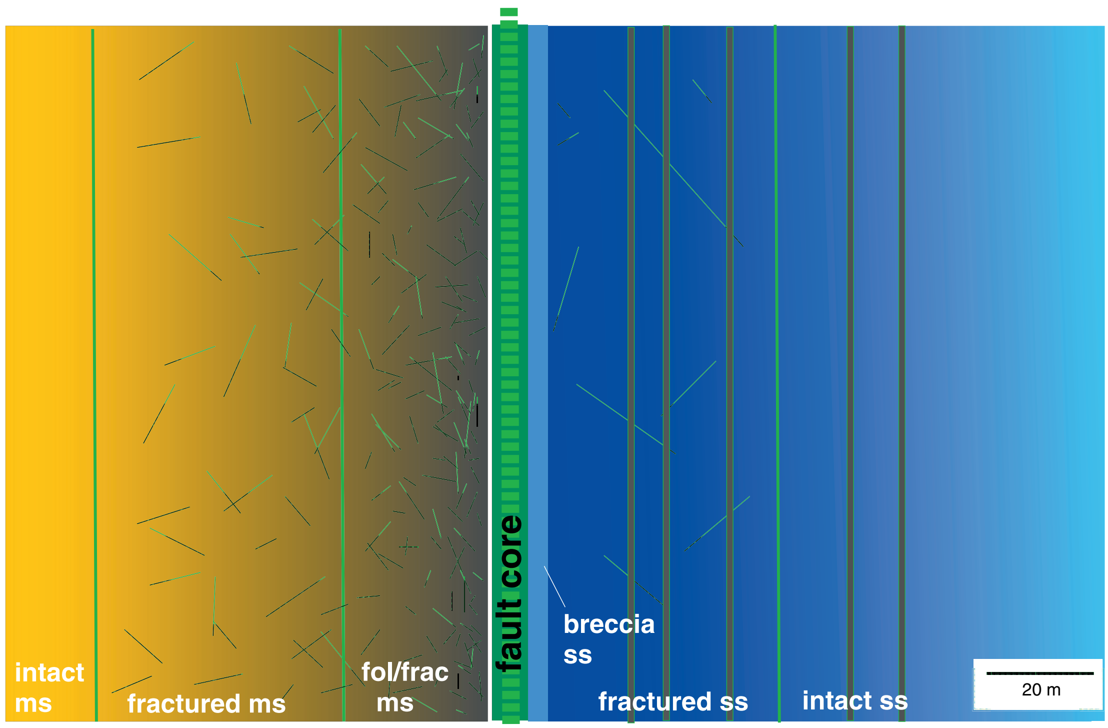
New Mexico Institute of Mining and Technology

Harold Tobin

New Mexico Institute of Mining and Technology

Large-scale, post-seismic crustal stress change modeling has shown promising results in terms of predicting earthquake likelihood (stress triggering) in large plate boundary domains, particularly in the region influenced by the San Andreas Fault (SAF) system. The numerical success of such analyses points to the next step: validation of prediction by in situ stress change monitoring through seismic wave propagation experiments. Such monitoring could include active/passive midband and high-frequency recordings with newly installed long-term, and short-term augmented, 3C arrays designed to image a patch, or set of patches, for stress-dependent petrophysical changes.

It should be recognized that a critical consideration--indeed, a first step–in the design and implementation of such monitoring strategies is the ability to calibrate and subsequently predict in situ physical changes to stress state modulation at the scale of the patch itself. We present a methodology for such calibration, using studies of the large strike-slip San Gregorio Fault zone (exposed at Moss Beach, CA) as an analog for the multi-stranded SAF in the vicinity of SAFOD. This calibration provides a realistic background for stress transfer modeling techniques, such as modeling the stress change response–and resulting seismic velocity changes–in a poroelastic sediment-hosted fault zone. Approached in this fashion, stress change monitoring could be a feasible scientific tool that would greatly supplement real-time hazard assessment and preparation, and could potentially be developed for SAFOD by the time Phase 3 is to be implemented.



25%	25%	20%	20%	28%	30%	ϕ
-17	-17.5	-18	-16	-15	-14	log [k] (perp)
1.5	3.0	10	5	2.0	1.5	k, para/perp
30	25	20	29	33	36	Ko (GPa)
0.30	0.33	0.40	0.35	0.32	0.28	υ

San Gregorio Fault zone physical/hydrologic property illustration. Data are derived from laboratory measurements made directly on core samples from the San Gregorio Fault, or from literature describing similar rocks (e.g., permeability anisotropy). This conceptual description, calibrated through laboratory and field studies, provides a possible analog to the 'patch' responsible for the recurrent target earthquakes that are the primary drilling target for SAFOD within the eastern block of the near-SAF crust.

Preservation of Proterozoic Terranes Within the Colorado Plateau: A Source of Strength?

Hersh Gilbert
University of Arizona

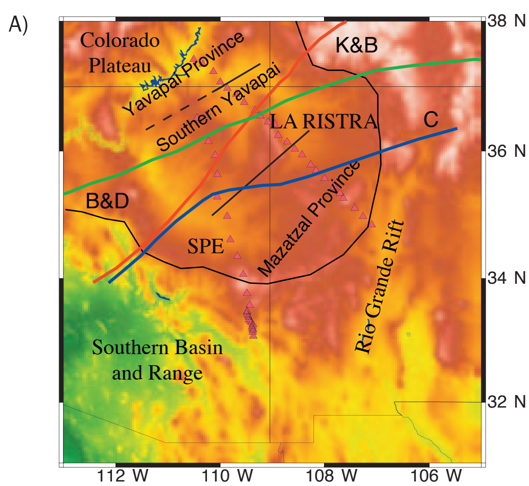
Aaron Velasco
University of Texas El Paso

George Zandt
University of Arizona

An outstanding question in studies of continental lithosphere is how much does present day structure reflect the most recent deformation or does it exhibit persevered structures that have persisted since accretion. Here we present a synthesis of results obtained by calculating receiver functions from a portion of the LA RISTRA and SPE broadband seismic arrays, which transect the southeastern portion of the Colorado Plateau (see Figure A). The relative lack of deformation within the plateau offers an ideal opportunity to determine if structures associated with Proterozoic terrane boundaries, or other inherited features from continental accretion, can be identified in present day crustal structures.

The continental Moho arrival can be clearly identified across most of both of these arrays and used to identify that the crust is near 40 km thick where each of these two transects sample the eastern Colorado Plateau (Figures B&C). The crust appears to thin to 30 km thick towards the plateau margins in the Arizona Transition zone and Rio Grande Rift valley. The structure of the Moho appears to vary within the Colorado Plateau maintaining a much more complex signature than within the adjacent Basin and Range or Rocky Mountains. Negative receiver function arrivals, which are usually symptomatic of low-velocity zones, are present beneath the crust near 60 km depth where the SPE line samples the Springerville volcanic field and appear to mark the locations of magmatic material. Petrologic investigations of magmas from this region have indicated a similar depth range for magma genesis. Interestingly though, other subcrustal and intra-crustal arrivals are clearly present in both transects, but do not clearly relate to present day structures at the surface. Many of these arrivals are not laterally extensive and some terminate abruptly. The extent of structures within the crust appears to coincide with the proposed locations of boundaries between the Mazatzal, Southern Yavapai, and Yavapai terranes. Because Paleozoic and younger sediments conceal much of the Precambrian basement, the proposed locations of these terrane boundaries within the Colorado Plateau have relied upon interpolation across long distances between outcrops and is a matter of some uncertainty among geologic studies. One such feature within the crust that appears confined to the Southern Yavapai province is a large negative arrival at 20 km depth in the SPE array and slightly shallower at the LA RISTRA transect (Figures B&C). Following this feature to the south illustrates that it terminates at the boundary with the Mazatzal terrane. Our receiver function observations indicate that we are able to identify coherent differences in crustal blocks across these arrays in which similar patterns of crustal structure juxtapose each other near regions of the proposed terrane boundaries. The Moho becomes virtually undetectable north of the boundary between the Yavapai and Southern Yavapai provinces. Our seismic investigation thus permits us to locate these boundaries with improved precision (Figure A).

The location of the large negative arrival within the southern Yavapai terrane correlates with a region characterized by a high isostatic gravity anomaly. Areas of high isostatic anomalies may result from the presence of a high-density body. If high seismic velocities also exist within such a high-density body, the base of this body could be responsible for producing the observed negative receiver function arrivals confined to the Southern Yavapai terrain. If such a body exists, as suggested by the gravity and seismic data, it could locally serve as a source of strength for the Colorado Plateau and help it resist deformation.



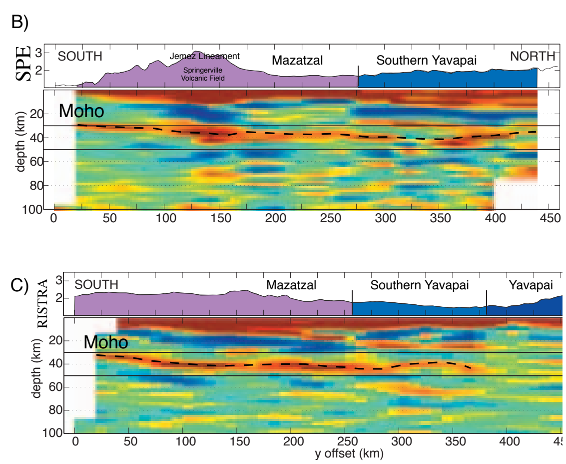


Figure Caption: (A) Topographic map focused on the southeastern portion of the Colorado Plateau showing station locations of SPE and LA RISTRA arrays used here. Also noted are locations of the Rio Grande Rift and Southern Basin and Range. Terrane boundaries between the Yavapai, Southern Yavapai, and Mazatzal Provinces, as inferred from the seismic observations presented here, are shown as black lines. For comparison, terrane boundaries from past studies are also presented: green B&D (Bennett and DePaolo, 1987), red K&B (Karlstrom and Bowring, 1988), and blue C (Condie, 1992). (B) Stacked receiver function cross-section from SPE array. Positive arrivals are shown as red, while negatives are blue. Note positive Moho arrival is marked with dashed line. Surface topography along transect is plotted and colored based on terrane boundaries. (C) Same as for B, but for receiver function cross-section for Colorado Plateau portion of LA RISTRA.

USMX and YESX: Continuation of United States's PBO into Mexico's Mainland

Javier Gonzalez-Garcia
New Mexico Institute of Mining and Technology

Rick Bennett
Department of Geosciences

Ken Hudnut
U.S. Geological Survey

Christian Walls
UNAVCO

Collaborative acquisition and integration of continuous GPS instrumentation for studying the Pacific-North America Plate Boundary zone in United States and Mexico is in progress.

In the past, three permanent Mexican stations were constructed in concert with the development of the Southern California Integrated GPS Network (SCIGN): SPMX (1998), in north central Baja California state; CORX (2000), in Isla Coronados Sur offshore San Diego/Tijuana metropolis; and GUAX (2001), in Guadalupe Island, which provides a unique location on the Pacific Plate and it is of strategic importance for the EarthScope's Plate Boundary Observatory (PBO). The IGS station in CICESE Ensenada, CICE established in 1995 and replaced by CIC1 in 1999 also became part of SCIGN.

Actually (2004-05), two new shallow-braced continuous GPS stations are operational in northern Mexico. These stations were installed with the assistance of a volunteer team of scientists and engineers from U.S. and Mexico, partial funding support from SCIGN to University of Arizona that agreed to collect no overhead, and borrowed GPS units from UNAVCO that we expect will be replaced by CICESE/CONACYT funded GPS units. The first site is located at the Universidad de la Sierra in Moctezuma (USMX), at east-central Sonora. The second site is located high in the Sierra Madre Occidental at Yecora (YESX), near the southern interstate border between Sonora and Chihuahua. These stations represent the first permanent sites on mainland Mexico east of the spreading center-transform fault system in the Gulf of California dedicated to tectonics. These sites will help to resolve the total plate motion between the Pacific plate (GUAX) and North American plate (USMX and YESX). Also, it will allow, together with forthcoming PBO stations in the Colorado Plateau, to assess ongoing intraplate deformation within the southern Basin and Range Province.

All data is openly available and currently these two sites are operating with Trimble NetRS receivers and radio links to internet connection with 15 sec and 1 Hz sample rates. These resources may be used for other purposes (e.g. measurement of seismic displacements, atmospheric monitoring, surveying, etc.) and can be adapted to "real time" applications. We are requesting support from SCIGN CB in order to build 5 more sites in Baja California peninsula by next year. We anticipate that this work will form the basis for more complete linked proposals to the NSF and CONACYT and other federal and local agencies in Mexico to increase and sustain continuous GPS network operations for studying the Plate Boundary zone in our North America continent. YES, we can do it. ¡Si se puede!

Four amigos at the continuous GPS site in the Universidad de la Sierra, Moctezuma, Sonora Mexico.

InSAR Deformation Map of the Western Basin and Range

Noel Gourmelen
University of Miami

Falk Amelung
University of Miami

We investigate surface deformation in the western Basin & Range using InSAR technique. We processed interferograms covering a 300 - 800 km area from the Central California shear Zone to the south to the Snake River Valley to the north. The area is covered by 9 existing permanent GPS station from the BARGEN network, including the LEWI GPS station which is known to undergo particular motion. The area comprises the Central Nevada Seismic Belt which has been very active during the 20th century producing several earthquakes of magnitude > 7, USGS GPS campaign have detected a relatively high strain rate for this area.

We acquired ~90 SAR scenes for the period between 1992 and 2001 and produced over 400 interferograms from a wide range of time and baseline separation in order to apply different post-treatment techniques such as stacking or small baseline time series analysis. The data processed over the Central Nevada Seismic Belt revealed a possible post-seismic deformation following the 1915-1954 earthquakes swarm. Model of visco-elastic relaxation of the Upper Mantle explain well the observe signal. The measurements also reveal several areas of subsidence associated with mining operations. For example, Gold mining in Crescent Valley causes a subsidence bowl with several tens of kilometers that may affect the position of the controversial LEWI permanent GPS station.

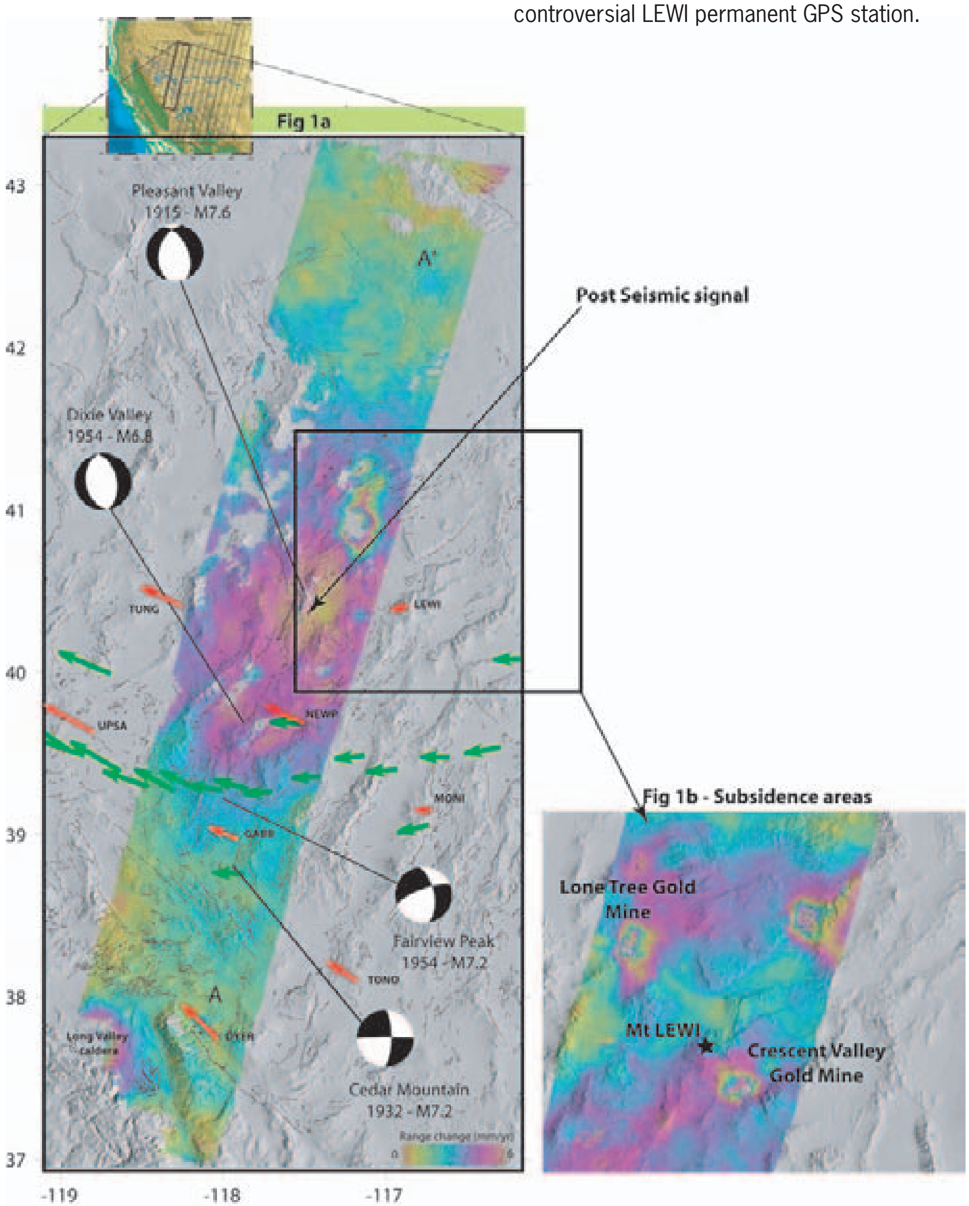


Fig 1a: Stack of 8 Interferograms showing possible post-seismic signal over the Central Nevada Seismic Belt. Fig 1b: Individual interferogram showing subsidence signals associated with Gold mine activities.

Plan for a National Volcano Early Warning System

Marianne Guffanti
U.S. Geological Survey

John Ewert
U.S. Geological Survey

Thomas Murray
U.S. Geological Survey

James Quick
U.S. Geological Survey

A National Volcano Early Warning System (NVEWS) is being formulated by the Consortium of U.S. Volcano Observatories (CUSVO) to ensure that the most threatening volcanoes in the U.S. are properly monitored in advance of the onset of unrest and to coordinate a national-scale monitoring effort. The underlying premises of NVEWS are that monitoring networks should be in place at volcanoes before unrest begins and that the level of early-warning monitoring at a particular volcano should be commensurate with the threat it poses. CUSVO was established in 2001 to strengthen interaction among Federal, state, and academic representatives of the five U.S. volcano observatories. Principal CUSVO partners are the USGS Volcano Hazards Program, University of Alaska, University of Washington, University of Utah, University of Hawaii, Advanced National Seismic System, NSF's Plate Boundary Observatory, Alaska Division of Geology and Geophysics, and Yellowstone National Park.

The NVEWS plan uses a 3-step methodology to prioritize monitoring targets. Step 1 is systematic evaluation of various hazard and exposure (risk) factors to determine a threat score for each of the 169 geologically active U.S. volcanoes; the resultant scores produce a relative ranking from very high threat volcanoes to very low threat ones. Step 2 of the NVEWS analysis involves rating the current monitoring capability at each volcano based on types, numbers, and proximity of instrumentation now in place. Step 3 is comparison of the current monitoring capability at each volcano to the level of monitoring called for by the threat assessment in Step 1; the result of the comparison is a list of volcanoes having significant "monitoring gaps" and thus targeted for additional monitoring resources.

35 volcanoes (in AK, CA, HI, OR, WA, and the Marianas) with very-high to high threat scores and significant monitoring gaps comprise NVEWS priority targets for improved monitoring. Additionally, 14 Alaskan volcanoes with moderate overall-threat scores but high aviation-threat scores and no ground-based monitoring are priority targets. Some NVEWS targets are also PBO targets, and NVEWS and PBO plans should be closely coordinated.

NVEWS will involve installation of monitoring instrumentation with data links to the observatories and partnering facilities. NVEWS also aims to implement standard formats and techniques for data storage, access, and analysis so that monitoring data are broadly accessible. A fully implemented NVEWS, when combined with current capabilities, will deliver:

- Robust real-time monitoring of the 55 most threatening U.S. volcanoes and basic real-time monitoring at volcanoes posing high risks to aviation.
- Improved eruption forecasts and lowered risks of surprise eruptions at high-threat volcanoes.
- Rapid hazard analysis and event notification during unrest and eruption at well-monitored volcanoes.
- A multi-parametric data stream on volcanic activity, broadly accessible for analysis with common IT tools, and a range of derived information products from graphical and map depictions of data to peer-reviewed research papers.
- 24/7 "situational awareness" of where volcanic activity is occurring in the U.S., including an NVEWS web site with a daily status report covering all monitored volcanoes.
- Efficient coordination of monitoring resources across agencies and institutions

CUSVO will be a primary mechanism for coordinating implementation of NVEWS. Coordination with PBO will occur through various EarthScope committees. NVEWS will coordinate development of its seismic networks with ANSS plans. Interagency coordination to provide ash-cloud warnings to the aviation sector will continue with the FAA, NOAA, and DOD. CUSVO will convene a workshop in 2005 to solicit additional input about NVEWS priorities and products from a broader group of stakeholders.

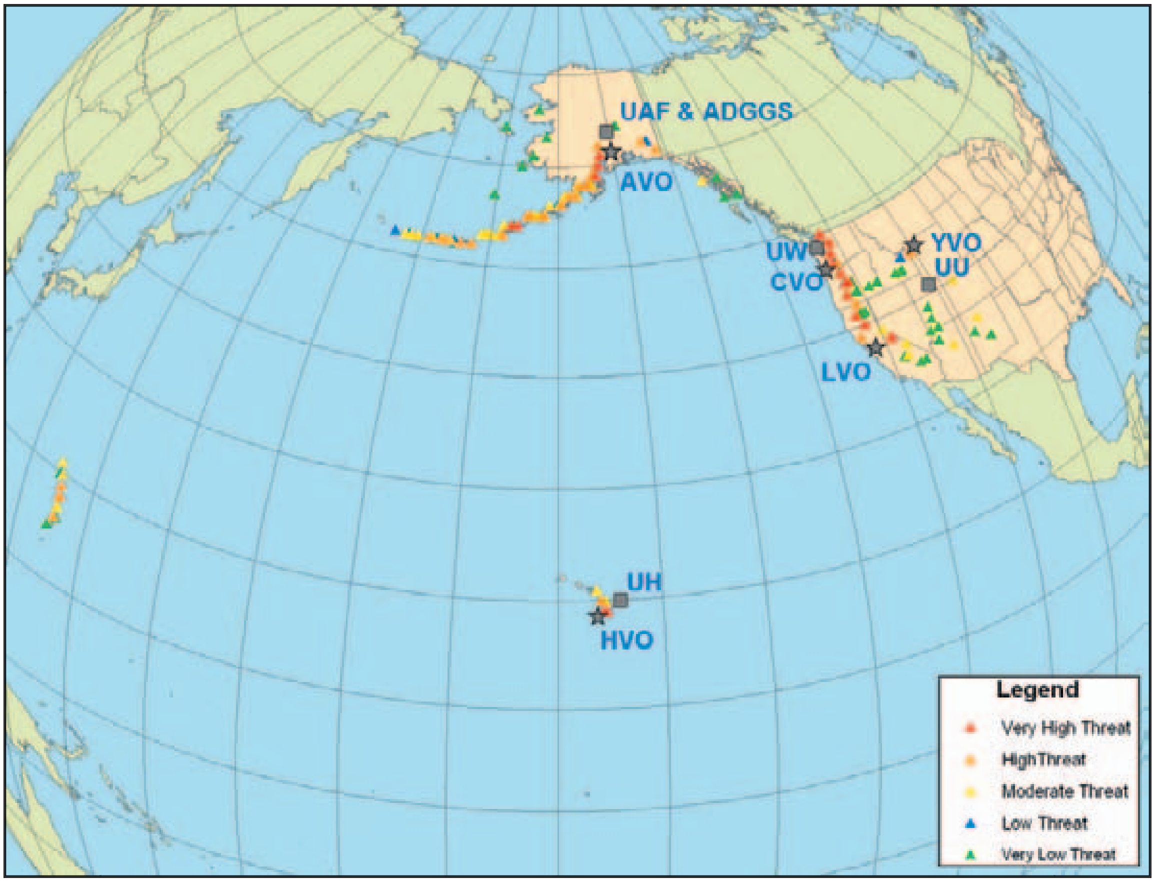
Figure on Page 131 >

Marianne Guffanti
U.S. Geological Survey

John Ewert
U.S. Geological Survey

Thomas Murray
U.S. Geological Survey

James Quick
U.S. Geological Survey

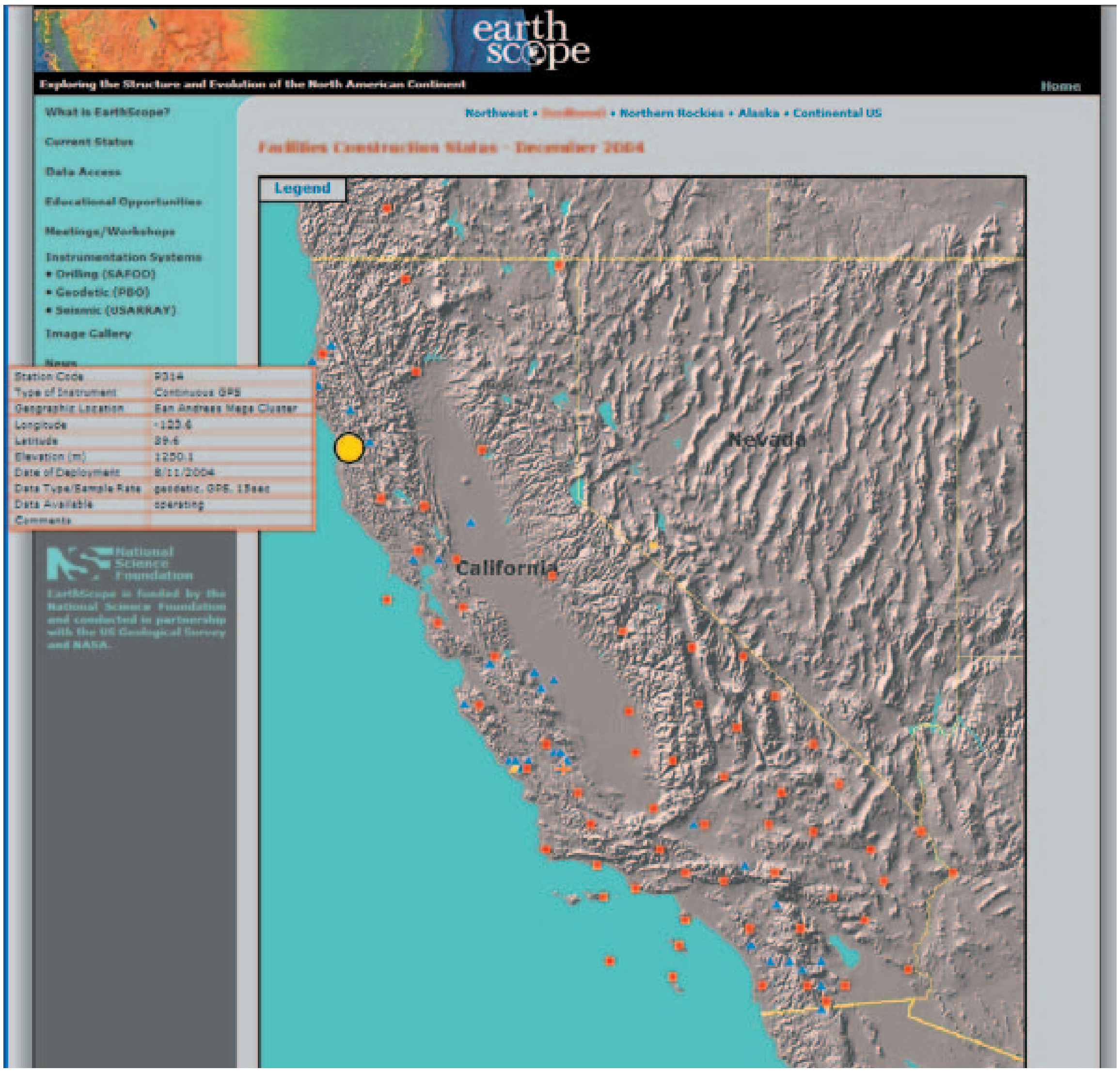


Locations of the 169 active volcanoes in the United States (triangles color coded by threat level), U.S. volcano observatories (gray stars), and affiliated cooperators (gray squares).

Reporting and Presentation of EarthScope Facilities Information on EarthScope Website

Christian Guillemot
EarthScope

As part of EarthScope commitment to provide timely information on the progress of instrumentation deployment through the construction phase of the facilities, a web-based application tool is being developed to facilitate the reporting and updating of station meta data. This information along with any status change will be available through the EarthScope web site as soon as it is entered into the station information database through the normal internal reporting process. The intuitive, easy-to-navigate tool will contain geospatial, operational, and pictorial information for each of the installed seismic, GPS, and drilling facilities, and may also serve as an entry point to the existing data archives for each station. To promote cross-browser compatibility, well-established scripting and standard gateway interfaces are being used, with no additional requirement on the part of the user to import or download additional software. Text-based information will be pre-loaded by the client browser and will be readily available for viewing after a single page refresh. Additionally, it will be possible to search, sort, and cross-reference station information.



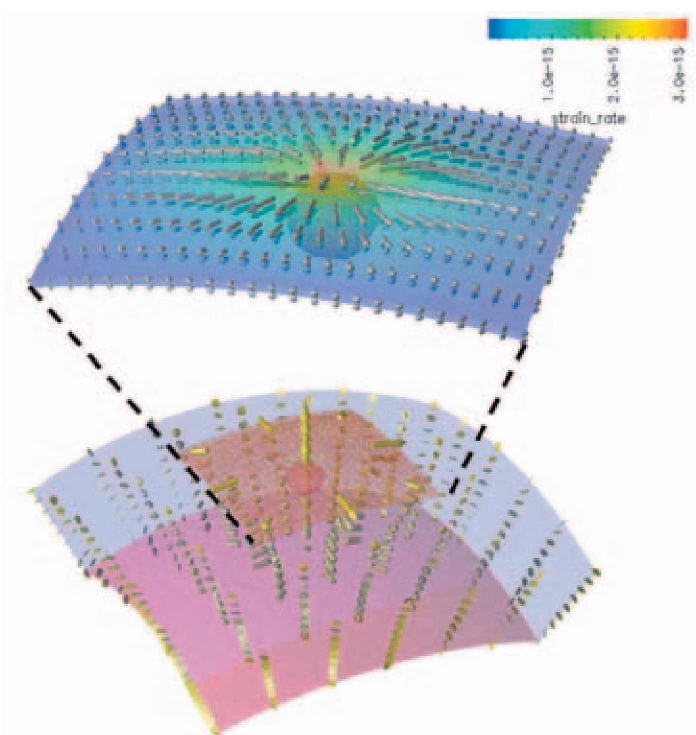
Computational Infrastructure for Geodynamics (CIG)

Michael Gurnis
California Institute of Technology

The broader vision of EarthScope will require that we embrace the unfolding revolution in computational science and information technologies. The traditional means by which computational geophysicists have developed software is inadequate. Our simulation software has largely been the product of individual efforts and although this approach has proven successful, its strength for solving emerging problems of interest is now starting to show its limitations as we share codes and algorithms or when we attempt to recombine codes in novel ways to produce new science. With funding from the NSF, the community has embarked on a Computational Infrastructure for Geodynamics (CIG) – http://geodynamics.org – that develops, supports, and disseminates software for the greater geodynamics community from model developers to end-users. The software is being targeted for problems ranging widely from mantle and core dynamics, crustal and earthquake dynamics, magma migration, seismology, and related topics. Be it on earthquake or longer-geological time-scales, the frontier has moved into multi-scale and multi-physics problems in which investigators now want to use simulation software for data interpretation, data assimilation, and hypothesis testing. CIG has largely been developed so that a broad segment of our community can use simulation software in these endeavors and be confident the software is well tested and well documented.

CIG is leveraging the state-of-the-art in scientific computing into a suite of reusable, well-documented and open-source tools and codes. The infrastructure which we are now starting to develop consists of: (a) the basic building blocks – an infrastructure layer – of software by which state-of-the-art modeling codes can be quickly assembled; (b) extension of existing software frameworks to interlink multiple codes and data through a superstructure layer; (c) strategic partnerships with the larger world of computational science and geoinformatics; and (d) specialized training and workshops for both the geodynamics and larger Earth science communities. The CIG initiative has already started to leverage and develop long-term strategic partnerships with open source development efforts within the larger thrusts of scientific computing and geoinformatics.

Complete codes built from common components and then linked to other codes will be a major activity of CIG. An example of crust-mantle interactions in which multiple codes have been linked is shown in the accompanying figure. Simulations like this will allow tomographic images refined through USArray to be integrated with the wide range of existing geological and geochemical observations of the continental crust.



A thermal plume rising through the mantle causes plastic deformation in the elastic crust. This was simulated by coupling an explicit finite-element model of the crust (SNAC) with an implicit finite-element model of the viscous mantle (CitComS) within the Pyre superstructure framework. Pyre orchestrates both parallel calculations, controls their time stepping, and the transfer of velocity and temperature constraints from CitComS to SNAC and tractions in the reverse direction. Courtesy of Eun-seo Choi, Caltech.

Southern Laurentia – EarthScope Investigation (SOEASI)

Harold Gurrola
Texas Tech University

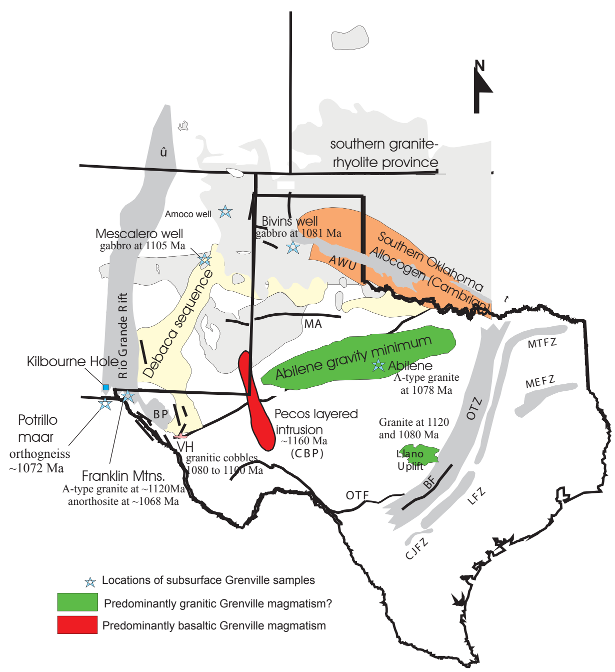
Calvin Barnes
Texas Tech University

Randy Keller
University of Texas El Paso

Kate Miller
University of Texas El Paso

The southern portion of Laurentia in New Mexico, Oklahoma and Texas is a key area in regard to understanding the tectonic evolution of the North America. The region is characterized by Proterozoic and Paleozoic accretion of several tectonostratigraphic terranes, and this growing continental sequence was episodically modified by emplacement of huge volumes of mafic and granitic magmas. At least two of these giant magmatic events (Pecos Mafic intrusive complex and Southern Oklahoma aulacogen) represent mantle-to-surface phenomena. Therefore, the basement rocks record a complex history of growth and modification of continental lithosphere/tectosphere.

Because of nearly pervasive Phanerozoic cover, our understanding of the basement of this region comes from a few key outcrops, and a rather limited sampling of the thousands of deep drill holes, and three modern (academic) seismic experiments, along with countless kilometers of industry seismic reflection data. None of these data sets permits us to address "big picture" issues of the timing, duration, and style of tectonism in southern Laurentia. This is ironic, because many of the tectonic events along the southern Laurentian margin affected areas to the north and west. Such answers require integrated data that includes geophysical analysis of the entire tectospheric section. This must be linked to detailed geochronology and petrogenetic work in order to understand the fourth dimension (time) that is part of EarthScope's 4-D vision.



Tectonic and petrologic provinces of Southern Laurentia and major tectonic features. The following abbreviations are used AWU – Amarillo - Wichita Uplift; BF – Balcones Fault; CJFZ – Charlotte Jourdanton Fault Zone; CBP – Central Basin Platform; DP – Diablo Platform; MEFZ – Mt. Enterprise Fault Zone; LFZ – Luling Fault Zone; OTF – Ouachita Tectonic Front; OTZ – Ouachita Thrust Zone; MTFZ – Mexia-Talca Fault Zone; MA – Matador Arch.

Some questions that an EarthScope investigation of this portion of Laurentia could address:

The Crust

1. What variations in crustal thickness and velocity structure exist in the region and what processes caused them?
2. What do major crustal boundaries, particularly between major terranes or terrane assemblages, look like?
3. What were the effects on the crust of the extensive granite-rhyolite magmatism at ~1.4 Ga? Are the granites of this age all shallow? What underlies them? Can a residual source region be identified? Can a zone of underplating be identified?
4. How widespread was circa 1100 Ma magmatism?
5. What processes were responsible for huge-volume magmatism at 1.4, 1.1, and 0.55 Ga?
6. What caused the Ancestral Rocky Mountains structures such as the Southern Oklahoma aulacogen and the Central Basin Platform and why they cut across apparent Precambrian trends in the region?
7. What are the sizes, ages, and tectonic significance of Proterozoic and early Paleozoic sedimentary basins?
8. What is the nature of the crust beneath the Gulf Coast Plain of Texas and Louisiana?

The Mantle

1. Do crustal boundaries (terrane boundaries) reach the upper mantle?
2. Does the mantle lithosphere preserve evidence for the 1.4 and 1.1 Ga magmatic events (e.g., lower density upper mantle associated with areas of intense granite-rhyolite magmatism; residue of basaltic underplate)?
3. What causes the "high" elevations in the Great Plains province?
4. Is the mantle beneath the Gulf Coast Plain as heterogeneous as gravity work appears to indicate?

The Tectosphere

1. Can mantle tectosphere be linked to terrane accretion events?
2. Does mantle on either side of these mafic features show the same velocity structure and anisotropy? Because the 1.4 Ga crust in the region was episodically punctured by through-going magmatic events (1.2 Ga Pecos Mafic complex, 0.55 Ga SOA), studies of the mantle on either side of these magmatic zones offer specific tests of the survivability of older tectosphere.
3. Is Ouachita lithosphere distinct from the older lithosphere?

Development and Evolution of Y Shears in Simulated Granite Gouge

Jafar Hadizadeh
University of Louisville

David Goldsby
Brown University

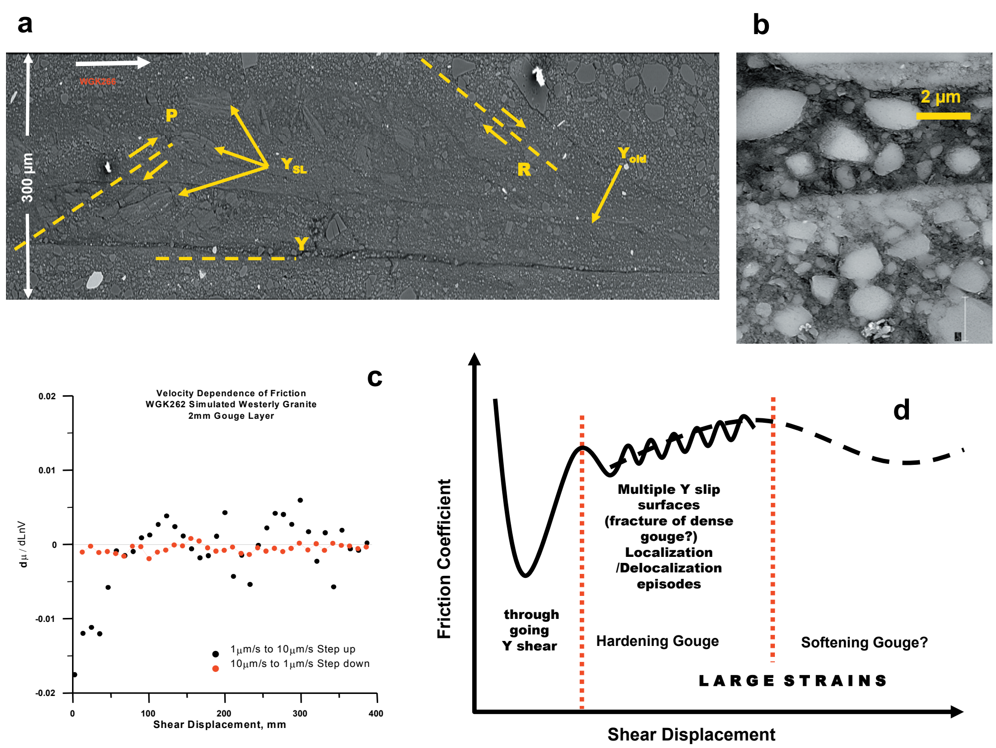
Anoaur Konkachbaev
University of Louisville

Terry Tullis
Brown University

Previous work suggests that development of Y slip surfaces in fault gouge are associated with significant shear localization and reduction in friction followed by hardening of the localized layers and consequent delocalization (Beeler et al. 1996). Developing a microstructural model of the process will be needed for a better understanding of the rate and-state-dependence of frictional strength of faults. Frictional sliding experiments were performed in rotary shear at 25 MPa normal stress on 2-mm thick layers of simulated Westerly granite gouge (particle size ~88µm, 35% initial porosity), sliding velocity regularly stepping between 1 and 10 µm/s in all the experiments. Successful trials were terminated at desirable states of frictional strength after 44, 79, and 386 mm of shear displacement. The later experiment involved several varied amplitude fluctuations in friction. Sheared gouge sections were imaged at 0.25K-500K time SEM magnification.

At the lowest displacement a single 5-10µm-wide linear Y slip surface appeared to have nucleated within the highly comminuted zone. The gouge also included a field of large survivor particles interlaced by numerous R slip surfaces. In contrast, a complex system of microstructures including full set of Riedel shear surfaces and pervasive comminution had occurred after 386mm of sliding. The most notable microstructures were intermittent zones of faulted, thrusted, and rotated sliver-shaped particles. The slivers appeared to be riding in a less competent surrounding gouge. Detailed microscopy revealed that in every case the slivers (5-25µm thick) have an internal layering defined by mass of particles graded in size from 20nm on one side to about 300nm on the other side. At the highest magnification the sliver material had image-estimated porosity ~5%, and consisted of a mixture of rounded and sub-rounded quartz and feldspar particles.

The data suggests that fluctuations in friction observed in the large-strain experiment may be related to occurrences of hardening and subsequent brecciation of the gouge during slip on multiple Y shear surfaces as well as to the discontinuous nature of the sliver breccias along the gouge zone. Some images indicate that Y shears nucleate and propagate as fractures in highly comminuted, densely-packed regions of the gouge. The internal layering of the brecciated slivers and their well-developed particle size grading indicates that, once created Y slip surfaces may continue to localize shear strain until particles that line the slip surface are reduced to a critical average size, or perhaps achieve a critical packing density. If subsequent studies show that it does involve an increase in packing density due to wider PSD, then the hardening could result from an increase in the contact area per volume or the contact area along potential shear surfaces.



Development and evolution of Y shears in simulated granite gouge. (a) Microstructures typical of localization and delocalization in large-strain samples. (b) Close up view of a Y slip surface from experiment wgk262. YSL indicates slivers of brecciated Y surfaces. (c) The deformation does not appear to be highly velocity dependent at large-strains but it is more velocity-dependent for increases in sliding velocity than for decrease in velocity. (d) A tentative model. After an initial phase the gouge deforms by creating and destroying multiple slivers of densely packed particles along established Y shears.

GPS Installation Progress in the Pacific Northwest Region of the Plate Boundary Observatory

Katrin Hafner
UNAVCO

Peter Gray
UNAVCO

Angie Diefenbach
UNAVCO

Ken Austin
UNAVCO

The Plate Boundary Observatory (PBO), part of the larger NSF-funded EarthScope project, will study the three-dimensional strain field resulting from active plate boundary deformation across the Western United States.

The PBO plan for the Pacific Northwest (PNW) region, calls for the installation of 149 continuous GPS stations by the year 2008. These sites are largely distributed along the Cascadia Subduction Zone and at Mt. St. Helens. As of February 2005, the PNW Region of PBO has reached its current installation goal of 16 GPS monuments. All but one of these installations is located in the state of Washington, and seven of these GPS sites were installed within the Mt. St. Helens National Volcanic Monument. The 2004-2005 eruption of Mount St. Helens, Washington, began with a small earthquake swarm on September 23, 2004. Activity peaked on September 24, gradually declined throughout the day, and then increased dramatically before culminating in a series of phreatic explosions on October 1-5. In response to this increased level of activity, the PBO Standing Committee and Magmatic Systems Site Selection Working Group requested reprioritization and immediate installation of five PBO permanent GPS stations on and around the flanks of Mt. St. Helens to monitor deformation associated with this volcanic crisis. Up to this time, permitting of these sites with the USFS was moving slowly. As a result of the increased activity, PBO was able to secure 5 permits within a few weeks. Field crews reached the volcano on October 12, 2004 and began assembly of the power systems and equipment enclosures. Each enclosure was slung by helicopter to a site where a GPS antenna and radome were fixed to existing EDM towers. Four sites were completed in two days and the fifth site was installed at the end of October once the weather had improved. The PBO Data Management and IT Group responded quickly to a request by USGS personnel that data downloads occur once per hour rather than once every 24 hours. Both hourly and daily data files are freely available through the UNAVCO Archive at ftp://data-out.unavco.org/pub/PBO_rinex.

Monitoring of the volcano, including data analyses from the newly installed sites, showed that one of the PBO sites located high on the SE flank of the volcano moved 4 cm SE between mid-November 2004 and January 2005. This was most likely due to growth of the new lava dome against the SE crater wall. As a result of this activity, the PBO obtained two additional permits from the USFS, and these sites were installed at the beginning February, 2005.

During Year 2 of the PBO project, the pace of installations increases dramatically. As of January 2005, the PNW office is completely set up, and fully staffed. By the end of September 2005, a minimum of 41 GPS monuments will have been completed. Installations will be focused in Southwest Oregon, on the Olympic Peninsula and at remaining sites on Mt. St. Helens (subject to USFS permit acceptance).

PNW Field Engineer Peter Gray welding the antenna base on to an EDM tower at P695 (Nelson Ridge, MSH).

An Interactive Map Tool for EarthScope Education and Outreach

Michael Hamburger
Indiana University

Anne Hereford
Indiana University

Lou Estey
UNAVCO

Susan Eriksson
UNAVCO

Charles Meertens
UNAVCO

Marianne Weingroff
Digital Library for Earth System Education

William Holt
State University of New York at Stony Brook

Glenn Richard
State University of New York at Stony Brook

We present a new, interactive, web-based map utility that can make EarthScope-related scientific results accessible to a large number and variety of users. The tool provides a user-friendly interface that allows users to access a variety of maps, satellite images, and geophysical data at a range of spatial scales. The EarthScope Voyager map tool allows users to interactively create a variety of geographic, geologic, and geodynamic maps of the EarthScope study area. The utility is built on the "Jules Verne Voyager" suite of map tools, developed by UNAVCO for the study of global-scale geodynamic processes. Users can choose from a variety of base maps (including "Face of the Earth" and "Earth at Night" satellite imagery, global topography, geoid, sea-floor age, strain rate and seismic hazard maps, and others), add a number of geographic and geophysical overlays (coastlines, political boundaries, rivers and lakes, earthquake and volcano locations, and stress axes, etc.), and then superimpose both observed and model velocity vectors representing a compilation of 5170 geodetic measurements from around the world. A remarkable characteristic of the geodetic compilation is that users can select from some 26 frames of reference, allowing a visual representation of both 'absolute' plate motion (in a no-net rotation reference frame) and relative motion along all of the world's plate boundaries. For the EarthScope Voyager, we are in the process of adding a number of EarthScope-specific features, including maps of proposed and installed USArray and PBO instruments, detailed maps of EarthScope focus areas, and "Did You Know" educational modules, which provide examples of EarthScope-related scientific results linked to EarthScope study areas. Two versions of the tool are available: (1) a Java-based map tool "EarthScope Voyager", a server-based map creation system which allows users complete control over base maps, overlays, and map scale; and (2) "EarthScope Voyager, Jr", an HTML-based system that uses pre-constructed GIF maps and overlays, allowing the system to rapidly create and display maps to a large number of users simultaneously. The tool allows users to zoom among at least four map scales. In addition, we are developing a number of companion educational materials, including "Exploring our Dynamic Planet", a Javascript-based interface that can incorporate the map tool, explanatory material, background material on EarthScope, and curricular activities that encourage users to explore Earth processes using the new EarthScope Voyager tool. The map tool and associated educational materials can be viewed through the Jules Verne map portal http://jules.unavco.org

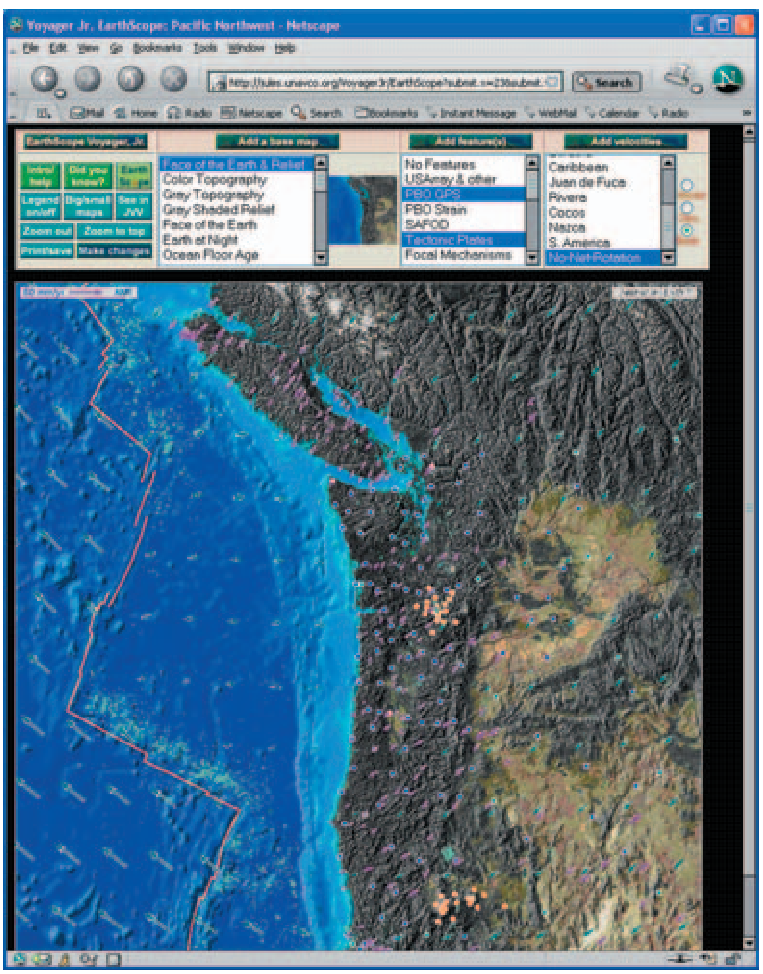


Image created using the EarthScope Voyager, Jr. map tool, showing proposed PBO sites (blue and orange circles for backbone and magmatic cluster sites, respectively), observed and modeled geodetic velocities (purple and blue vectors, respectively), seismicity and plate boundary locations, superimposed on a base map showing Face of the Earth imagery that combines satellite reflectance data with high resolution topographic and bathymetric data.

Understanding Northwest Basin and Range Tectonics, from the Northern Walker Lane to the Central Nevada Seismic Belt, Using EarthScope Data

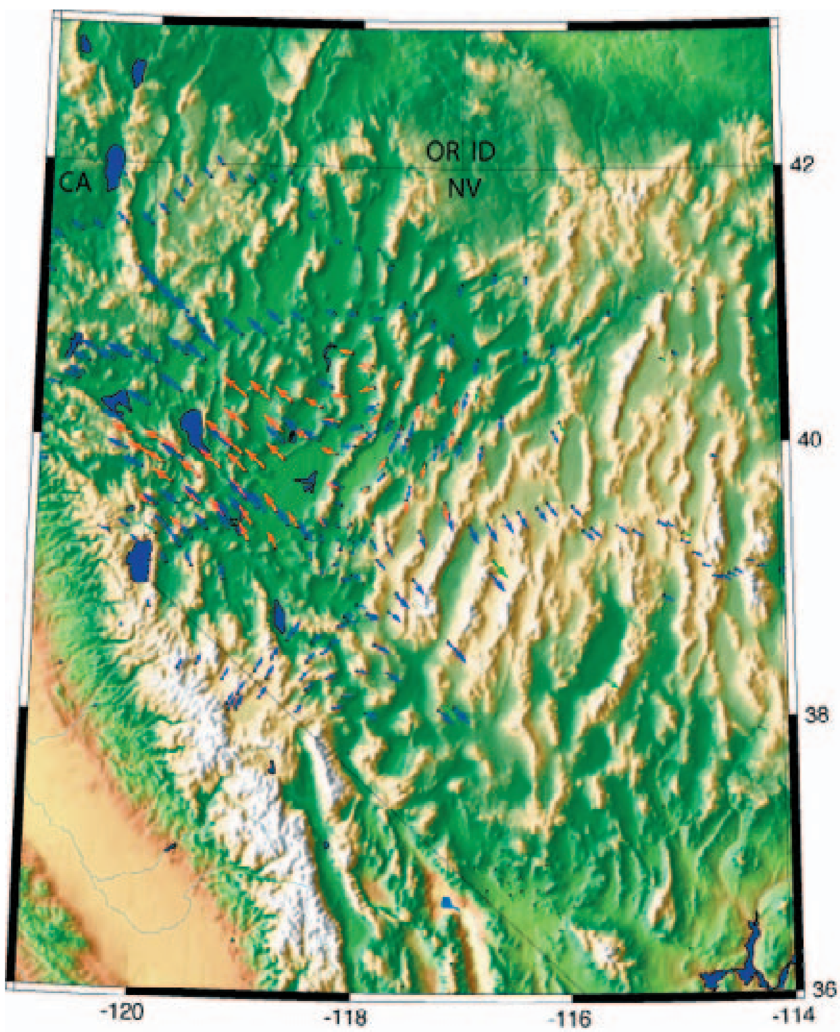
William Hammond
University of Nevada Reno

Corné Kreemer
University of Nevada Reno

Geoffrey Blewitt
University of Nevada Reno

In the western part of the Basin and Range province, geodetic and paleoseismic investigations have shown that recent tectonic deformation is focused east of the northwest translating Sierra Nevada microplate. In the central Walker Lane Belt, south of 39°N latitude, the shear and dilatation are focused in a zone ~150 km wide. North of 39°N latitude, however, the deforming zone nearly doubles in width. Furthermore, dilatation and shear, that are co-spatially present to the south, separate and diverge to the north. A new compilation of Global Positioning System (GPS) data indicates that a zone of dilatation trends north-northeast along the historic ruptures of the Central Nevada Seismic Belt (CNSB), while the dextral shear trends northwest, following the northern Walker Lane and Sierra Nevada range front. While the general trend of focused deformation, and other factors, suggest pervasive weakness of the Walker Lane lithosphere, the northern divergence of dilatation from shear suggests that either 1) the CNSB is another one of these weak zones, or 2) transient (e.g. CNSB postseismic) processes are an important part of the northwest Basin and Range geodetic velocity field.

Understanding the regional secular tectonic deformation pattern is of practical, as well as scientific interest, since geothermal energy potential in the Great Basin is strongly correlated to the presence of geodetic transtension. Thus we are taking multiple paths toward understanding the relative contributions of secular strain and post-seismic relaxation at the CNSB. Our new semi-continuous 56-site GPS network (the Mobile Array of GPS for Nevada Transtension - MAGNET) is supported by the Department of Energy to evaluate geothermal favorability. It is also ideally placed to measure CNSB postseismic effects, and will complement the future Basin and Range Plate Boundary Observatory (PBO) GPS coverage supported by the National Science Foundation. The combined networks will provide greater quantities of more precise data with greater spatial coverage compared to previous studies of CNSB relaxation. We will obtain geodetic time series from these data and use them with seismic and paleoseismic data on earthquake size, location and recurrence to constrain geodynamic models of postseismic relaxation.



Predicted geodetic velocity pattern in the year 2005 based on postseismic viscoelastic relaxation of the lower crust following the historic earthquakes of the Central Nevada Seismic Belt. Red vectors are at existing MAGNET sites, black vectors are at U.S. Geological Survey campaign GPS sites, green vectors are at BARGEN continuous GPS sites.

Collaborative Research: St. Eilias Erosional/Tectonics Project (STEEP)

Roger Hansen
University of Alaska Fairbanks

Gary Pavlis
Indiana University

Natalia Ratchkovski
University of Alaska Fairbanks

This five year, multi-disciplinary study addresses the evolution of the highest coastal mountain range on Earth - the St. Elias Mountains of southern Alaska and northwestern Canada. This orogen has developed over the past few million years as the Yakutat block, a continental-oceanic terrane, has attempted subduction beneath the eastern end of the Aleutian arc-trench system. The ~500 km-long, 150-km-wide St. Elias mountain range is the product of the dynamic balance between rapid uplift induced by crustal covergence and rapid exhumation by a regional system of large, fast-moving temperate glaciers. Most sediments are deposited either on a broad shelf or in deepsea fans and provide a complete record of the tectonic, climatic, erosional, and eustatic events that have accompanied the orogeny. Such a fresh and currently active “mini-orogen” is ideal for the integrated project we propose here.

The overarching goal of our project is to develop a comprehensive model for the St. Elias orogen that accounts for the interaction of regional plate tectonic processes, structural development, and rapid erosion. Our focus is on the partitioning of deformation within the system from upper mantle flow to near-surface faulting and exhumation. Three basic questions guide us:

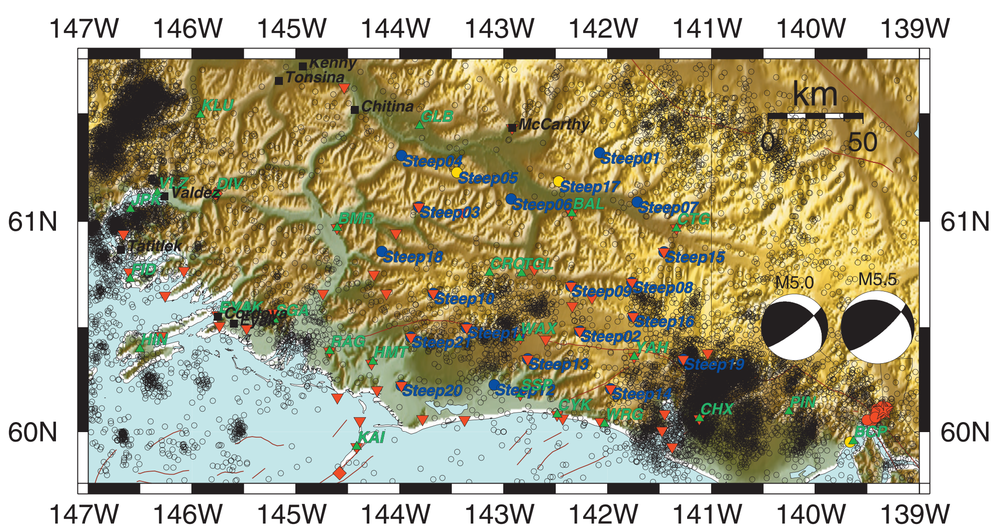
1. What is the nature of the upper mantle interactions that drive this orogenic system? In particular, is the orogen driven by passive subduction of a microplate or by forceful subduction driven by the Pacific plate; is continental crust being subducted; and how does upper mantle flow respond to the plate interaction?

2. How does the sedimentary cover respond to interaction of the three-plate/microplate interaction as it is stripped from basement along large-scale fault systems? That is, is the microplate behaving as an indentor or is it forcing lateral escape of the cover as the collision progresses? At what depth, and with what geometry do these separations occur?

3. How do surface processes, particularly areas of rapid glacial erosion, affect localization of deformation and slip-partitioning? Specifically, is the spatial association of large glaciers with areas of active deformation coincidental, or is the active deformation localized by rapid exhumation?

To address these questions we propose an integrated onshore-offshore study involving active source and passive source seismology, GPS-based geodetic studies, geologic studies, surface process studies, geochronology, and geodynamic modeling. Question 1 (crustal structure and upper mantle) will be addressed by a large-scale passive seismic study as well as offshore seismic profiling. These studies collectively will constrain the geometry and kinematics of the large-scale plate/microplate interactions in the system. Question 2 (sedimentary cover response) will be addressed through a combination of geologic studies onland, analysis of offshore seismic data (both existing data and the new data to be acquired in this study), GPS-based geodesy, and thermochronology. Question 3 (erosion/tectonics linkage) will be addressed by adding additional data from surface process studies and modeling.

This poster will concentrate on the seismicity of the region and the plans for the passive seismic experiment utilizing the IRIS PASSCAL Program instruments. As part of this project we will prototype a USARRAY seismic station that can operate and telemeter data in the harsh environment of Alaska with little built infrastructure, harsh weather conditions, lack of sunlight in winter months, and rugged terrain with large animals.



Station network configuration and seismicity within the STEEP project. Green triangles - existing stations; red inverted triangles - proposed GPS sites; filled circles - proposed seismic sites; open circles - M>=1.5 events from the AEIC earthquake catalog; red stars - February 11, 2005 M5.5 and M5.0 earthquakes in the Yakutat Bay area with focal mechanisms.

Thermal Processes and EarthScope Science

Robert Harris
University of Utah

Kevin Furlong
Pennsylvania State University

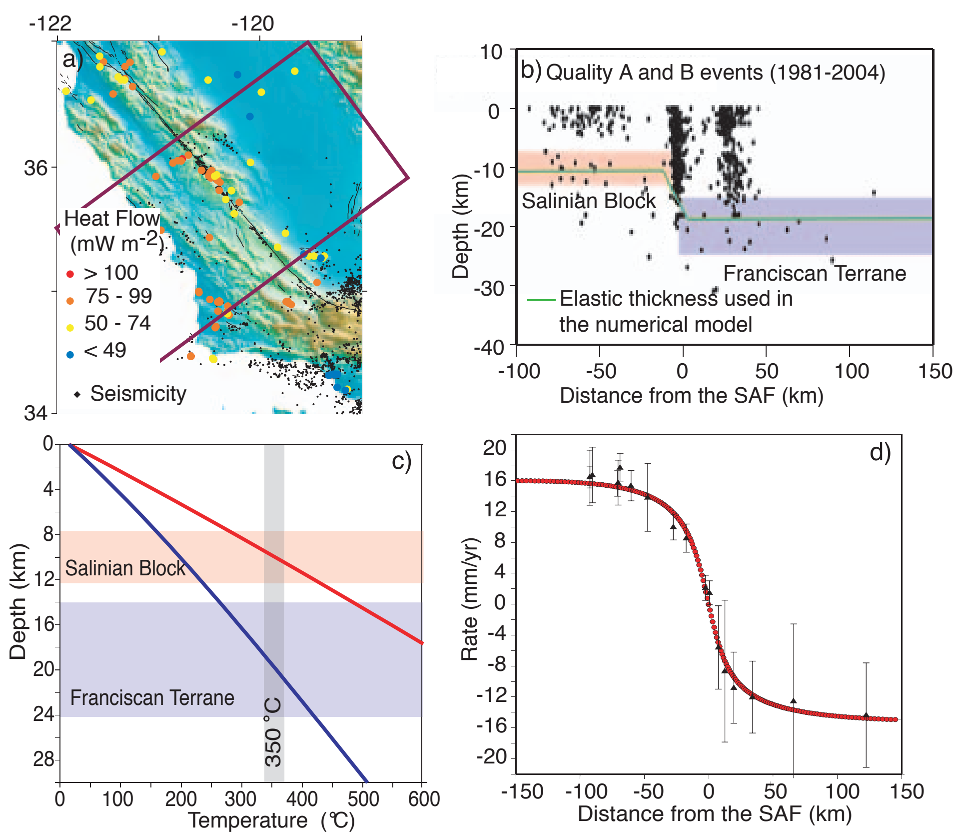
Colin Williams
U.S. Geological Survey

Demian Saffer
Pennsylvania State University

An understanding of thermal processes and structure plays a fundamental role in elucidating the dynamics and evolution of North America. To exploit most effectively the links between EarthScope science and thermal processes, a workshop was held to bring together practitioners from the fields of seismology, geodesy, geodynamics, and thermochronology, with researchers who focus on thermal processes. The goal was to define the high priority issues to be addressed through integration of thermal geophysics with EarthScope science.

High priority issues developed at the workshop include: 1) An important component to achieving EarthScope goals is the ability to separate the influences of temperature, composition, and fluid content in the crust and upper mantle on seismic velocity variations, geodetic data, and other geophysical data. Discerning the influences of these parameters of state on Earth processes is a high priority. 2) Understanding lateral thermal transitions zones within the lithosphere, including their spatial and temporal characteristics is a high priority due to their implications for strain, seismicity, and deformation. 3) Whereas SAFOD represents one example of a continental geothermal observatory, small scale observatories with thermistor strings and water level instruments will also be critical to capturing transient thermal events associated with deformation. The combination of temperature and water level data may be a useful proxy for stress and strain transients. 4) An improved understanding of the distribution of heat producing elements within the crust as a function of space, is needed to improve estimates of the lithospheric temperature field, and is necessary to separate thermal from compositional sources of seismic velocity variations.

EarthScope will produce data sets of unprecedented quality, resolution, and spatial coverage to address fundamental questions related to geodynamics, tectonics, and continental dynamics. Thermal data are critical for properly interpreting these data sets, and thus are necessary in order to realize many of EarthScope's goals.



Deformation across the San Andreas Fault (SAF) at the Corrizo Plain. a) Location map showing shaded relief, epicenters, and heat flow determinations colored by magnitude. b) Hypocenter depths. The horizontal boundaries at 11 km and 19 km (southwest and northeast of the SAF, respectively) lie below 95% of the events shown. c) Model geotherms for central California based on limited available heat flow and heat production data. The depth range for the 350 °C isotherm is shown as a grey band; note approximate correspondence with seismic data in Figure 6.2b. d) Finite element model for the GPS velocity data (component parallel to SAF) from the SCEC version 3.0 velocity field, using a contrast in elastic layer thickness (11 km SW of the fault; 19 km NE of the fault) consistent with the seismic and thermal data. Figure modified from Schmalze et al. [2003].

Thermal Isostasy and the Elevation of North America

Derrick Hasterok
University of Utah

David Chapman
University of Utah

Robert Harris
University of Utah

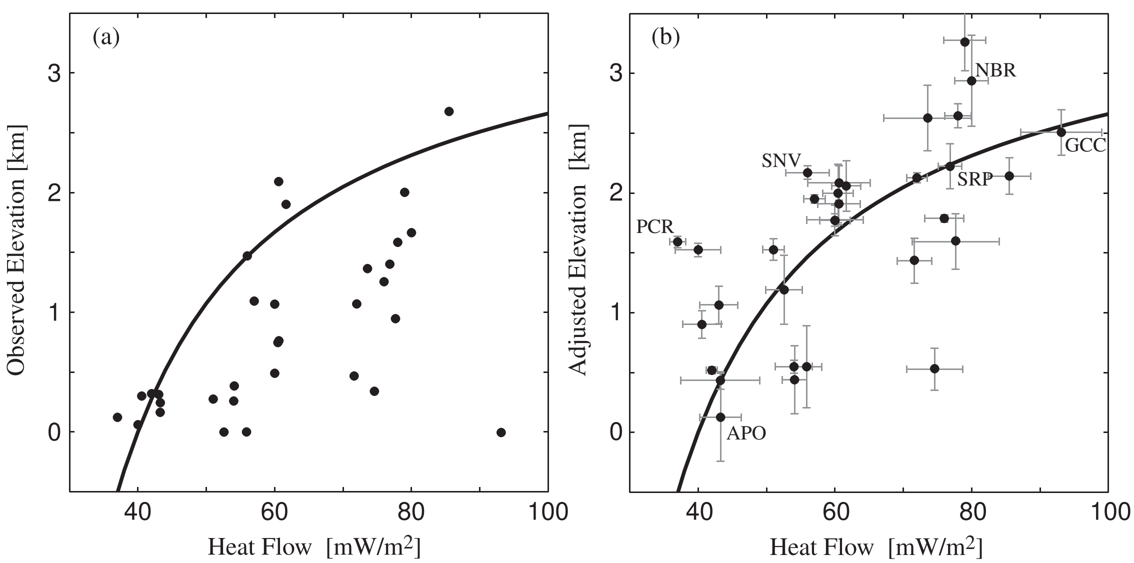
Continental elevations result from a combination of compositional, thermal, and geodynamic buoyancy. Extreme variations in lithospheric bulk density and crustal thickness can produce relief greater than nine kilometers, whereas variations in lithospheric thermal regimes can produce nearly three kilometers of relief between cold shield platforms and hot rift zones. Geodynamic contributions to elevation are at most a few kilometers.

The elevation of 32 North American tectonic provinces are adjusted for the effect of compositional buoyancy by computing the density-thickness product relative to a standard crustal section (average density of 2830 kg/m^3 and a 40 km thick crust). The crustal thickness and P-wave seismic velocity (V_p) structure are determined for each province from seismic models (Chulich and Mooney 2002). Densities are computed using an empirical relationship derived from laboratory pressure-temperature-velocity-density data (Christsen and Mooney 1995).

Thermal buoyancy is estimated by integrating the difference between a geotherm derived from observed values of heat flow and a standard continental lithospheric geotherm characteristic of a shield (surface heat flow 40 mW/m^2) to 500 km depth.

A continental heat flow–elevation relation is used to identify outliers in adjusted province elevations. These anomalous elevations may reflect a non-steady state thermal regime, dynamically supported elevation, anomalous mantle or some combination of these states. Discriminating between these sources of elevation will provide insights into the geodynamics of North America.

Current uncertainties in compositionally adjusted elevation range from ~200 m to > 600 m. EarthScope data will decrease these uncertainties through improvements in the spatial coverage of seismic sampling, better resolved seismic models, relationships between seismic velocities and density, and thermal observations. EarthScope data will enhance our ability to resolve and understand compositional, thermal and geodynamic contributions to continental elevation.



The elevation of North America, a) observed elevation of tectonic provinces and b) elevation adjusted for compositional variation. Tectonic province abbreviations: APO, Southern Appalachian Orogen; PCR, Pacific Coast Ranges; SNV, Sierra Nevada; SRP, Snake River Plain; NBR, Northern Basin and Range; and GCC, Gulf of California Coast.

PBO Facility Construction: Borehole Strainmeter Network Status

Michael Hasting
UNAVCO

Bob Mueller
UNAVCO

Wade Johnson
UNAVCO

Philip Gibicar
UNAVCO

The Plate Boundary Observatory (PBO), part of the larger NSF-funded EarthScope project, will record the three-dimensional strain field resulting from active plate boundary deformation across the Western United States. PBO is a large construction project involving the reconnaissance, permitting, installation, and maintenance of 875 permanent GPS stations and up to 175 Borehole Strainmeter (BSM) stations in five years. PBO has a demanding 5-year installation schedule, for both GPS and BSM installations, with 16 BSM stations scheduled for installation in FY05.

Year 1 of the project required reprioritizing the BSM station deployments to better record slow earthquakes in the Pacific Northwest (PNW) and plate boundary deformation along the entire Cascadia Subduction Zone. The PBO Siting Committee increased the station density from 4 to 12 BSM stations in the PNW for FY05 and created three more BSM arrays south of the Olympics and north of the Mendocino triple junction, scheduled to be installed in FY06-08. Year 1 activities also consisted of designing and specifying the system requirements, permitting 16 BSM sites on the Olympic Peninsula, Vancouver Island, and Parkfield regions, specifying drilling requirements, contracting drilling operations, ordering equipment, and commencement of drilling operations.

Siting and permitting in the PNW was completed August 2004 with permits being acquired for 4 sites (8 stations). Two sites (4 stations) located on Vancouver Island still need to be permitted but siting has been competed and paperwork is in the hands of the Canadian Government. Reconnaissance and permitting for Parkfield was completed in July 2004. Additional reconnaissance is being conducted in both the PNW and California for future stations.

Drilling/Coring on the Olympic Peninsula started in November 2004 and will be completed in March 2005. Drilling is accomplished in three phases; 1) hammer drilling a 8” diameter borehole to 400-500ft and then cementing a 6-5/8” casing in the borehole, 2) rotary drilling through the cement shoe plus 40-100ft below the casing, and 3) coring 40-100ft into the rock to find suitable installation zones. The first two phases were completed in January 2005. The third phase started in mid January 2005 and should be complete by mid March 2005. Drilling and coring operations for Vancouver Island and Parkfield are scheduled to start between May - July 2005.

A BSM station consists of a 4 component tensor strainmeter manufactured by GTSM Technologies, a 3 component 2Hz borehole gimbaled seismometer, a Paroscientific digiquarts pore pressure transducer, a Setra model 270 barometer and a rain gauge. Some stations will also have a PBO GPS antenna attached to the top of the casing as part of the 875 GPS station network. The strainmeters will be installed at depths between 450ft and 800ft with the seismometer installed about 30ft above the strainmeter. The pore pressure transducer will be installed in a 2” PVC pipe with a 10ft screen section somewhere in the aquifer above the seismometer. Data from the strainmeter and rain gauge will be recorded on the strainmeter recording system while the seismometer, pore pressure and barometer will be recorded on a separate 24bit digitizer. Strainmeter data will be sent, via the Internet, to UNAVCO/PBO while seismic data will be sent to the Array Network Facility.

Installation of the first BSM station, located on the Olympic Peninsula, is scheduled to take place in mid March. The remaining 15 stations will be installed over the summer and should be completed by the end of FY05.

Lithosheric Structure of Eastern North America: Unique EarthScope Opportunities

Robert HatcheR
University of Tennessee
Knoxville

William Thomas
University of Kentucky

Krishna Sinha
Virginia Tech

Eastern North America lithosphere records two complete Wilson cycles and the beginnings of a third. Supercontinent Rodinia was constructed ~1 Ga along the eastern Laurentian margin by collision with pre-Gondwanan continents. The Grenville event truncated older E-W trending crustal elements, e.g., the (1.4-1.55 Ga) granite rhyolite province, as Rodinia formed. Rodinia broke up ~530-750 Ma, forming a continental margin around eastern, southern, and western Laurentia. This continental margin evolved into the early Paleozoic platform that was uplifted ~460 Ma across the eastern two thirds of Laurentia. Shortly thereafter subduction began along the eastern margin accreting a volcanic arc system that extended from southeastern Laurentia to Scandinavia (Taconic orogeny). An ocean that remained off eastern Laurentia closed obliquely beginning in the middle Paleozoic (Acadian-Neoacadian orogenies) with collision of the Neoproterozoic to early Paleozoic Avalonian (including Carolina) arc system with Laurentia. ~320 Ma thermal activity marked the beginning of the Alleghanian orogeny and construction of Pangaea as Gondwana collided with Laurentia. An accretionary and subduction complex formed off southern Laurentia mmediately prior to this, producing the Ouachita orogeny that ended before the mid-Alleghanian began. Alleghanian collision was oblique north to south, zipper-like, producing dextral strike-slip in blocks escaping collision, followed by late Pennsylvanian and Permian head-on collision from New York southward producing the Blue Ridge Piedmont megathrust sheet, driving foreland fold-thrust belt deformation in front of it. Interestingly, Pangea remained intact for only ~40 m.y. and broke apart in the Late Triassic, whereas Rodinia existed 250-350 m.y. before breaking apart. Breakup of Pangea produced the present Atlantic Ocean and continental margins. Numerous opportunities can be addressed by EarthScope science in the Middle Proterozoic to Holocene Eastern North American collage. The deep crustal to lithospheric signatures of each major crustal component should be explored to better understand their internal structure, boundaries, and influence on younger processes, e.g., intraplate seismicity, and features (Fig. 1). Focused investigations could address lithospheric characteristics in areas of a few 10,000s of km^2 , and produce advances that would enhance our preprations for arrival of the transportable array. These include an area in South Alabama and Mississippi where Ouachitas, departed Precordilleran, Appalachian, Grenville, African, and older lithospheres truncate each other, and in southern New England where Appalachian and accreted terranes lithospheres converge.

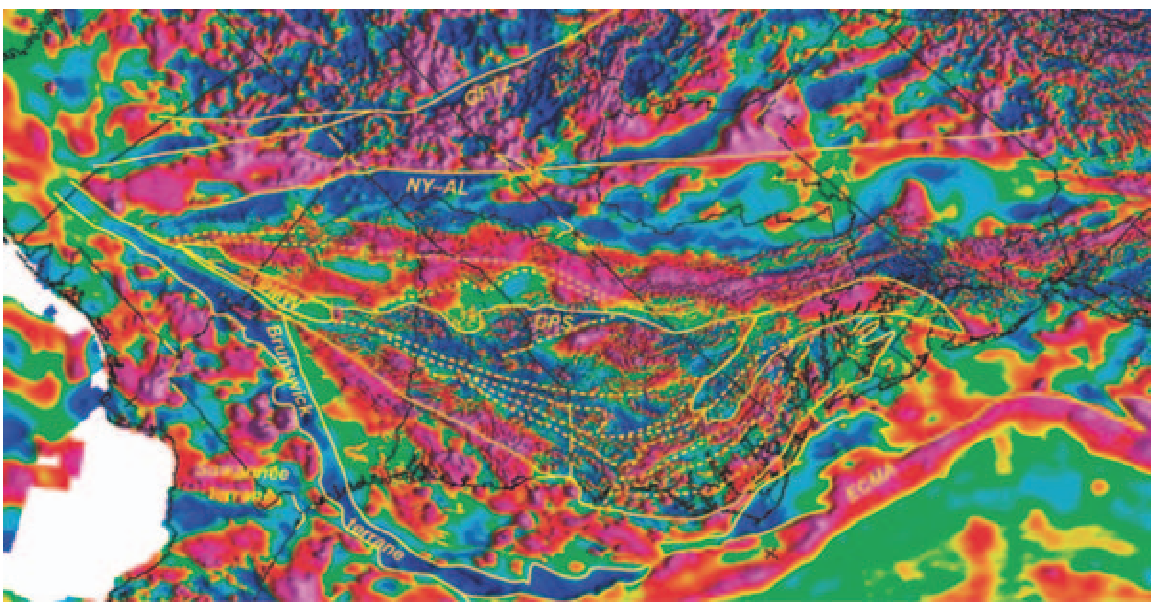


Figure 1. Part of the ENA magnetic map showing major crustal boundaries and tectonic units. GFTZ Grenville front tectonic zone. NY-AL–New York-Alabama magnetic (and gravity) lineament. CPS Central Piedmont suture. PMW–Pine Mountain window. ECMA–East Coast magnetic anomaly.

EarthScope Data Generation and Data Flow

Christel Hennet
EarthScope

Tim Ahern
IRIS

Greg Anderson
UNAVCO

William Ellsworth
U.S. Geological Survey

Susan Eriksson
UNAVCO

Christian Guillemot
EarthScope

Fred Pieper
Institute for the Application of Geospacial Technology

John Taber
IRIS

Charles Weiland
Stanford University

Over the next five years, EarthScope will install 1,494 stations across the country. EarthScope stations will include permanent GPS stations, borehole strainmeter stations, long-baseline strainmeter stations, ANSS Backbone seismic stations, and Transportable Array seismic stations, and the SAFOD drill site. In addition, EarthScope will purchase 2,500 campaign GPS and seismic instruments, which will be available for temporary deployments and individual research experiments. Seismic and geodetic data are being produced by all EarthScope components, often with identical instrumentation and shared know-how.

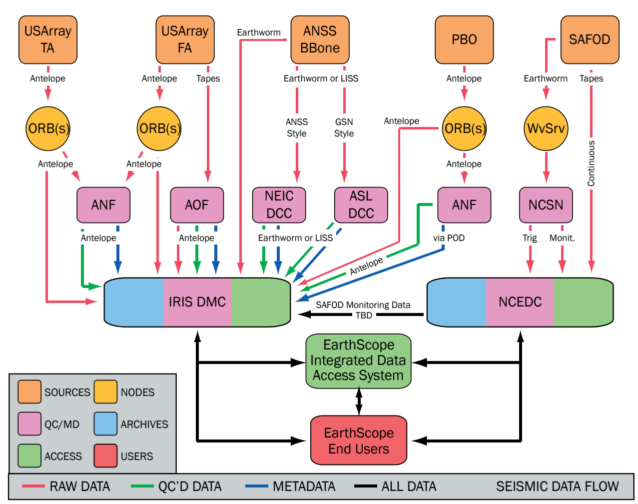
Seismic data will be recorded by 400 Transportable Array stations, 2400 Flexible Array stations, 100 ANSS Backbone stations, up to 174 PBO stations, and by more than 100 channels of triggered and continuous data at the SAFOD site. The overall seismic data and metadata flow are shown in the figure below. As EarthScope is leveraging the existing capabilities within its components, several efficiencies have been identified and are being explored for quality control and data storage: USArray and PBO seismic data will be quality controlled at the Array Network Facility in San Diego and archived at the IRIS DMC in Seattle, Washington. SAFOD seismic data will be quality controlled at the NCSN and archived at the NCEDC in Berkeley, California. The IRIS DMC will maintain a complete seismic archive. UNAVCO will serve as a backup archive for all EarthScope seismic data.

Continuous GPS data will be recorded at 875 permanent GPS stations, at 16 stations installed at Global Seismic Network stations, and by a pool of up to 100 campaign stations. GPS data will be analyzed at both UC Berkeley and Central Washington University. The primary data archive for GPS data is the UNAVCO facility in Boulder, Colorado. The IRIS Data Management Center in Seattle, Washington acts as a backup for all EarthScope GPS data.

Borehole Strainmeter (BSM) data will be recorded at 174 PBO sites and at the SAFOD drill site. Each PBO station will collect four channels of strain data at 20 samples per second, as well as pore fluid pressure data, surface atmospheric pressure data, downhole thermistor data, rainfall, and surface temperature data. SAFOD will record continuous strain data from two sensors, a fiber-optic vertical strainmeter and an in-hole 3-component strain meter. All Borehole Strainmeter data will be analyzed at the BSM Analysis Center in Socorro, New Mexico and archived both at the NCEDC in Berkeley, California and the IRIS DMC in Seattle, Washington.

EarthScope will record Laser Strainmeter (LSM) data at 5 sites. Each LSM station will record 12 channels of strain and environmental data at 1 sample per second. Initial quality control will be provided by two data collection facilities: one in Boulder, Colorado and the other in Socorro, New Mexico. LSM data will be analyzed at the LSM Analysis Center at UC San Diego, California and archived both at the NCEDC in Berkeley, California and the IRIS DMC in Seattle, Washington.

Data generation and archiving began within months of EarthScope's start date and by project Year 5, we expect to have collected about 30 TB of data. All EarthScope data will be openly available at the individual data centers and through seamless, single point access through the EarthScope Integrated Data Access System (IDAS).



Integrated data flow chart for all seismic data collected by EarthScope. ORB(s) - Object Ring Buffer, ANF - Array Network Facility at UCSD in San Diego, CA, AOF - Array Operations Facility at New Mexico Tech. in Socorro, NM, NEIC DCC - National Earthquake Information Center Data Collection Center, ASL DCC - Albuquerque Seismological Laboratory Data Collection Center, NCSN - Northern California Seismic Network. The primary data archive for USArray and PBO seismic data is the IRIS DMC in Seattle, WA. The primary data archive for SAFOD seismic data is the NCEDC in Berkeley, CA. End users can access seismic data directly at the data centers or through seamless, single point access with the EarthScope Integrated Data Access System (IDAS).

The EarthScope Integrated Data Access System

Christel Hennet
EarthScope

Tim Ahern
IRIS

Greg Anderson
UNAVCO

William Ellsworth
U.S. Geological Survey

Susan Eriksson
UNAVCO

Christian Guillemot
EarthScope

Fred Pieper
Institute for the Application of Geospacial Technology

John Taber
IRIS

Charles Weiland
Stanford University

EarthScope has the mandate to provide seamless, single-point access to all EarthScope data, data products, and tools, and to make all information open and accessible to a wide range of users, the scientific and educational communities, government agencies, the media and public, and informal education services.

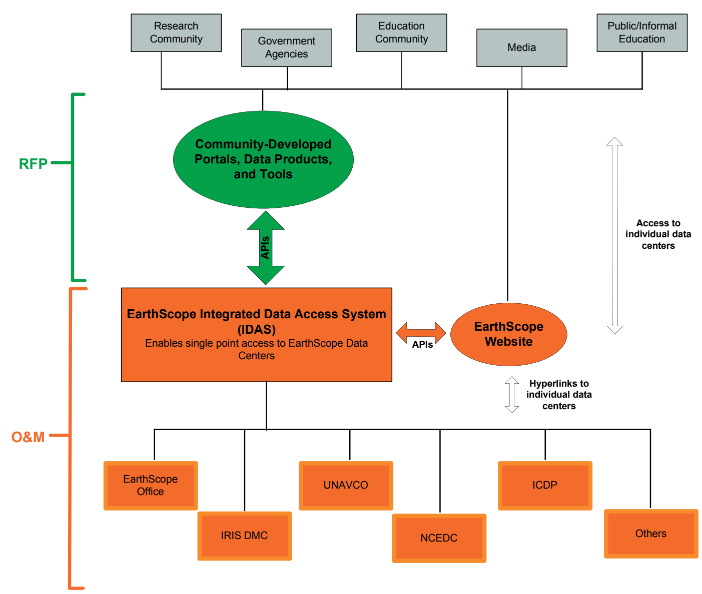
A key task for EarthScope is the development of the system for seamless, single-point access to all the data products. We call this system the EarthScope Integrated Data Access System (IDAS). While the EarthScope Office will have primary responsibility for development of the IDAS, each EarthScope element will develop, operate, and maintain the infrastructure needed to make that element's data products accessible to the IDAS.

The IDAS system will integrate the data handling interfaces (DHI) already in use at each EarthScope facility. These applications run on a variety of software and hardware platforms in a distributed environment. Without the IDAS, the current lack of integration requires a data requester to become familiar with the application interface used for data retrieval at each data center. For instance, a simple EarthScope "combined" data query from a community user may involve completely different programmed interfaces at PBO and USArray, thus making the transaction process difficult to automate and placing the burden of integrating this information on the user. In turn, data users will be placing a burden on the various data archives to make data compatible with various developers of EarthScope products and tools.

To minimize the differences between existing hardware and software platforms we intend to build a layer around the data handling interfaces which will effectively link these heterogeneous data management systems without having to modify the underlying legacy systems. We believe this approach will be the most effective in leveraging EarthScope's existing capabilities and will minimize the additional cost required towards developing a seamless access interface.

At present, the EarthScope Data Working Group anticipates that the IDAS will be largely based on web services. The term web services in general refers to a set of protocols and standards used for exchanging information between software applications over computer networks, to allow applications to work together regardless of the computer language in which they are programmed or the kind of computer system on which they operate. A specific web service-enabled application is one that can be found and accessed remotely via a computer network, using the protocols of the web services framework.

The IDAS system requires tight coordination among the EarthScope elements to develop solutions that will satisfy the architecture requirements for interoperability, encapsulation, and availability. In addition, flexibility will be built into the IDAS applications to quickly adapt to the variety of new data products, data tools, and data portals that will be generated by the broad scientific and educational community as EarthScope evolves.



The above figure illustrates the EarthScope Integrated Data Access System (IDAS) infrastructure that is being developed based upon existing IT capabilities at all EarthScope data centers. In this diagram, services and capabilities included in the O&M proposal are shown in brown. Services and capabilities that may be developed through the NSF peer-review process as shown in green. IDAS is designed to effectively link the heterogeneous data management systems to meet the scientific and educational requirements of providing seamless single-point access to all EarthScope data and data products. Integrated throughout the system will also be the necessary capabilities to evaluate EarthScope's performance and its scientific and educational impact. As indicated, access to the individual data centers will of course continue to be available for disciplinary research users.

UAVSAR: An Airborne SAR for Differential Radar Interferometry

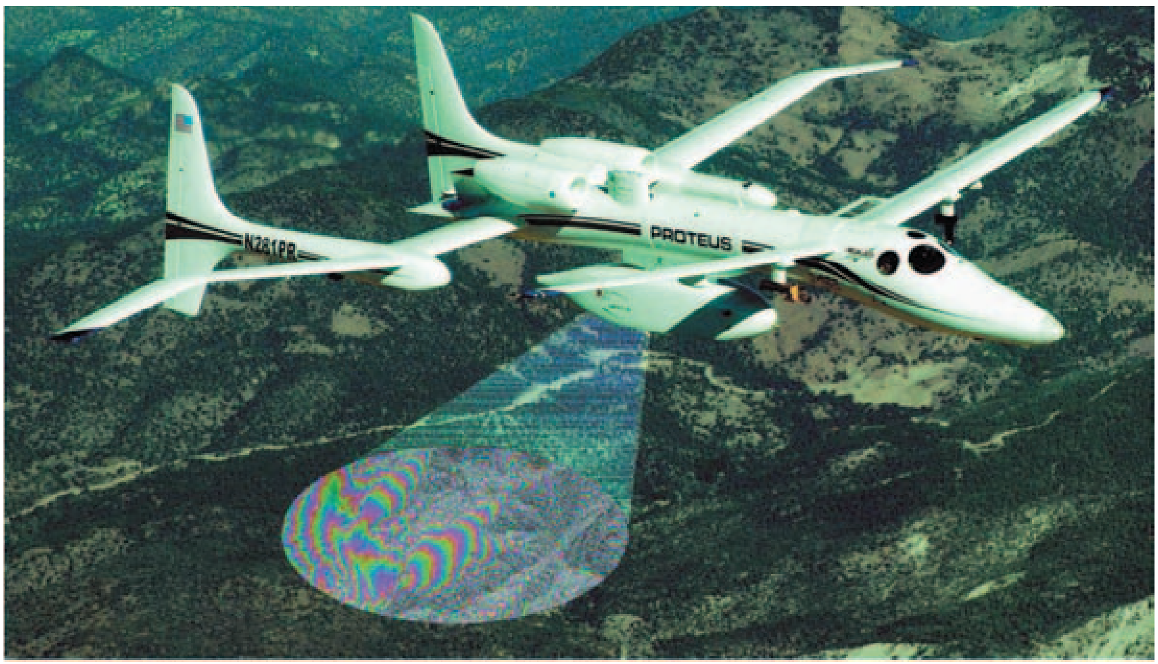
Scott Hensley
Jet Propulsion Laboratory

Paul Rosen
Jet Propulsion Laboratory

Kevin Wheeler
Jet Propulsion Laboratory

Howard Zebker
Stanford University

Spaceborne repeat pass radar interferometry for deformation mapping has become an integral tool for the investigation of geophysical processes such earthquakes, volcanoes, ground material extraction and glacier dynamics. Repeat pass observation intervals are limited by the repeat pass times of existing satellite radar systems that range from 24-44 days. To make targeted observations of geophysical events having deformation signals of interest on time scales less than that supported by satellite observations we have proposed an airborne system to make these observations. Although airborne systems can make repeat observations on the time scales of interest, hours to years, the implementation of a robust airborne capability is considerably more complex than a spaceborne capability. This talk describe the NASA/JPL UAVSAR system currently under development at JPL designed to make robust repeat pass deformation measurements suitable for geophysical analysis.



Artist conception of the UAVSAR hosted on a the Scaled Composites Proteus platform making repeat pass measurements of a deforming surface.

Complementary Geophysics: Adding Value to EarthScope Science

Tom Henyey
University of Southern California

Important to the success of EarthScope as a science initiative will be the integration of data and results from the core facilities, as well as from other complementary geological, geochemical, and geophysical studies. By integrating scientific information from an expanded set of observational disciplines, EarthScope will be in a position to generate a more comprehensive structural and time-dependent picture of the North American continent than has been previously possible. Moreover, a truly interdisciplinary approach is required if EarthScope is to rise to the next level of continental exploration through the focused study of entire geosystems, including fault systems, magmatic systems, sedimentary basins, and modern and ancient orogenic systems, as well as to significantly improve relationships between processes in Earth's interior and their surface expressions.

An effective interdisciplinary effort, given the scope of EarthScope, will also require the latest in information technology, including high-speed telecommunication links, state-of-the-art data acquisition, storage, and distribution centers, accessible on-line plug-and-play software, high-performance computing environments, and visualization resources. In short, EarthScope science funding will need to be sufficiently large to accommodate multidisciplinary activities beyond the core facilities if we expect to achieve the EarthScope mandate we set before ourselves.

This report will present some of the major findings and suggested action items from a workshop on Complementary Geophysics, held in Denver, Colorado, March 2-4, 2003. The workshop explored the "value added" contributions of non-core geophysical instrumentation and/or data that might be linked in various ways to the core EarthScope facilities and data centers. Complementary geophysics refers to geophysical instrumentation not part of the MREFC facilities, as well as existing data and data to be collected by non-MREFC instrumentation and facilities. Geophysical disciplines considered by the workshop included gravity, magnetics, magnetotellurics, electromagnetics, petrophysics, heat flow, and remote sensing. In addition, the role of industry seismic data and the issue of "controlled sources" for the flexible array were discussed.

Specific questions addressed to various degrees by the workshop included:

What complementary data sets are important and bring added benefit to the broader EarthScope scientific goals and projects,

What complementary datasets are currently available, and easily accessible,

For existing data sets that are not easily accessible, what needs to be done to make them readily accessible and easy to use,

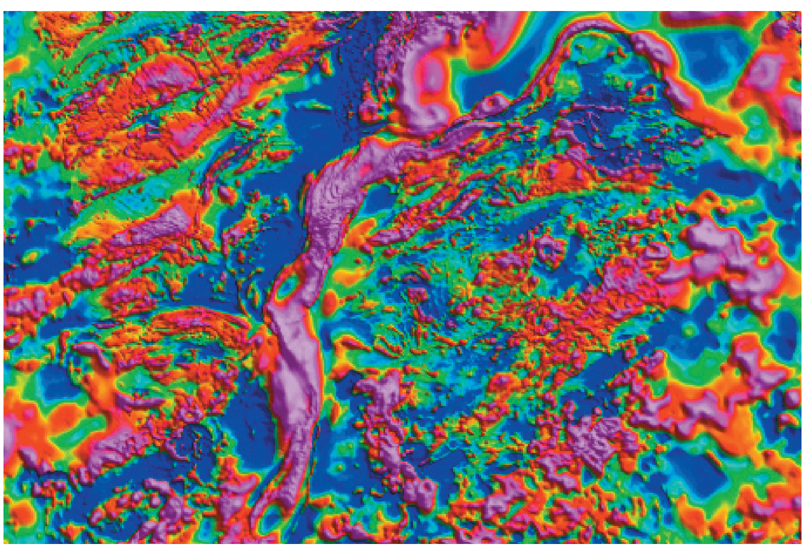
For datasets that are important, but either not complete or non-existent, which are best acquired through a community initiative, and which are best justified in the context of specific science or facilities proposals,

What complementary geophysical instruments and facilities already exist and could be made available to the scientific community to acquire new data,

What additional community operated and maintained complementary geophysical instrumentation might be needed to achieve EarthScope goals,

How might such instrumentation be coordinated with the core EarthScope facilities, and

What should the data and IT policies and procedures for new complementary geophysics be?



A portion of the U.S. aeromagnetic map covering portions of the states of Minnesota, Wisconsin, and Iowa.

Exploring Our Dynamic Continent: Educational Materials in Support of the EarthScope Voyager Map Tools

Anne Hereford
Indiana University

Michael Hamburger
Indiana University

Lou Estey
UNAVCO

Susan Eriksson
UNAVCO

Charles Meertens
UNAVCO

Marianne Weingroff
Digital Library for Earth System Education

William Holt
State University of New York at Stony Brook

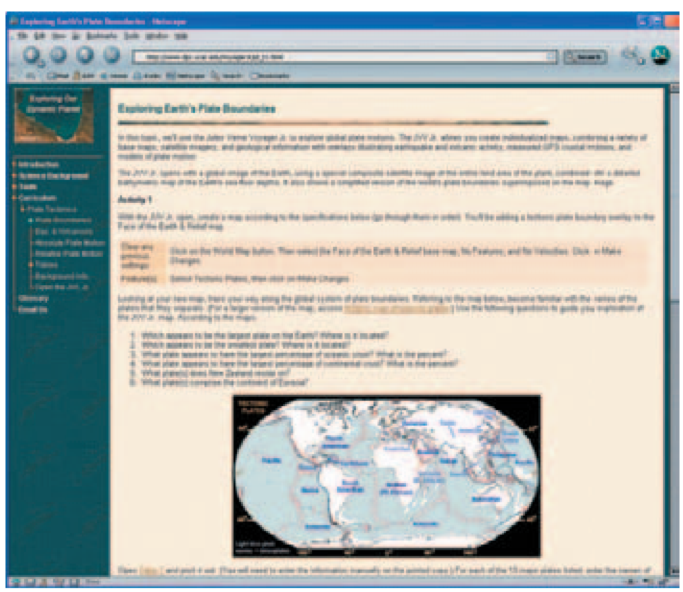
Glenn Richard
State University of New York at Stony Brook

Visualization of detailed and highly diverse earth science data is essential for both scientists and students in developing a conceptual understanding of Earth processes. The Voyager map tools provide an interactive, web-based map environment that makes scientific results accessible to a large number and variety of researchers, educators, and students. Voyager users can access a variety of maps, satellite images, and geographical and geophysical data at a range of spatial scales. A portal to these map tools can be found at: http://jules.unavco.org. We present educational materials to accompany the Voyager map tools to guide students in their exploration of global geodynamic processes.

"Exploring Our Dynamic Planet" (EDP) is a Javascript-based educational interface that enables scientists, educators, and students to better understand the relationships among geophysical and geological processes, structures, and measurements. EDP links to our on-line map tools and provides background information, a glossary, and a complete guide to the features of the map tools. At the heart of EDP is a series of inquiry-based interactive modules that encourages students to use the map tool in a guided exploration of global dynamic processes. The "Plate Tectonics" module promotes a conceptual understanding of plate tectonic processes by encouraging students to make observations about the distribution of earthquakes and volcanoes, to compare relationships between plate boundary types and physiographic features, and to work with observed and model plate motion data. In the process, students also become familiar with basic mapping concepts, such as the use of latitude/longitude, legend, and scale. The interface is designed to be expandable, allowing for diverse contributions from the scientific community. We are currently testing the module in university and high-school classrooms, and anticipate more formal assessment of the curricular materials. EDP is currently designed for use with the global-scale map tool (Jules Verne Voyager Jr), but we are in the process of developing a parallel set of exercises for use with the North America version (EarthScope Voyager Jr). As EarthScope develops, maps will be updated in near-real time so that students can take advantage of emerging data from the EarthScope program. EDP can be viewed at http://www.dpc.ucar.edu/VoyagerJr/.

Among the geophysical overlays that can be displayed in EarthScope Voyager Junior are data that relate to strain rate models. Included are PBO GPS stations and strain meters, stress axes, tectonic boundaries, plate velocities, and faults. Making this data available through the map tool and providing links to strain rate movies of southern California and other materials are integral pieces of educational modules that are being developed to enable students to explore strain rate models and supporting concepts.

"Did You Know?" (DYK) modules are interactive explorations of geodynamic processes at selected study areas, linked from the EarthScope Voyager map tool. Each DYK will include detailed maps, and will provide extensive background information, targets for student inquiry, links to external sites, and information about EarthScope deployments in the area. A prototype DYK module has been developed for Long Valley Caldera, and additional modules are envisioned for Cascadia, the San Andreas Fault, the Basin and Range, the Appalachians, Yellowstone, New Madrid Seismic Zone and others. The site design allows researchers to easily contribute modules specific to their study areas and provides a logical conduit for dissemination of emerging results from the EarthScope project.



Introductory Plate Tectonics module from "Exploring our Dynamic Planet"

The Value of Modern Detrital Samples for Reconnaissance Regional Thermochronometry

Kip Hodges
Massachusetts Institute of Technology

Detrital sediments in modern river catchments provide a valuable synthesis of the bedrock geology of their source region. Many thermochronologic studies of detrital minerals from ancient sedimentary basins have been aimed at reconstructing regional erosion and sediment transport histories. A less common application of this approach is the study of detrital mineral age populations in modern fluvial systems. Such studies constitute a rapid and cost-effective way to develop a first-order sense of catchment-wide bedrock exhumation. By examining the variations in cooling age populations from catchment to catchment, it is possible to establish a sense of regional exhumation patterns that can be related to both tectonics and landscape evolution. In Precambrian terrains, such patterns can be extremely valuable indicators of the timing of continental assembly.

Despite years of bedrock thermochronology in the United States, large tracks of igneous and metamorphic rocks exist for which there have been no systematic thermochronologic studies. The Earthscope initiative provides a tremendous opportunity to rectify this problem by integrating detrital thermochronology with topical studies of critical terrains in conjunction with other Earthscope activities. The technology is now available for automated, high-throughput, $^{40}Ar/^{39}Ar$ and (U-Th)/He analyses of detrital mineral suites, providing data over a range of closure temperatures that are appropriate for addressing a wide range of tectonic and thermochronologic problems. Examples from the Nepalese Himalaya will be presented to illustrate the methods.

PBO Strainmeters on the Olympic Peninsula, Installation and Data Products

Kathleen Hodgkinson
UNAVCO

Greg Anderson
UNAVCO

Michael Hastings
UNAVCO

Bob Mueller
UNAVCO

The first PBO strainmeter will be installed at Hoko Falls on the Olympic Peninsula in the Pacific Northwest in Mid March 2005. The borehole, one of eight that were drilled between November 2004 and January 2005, was cored in February 2005 by DOSECC and the site found to be suitable for strainmeter deployment. As of this writing 4 of the remaining 7 holes have been cored and 3 of them found to be suitable and one not very promising. Strainmeters and seismometers for suitable holes will be installed later this summer when instruments become available. These sites will comprise the first of 143 strainmeter sites that have been prioritized by the scientific community. The Olympic Peninsula was chosen as the first region of interest so as to capture deformation caused by the next silent earthquakes in Cascadia, which is anticipated in the fall of 2005.

PBO will install three component tensor strainmeters manufactured by GTSM Technologies. The strainmeter has four independent strain cells, one being redundant. The cells measures change in borehole diameter along one axis and are oriented at 120 degrees to each other. Areal and shear strain can be derived by combining these three gauge measurements. Additionally a 2 Hz three-component seismometer will be installed in each borehole, approximately 30 feet above the strainmeter. The seismic data will be sent to the Array Network Facility at Scripps where it will be processed and archived along with USArray data. When complete this will make the PBO seismic network the second largest borehole seismic network in the world.

The GTSM collects data at 20 samples per second. The data will be buffered on-site and downloaded in near real time via internet connections. The data are passed through Quality Control and then sent to the Borehole Strainmeter Analysis Center (BSAC) for processing. At the BSAC the data will be reduced to 300-second data by repeatedly filtering and decimating using a causal minimum delay FIR filter. The strainmeters will be calibrated in-situ by comparing the observed M2 and O1 tidal amplitudes with that measured by each gauge. The long-term trends observed in borehole strainmeter data are those created by borehole relaxation and the grout, in which the strainmeter is placed, curing. These trends can typically be described by two exponentials, one with a time constant of 10 to 40 days and the second on the order of a few 100 days. PBO will provide the parameters used to describe the borehole correction trends and the matrices required to combine the individual gauge measurements into tensor strain.

The raw data, the level 0 strainmeter data product, will be transferred to the strainmeter archives at IRIS DMC and NCEDC within minutes or arriving in the Strainmeter Analysis Center. The level 0 data will be available in the full 20 Hz sample rate in miniSEED and the data logger native format. The Level 1 data product, strain in natural units, are derived directly from the Level 0 product and therefore are available as rapidly as the Level 0 product. The cleaned 300-second real and shear strain data with borehole and tidal corrections will be available within 14 days of data collection in XML format. The entire data set will be reprocessed every three months allowing for post processing and recalibration to produce the best possible modellable data set.

Cement pump truck at an Olympic Peninsula strainmeter borehole.

Stable Interior - Northern U.S. (SINUS) Region: Scoping Out an EarthScope Opportunity

Daniel Holm
Kent State University

Val Chandler
Minnesota Geological Survey

W. Cannon
U.S. Geological Survey

D. Schneider
Ohio University

W. R. Van Schmus
University of Kansas

J. Miller
Minnesota Geological Survey

As a traditional center for studies of Precambrian geology and early crustal evolution, the north-central U.S. provides unique and exciting opportunities for study under the EarthScope initiative. A multi-disciplinary working group is being established to promote an integrative ES-USArray study of the stable interior - northern U.S. (SINUS) region. It is one of the few areas in the midcontinent U.S. that provides ground control on the Archean to late Mesoproterozoic bedrock architecture that comprises the North American craton. Also, the region is not overprinted by young tectonic events as more exterior, albeit better exposed Precambrian regions such as the Rocky Mountains. SINUS straddles several important terrane boundaries, including the transition from Archean lithosphere (southern Superior Province) to juvenile Paleoproterozoic lithosphere (Penokean, Yavapai, Mazatzal), all of which are cut by the 1.1 Ga Midcontinent rift (MCR). New studies can build on knowledge gained from GLIMPCE and COCORP deep crustal investigations of the 1980's. There now exists a battery of basic field, geochronologic, seismic reflection and refraction data, and relatively new potential-field data that are being used to reinterpret the geologic evolution of SINUS.

A new SINUS region aeromagnetic map shows a complex, yet distinctive pattern that reveals important new aspects of the Precambrian geology related to the assembly of southern Laurentia. To the north, aeromagnetic data help delineate Proterozoic sutures and deformational boundaries that reflect complexities associated with 1) an irregular southern margin of Laurentia (Minnesota River Valley promontories), and 2) significant structural and magmatic modification. The latter can be attributed to the long-lived convergent nature of southern Laurentia that resulted in orogenic collapse structures (gneiss dome corridor), progressively younger deformational fronts, and intrusion of the East-central Minnesota and Wolf River batholiths possibly associated with north-directed subduction. In the south, the aeromagnetic map reveals an extensive area of folded Paleoproterozoic Baraboo Interval quartzites and associated rocks beneath thin Paleozoic cover. This terrane shows a sharp ENE-trending northern boundary against Archean crust in northwest Iowa, southern Minnesota, and central Wisconsin. The SINUS working group interprets the Spirit Lake-Trempeleau discontinuity to be a fundamental Yavapai-age Proterozoic boundary, perhaps equivalent to the Cheyenne belt paleosubduction zone in southern Wyoming. Younger, Mazatzal-age compressional deformation is observed in juvenile rocks far afield of the margin. The Yavapai-Mazatzal terrane boundary is intruded by 1.5-1.3 Ga Granite-Rhyolite province rocks, although it must occur south of deformed Baraboo interval quartzites in northeast Iowa. In total, the assembly of the southern margin lasted a few hundred m.y. and involved several accretionary episodes that ultimately distilled the lithosphere and produced a stabilized craton.

Discordant to the terrane boundaries across a significant portion of the map, the MCR is exhibited by a magnetic and gravity high which widens northward from Kansas and bifurcates under Lake Superior. Crustal thickness under the extended region remains in excess of 40 km, illustrating an outstanding geodynamic problem deserving resolution. Although the Mid-continent rift is well mapped and dated in the Lake Superior region, much about its deeper crust and upper mantle structure remains largely unknown.

The SINUS working group will connect diverse investigators in a fruitful collaboration toward understanding ancient crustal and lithospheric evolution of the North American midcontinent. Infecting the SINUS region with hypotheses testable by future USArray experiments is a major goal.

SINUS Working Group:

R. Anderson
Iowa Geological Survey

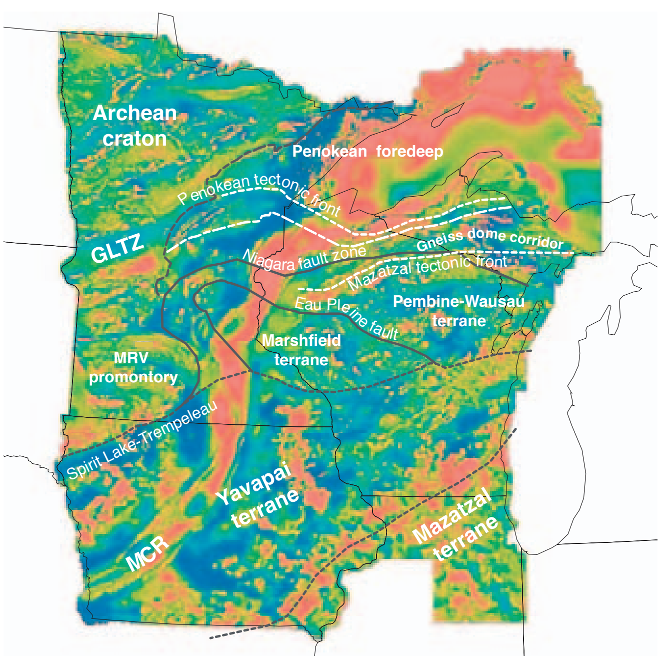
K. Schultz
U.S. Geological Survey

L. Woodruff
U.S. Geological Survey

T. Boerboom
Minnesota Geological Survey

M. Jirsa
Minnesota Geological Survey

D. Iles
South Dakota Geological Survey



Aeromagnetic map of northern US Midcontinent, illustrating major suture zones, terrane boundaries, and geologic features that are defined by geologic and geochemical data. GLTZ: Archean Great Lakes tectonic zone; MRV: Minnesota River valley; MCR: Mesoproterozoic Mid-continent Rift, which extends north to the Penokean foredeep. Gneiss dome corridor is defined by the GLTZ to the north and the Niagara fault to the south.

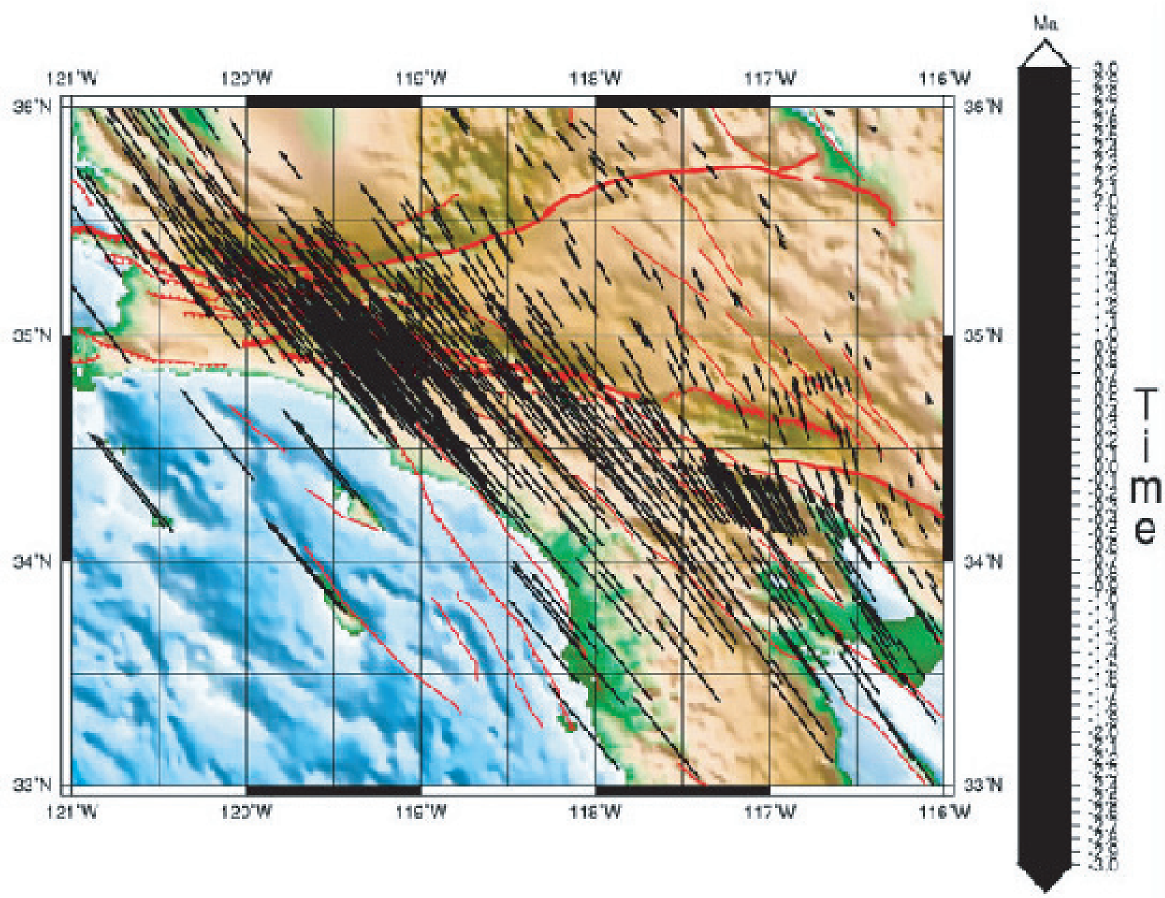
Finite Strain Movies in the Plate Boundary Zone of the Western United States: A Visualization Tool for Education and Research

William Holt
State University of New York at Stony Brook

Barbara Birkes
Ashland University

Glenn Richard
State University of New York at Stony Brook

We have generated strain rate model animations that focus on southern California. These movies, which portray plate motions, landform uplift, and subsidence, are useful for enabling students to visualize the dramatic changes that occur within plate boundary zones over geologic time. The models use instantaneous rates of strain derived from both global positioning system (GPS) data collected over periods of time and known slip rates of Quaternary faults. The velocities calculated from GPS data and Quaternary fault slip rates are interpolated to define a continuous, instantaneous velocity field for southern California. This velocity field is then used to track topography points and fault locations through time (both backward and forward in time), using time steps of 100,000 years, to produce an animation representing a period from 3 million years ago to 3 million years into the future. After each time step, the strain rate field is updated in order to prepare for the next step. This update takes into account the changes that have occurred in boundary conditions of plate motion, and changes in fault orientation. Assuming constant volume, Airy isostasy, and a volume of eroded material equivalent to half the uplift volume, the topography is also calculated as a function of time. The animations provide interesting moving images of the transform boundary between the North American and Pacific Plates, highlighting ongoing extension and subsidence, convergence and uplift, and large horizontal movements of crust occurring within the strike-slip regime. Moving images of the strain components, uplift volume through time, and inferred volume of eroded material through time have also been produced. These animations are an excellent demonstration for education purposes and also hold potential as an important tool for research enabling the quantification of rotations of fault blocks, potential erosion volume, uplift volume, and the influence of climate on these parameters. To facilitate inquiry-based learning exercises that use these moving images, we are also developing educational modules. These modules utilize the EarthScope Voyager Map Tools, animations of the deformation of continental crust in the vicinity of tectonic plate boundaries, and other interactive materials. Understanding of these models requires a comprehension of underpinning concepts such as tectonic plate motions, reference frames, strain rates, isostasy, erosion, fault movement, and global positioning system time series. The educational modules will enable students to explore these concepts and understand the moving images.



An animation frame for southern California, illustrating velocities, faults, and topography calculated three million years into the future.

A New Method for Measuring Deformation in Non-urban Settings Using InSAR Persistent Scatterers

Andrew Hooper
Stanford University

Howard Zebker
Stanford University

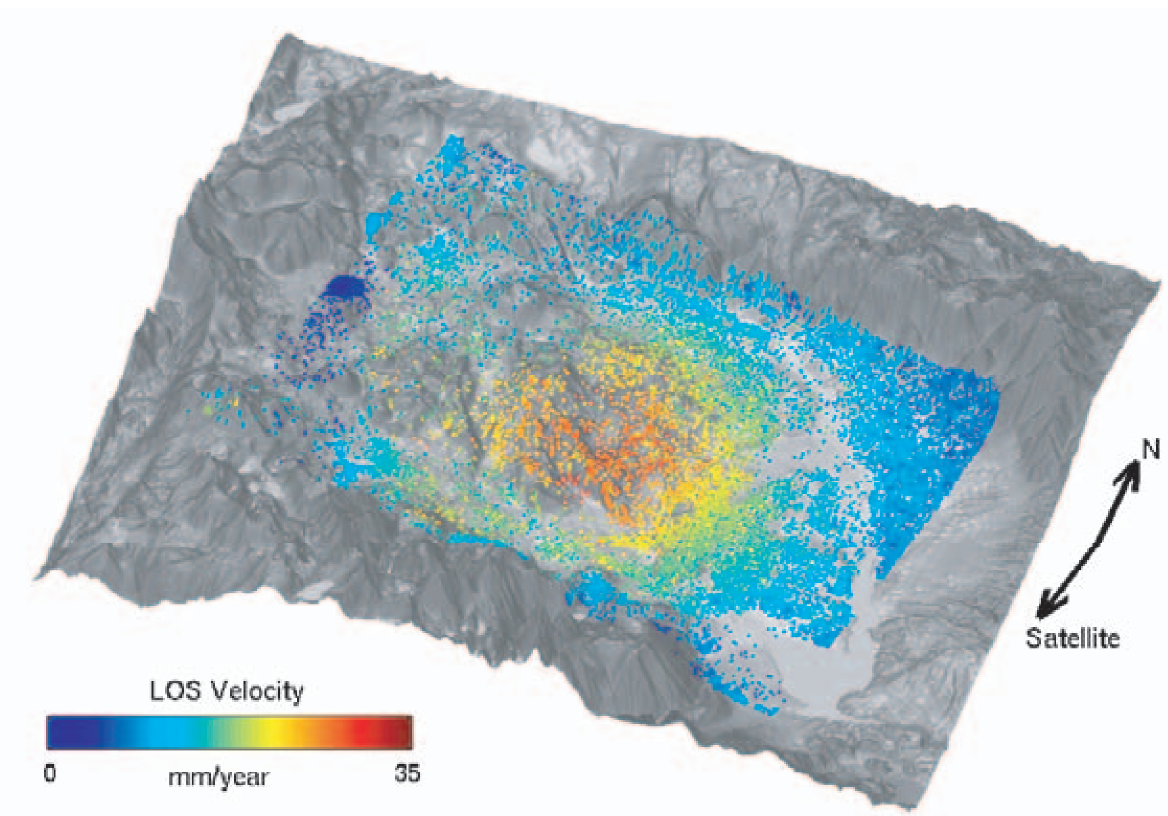
Paul Segall
Stanford University

Kampes Bert
German Aerospace Center

Persistent scatterer (PS) analysis of InSAR data has proven to be a very sensitive technique for measuring steady or functionally-simple deformation with time when applied to urban areas. Applying these methods to estimate deformation in non-urban settings is, however, more challenging because they lack the man-made structures that are most easily detected by the PS algorithm. Furthermore, PS are often not detected in areas where deformation proceeds at an irregular rate e.g., many volcanoes and landslides.

We have developed a new method for identifying PS pixels in a series of interferograms, based on their phase characteristics, that is applicable to the study of natural targets. The phase-based method avoids one major problem with the existing algorithm: low amplitude pixels with actual phase stability are not identified. Our method also uses the spatial correlation of the phases rather than a well-defined phase history so that we can observe temporally-variable processes. The method involves removing a residual topographic component of the phase for each PS, assumed proportional to the interferometric baseline, and then unwrapping the phase of the PS interferogram stack both temporally and spatially, using a three-dimensional phase-unwrapping algorithm. Our technique finds scatterers with stable phase characteristics, independent of amplitudes associated with man-made objects. It is applicable to areas where conventional InSAR fails due to complete decorrelation of the majority of scatterers, but there are a few stable scatterers distributed amongst them.

We created and analyzed a stack of 21 interferograms for Long Valley Caldera in California, and identified 23,000 PS pixels in the study region, as opposed to about 400 found with Ferretti's (2001) algorithm. The resulting unwrapped phases, when transformed into estimates of line-of-sight displacements, agree with GPS, leveling and EDM measurements made over similar time intervals, validating the technique.



Average line-of-site velocities of PS in Long Valley Caldera for the period June 1992 to August 2000, superimposed on a shaded relief map.

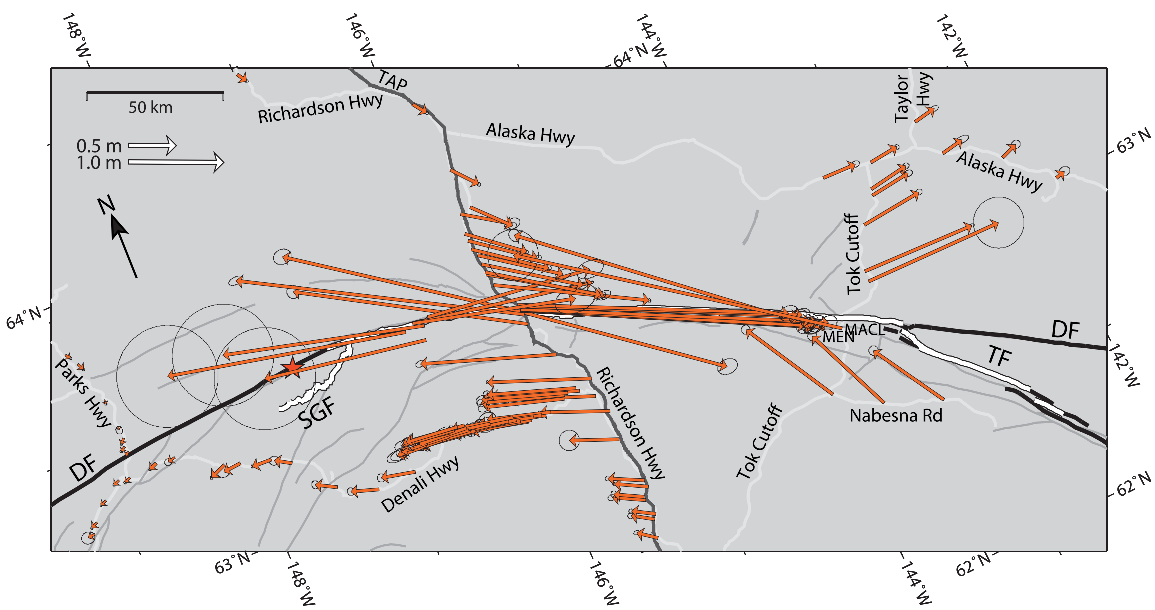
Coseismic Slip Distribution of the 2002 M_w7.9 Denali Fault Earthquake

Sigrun Hreinsdottir
University of Alaska Fairbanks

Jeffrey Freymueller
University of Alaska Fairbanks

Roland Bürgmann
University of California Berkeley

We estimate coseismic displacements from the 2002 M_w7.9 Denali Fault earthquake at 232 GPS sites in Alaska and Canada. Displacements along a N-S profile indicate right-lateral slip on a near vertical fault with a significant component of vertical motion, north-side up. We invert both GPS displacements and geologic surface offsets for slip on a 3D fault model in an elastic half-space. We restrict the motion to right-lateral slip and north-side up dip-slip. Allowing for oblique slip along the Denali and Totschunda faults improves the model fit to the GPS data by about 30%. We see mostly right-lateral strike-slip motion on the Denali and Totschunda faults but in a few areas we see a significant component of dip-slip. The slip model shows increasing slip from west to east along the Denali fault, with four localized higher-slip patches, three near the Trans-Alaska pipeline crossing and a large slip patch corresponding to a M_w7.5 subevent about 40 km west of the Denali-Totschunda junction. Slip of 1-3 m was estimated along the Totschunda fault with the majority of slip being at shallower than 9 km depth. We have limited resolution on the Susitna Glacier fault but the estimated slip along the fault is consistent with a M_w7.2 thrust-sub-event. Total estimated moment in the Denali Fault earthquake is equivalent to M_w7.9. The estimated slip distribution along the surface is in very good agreement with geological surface offsets but we find that surface offsets measured on glaciers are biased toward lower values.



Coseismic displacements from the Denali Fault earthquake. The largest horizontal displacements, just over 3 m, were measured at MEN and MACL (Tok Cutoff, just south of the fault). The star indicates the epicenter of the Denali Fault earthquake and the white line shows the surface rupture along the Susitna Glacier (SGF), Denali (DF) and Totschunda faults (TF). The Trans-Alaska pipeline (TAP) and major roads are shown for reference.

USArray and the Great Plains: Summary of a Pre-EarthScope Workshop

Mary Hubbard
Kansas State University

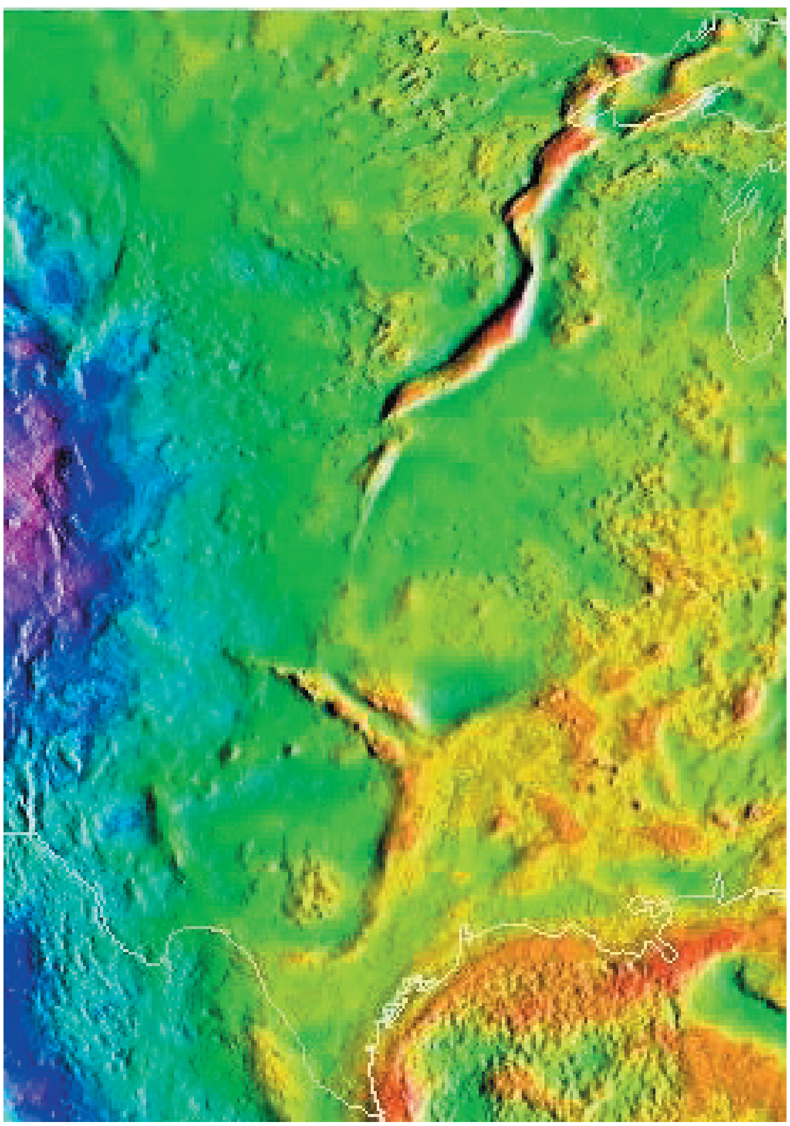
Steve Gao
Kansas State University

Kelly Liu
Kansas State University

Jack Oviatt
Kansas State University

Kirsten Nicolaysen
Kansas State University

In April, 2003, the Department of Geology at Kansas State University hosted a workshop to bring together geoscienctists with experience and/or interest in Great Plains geology and geophysics. About 40 people attended from over 25 colleges, universities, and state surveys. The meeting consisted of 3 days of invited talks, volunteered poster presentations, large-group brainstorming sessions and smaller working group sessions. The goal was to identify some of the major points of interest in the Great Plains cratonic region. The result was discussion of five major topic areas: rift features, terrane boundaries, basins and uplifts, Rocky Mountain-Great Plains transition, and occurrence of kimberlites and other anomalous intrusives. In the rift feature category there was interest in the Mid Continent rift, the New Madrid/ Reel Foot fault zone, and the Rio Grande rift and its far reaching effects. For the Mid Continent rift specific questions centered on the thick crust, mantle velocities, mantle fabrics, and possible lingering thermal effects. A number of Terranes underlie the Great Plains region, such as the Superior Province, the Trans-Hudson Orogen, the Wyoming Province, and the Yavapai and Mazatzal terranes. The geological and geophysical properties associated with the boundaries between these terranes clearly warrant detailed study. Basin discussion focused on the Michigan and Illinois basins with the uplift topic largely centered on the Black Hills uplift. Rocky Mountain tectonic activity has had an impact on the uplift of the high plains. Further geology studies coupled with geophysical investigations are needed to determine variation in timing, role of thermal processes, and nature of the mantle in this region. Mesozoic and Cenozoic intrusive activity in the Great Plains region remains a mystery. Petrologic studies coupled with geophysics could help address where the melts originate and the relation to other tectonic activity. This workshop resulted in several proposal submissions with a number of others still planned for the near future.



Extensional Styles: Importance of Evolving Strength of the Lithosphere and Thermal Structure

Audrey Huerta
Pennsylvania State University

The West Antarctic Rift System experienced protracted extension during Cretaceous and Tertiary time resulting in thinning of continental crust over a region >800 km wide. In the northern reaches of the WARS, a late stage of extension focused in the Terror Rift, located at the boundary with the East Antarctic Craton.

This extensional history has many similarities to Basin and Range- the type-section of diffuse continental extension where crustal thinning is accommodated across a broad region many of hundreds-of-kilometers wide over a protracted time tens-of-millions of years in duration. And, similar to the Terror Rift, the southern reaches of the Rio Grand Rift is situated between the stable craton of North America and the extensional regime of the southern B&R.

Recent numerical models of WARS evolution indicate that the development of diffuse extension is highly dependent on the evolving strength profile of the lithosphere, which in turn is highly dependent on the initial thermal structure. Additionally, there is a limited class of models that can simulate the transition from diffuse extension to focused extension within geologically reasonable time. This class of models is defined by the initial temperature of the uppermost mantle and includes a range of crustal thicknesses, extension rates, and lithospheric thicknesses.

Delamination Origin for Columbia River Flood Basalts and Wallowa Mountain Uplift in NE Oregon

Eugene Humphreys
University of Oregon

The Wallowa Mountains define the high center to a 200-km diameter circular "bulls eye" pattern of oscillating uplifts and sags, and they are comprised of the largest of the few granitic plutons in the area.

The bulls eye region is the source area for most Columbia River Basalt (CRB) eruptions. Existing elevation maps of CRB flow interfaces are used to quantify the magnitude, timing and distribution of surface uplift, and teleseismic data is used to tomographically image the structure of the underlying mantle. The bulls eye area is characterized by mild pre-eruptive subsidence, syn-eruptive uplift of several hundred meters, and a persistent km-scale uplift of the Wallowa Mountains, and it overlies an anomalous volume of mantle that is devoid of partial melt compared with adjacent areas. Predictions of hotspot plume models and passive magmatic proceses are inconsistent with the history, spatial patttern and magnitude of uplift. Within the context of current geological understanding, only delamination of compositionally dense plutonic roots can explain the uplift timing and magnitude and the imaged upper mantle structure.

This suggests that CRB magmatism is a consequence of lithospheric processes rather than arrival of a mantle plume; it is possible that delamination was triggered by the arrival of hot mantle, and that the local intensity of CRB magmatism resulted from the combined effects of anomalously hot mantle and lithospheric delamination.

USArray – Construction of a Large Seismological Research Facility

Shane Ingate
IRIS

Tim Ahern
IRIS

Mark Alvarez
IRIS

Kent Anderson
IRIS

EarthScope is nearly one third complete in its five-year task of facility construction, which brings forth a new suite of facilities for research on the structure and dynamics of the North American continent. The seismological resources of EarthScope/USArray are being implemented through the four programs of the IRIS Consortium and consist of four major elements: a Transportable Array to systematically traverse the entire US with seismic and magnetotelluric (MT) instrumentation; a Flexible Array of portable instruments for detailed studies of source and structure; the addition of permanent seismic and MT stations, in collaboration with the USGS, to augment the ANSS Backbone Network; and the management of all USArray data.

This poster will summarize activities in the first 16 months of USArray operations including defining a staff structure and hiring of new staff; purchasing of sensor and data acquisition systems and identification of prospective MT instrumentation after a competitive bidding and evaluation process; completing the buildup of the DMC to meet the data QC, archiving and distribution of USArray seismic data; buildup of the Array Operations and Network Facilities hosted respectively by NMT and UCSD, site selection of Backbone MT stations, installation of a museum display in a National Park, the USArrray web site, and examples of extensive monthly narrative and fiscal reporting to NSF and the EarthScope Office.

Seasonal Variations in GPS Site Positions in a Center of Lateral Figure (CL) Reference Frame

Daniel Johnson
University of Puget Sound

Implementation of a Stable North American Reference Frame (SNARF) should take into account annual site motions due to loading effects. This poster presents results of a compilation of seasonal motions observed at GPS sites across North America.

Seasonal degree-one deformation related to loading effects are a source of misfit between observed site coordinates and assumed positions that are based on a linear motion reference frame model. With a Center of Surface Figure (CF) reference frame, this discrepancy may be partly absorbed by the GPS "scale" parameter, producing a pattern of annual apparent "scale" variation. This effect, in turn, spreads annual deformation artifacts to sites elsewhere on the Earth's surface. In the presence of degree-one deformation, a suitable reference frame model should allow for non-linear site motion. The Center of Lateral Figure (CL) reference frame is one possible solution. With the CL frame model, station motions are constrained to move with constant horizontal velocities, and the vertical component is not used in the solution. This solution confines degree-one deformation to the vertical component, which is not constrained to linear motion.

A CL reference frame is demonstrated here using time series results from a GIPSY/OASIS II fiducial-free analysis of approximately 1000 globally distributed GPS sites. Applying reference frame constraints is done utilizing only the horizontal component of site positions and the GPS "scale" parameter is omitted in the initial solution. Results show a pattern of seasonal deformation in the vertical component consistent with loading. For sites in North America, peak to peak amplitudes of seasonal vertical deformation are in the range of 8 to 13 mm and vary by location. In general the phase of seasonal motion at sites in the southern portion of North America is advanced compared to more northerly sites. Seasonal horizontal motions are observed in this solution, indicating localized seasonal effects in addition to degree-one deformation.

An Integrative Seismological and Geodynamical Approach to Assess the Mechanism Underlying the Yellowstone Hotspot

Michael Jordan
University of Utah

Robert Smith
University of Utah

Yellowstone Hotspot Team

The goal of this study is to reveal the mechanism behind the Yellowstone Hotspot and its relation to the Newberry volcanic trend. Yellowstone is characterized by a Hotspot track like age-progression of volcanics along the Snake River Plain, high heatflow, a large positive geoid and negative Bouguer gravity anomaly. Similar bimodal volcanism and a coincident origin in space and time indicate a common source of both volcanic trends, which have been supposed to be caused by a mantle plume. However, while the spacial alignment of the Yellowstone Hotspot track is in good accordance with plate motion, the direction of the Newberry related age progressive volcanics are almost 180 degrees off, which does not seem to support a plume origin of the Yellowstone Hotspot.

Though many different models for possible mechanisms behind this system have been debated, the origin of the Yellowstone Hotspot and the Newberry volcanic trend are still unclear. To examine a possible deep origin of the Yellowstone volcanism, a 3D high resolution regional seismic tomography is conducted down to 800 km depth. A priori information, such as local crustal models, geologic data, topography of the major discontinuities and gravity data, are incorporated into the inversion to provide further constraints to the resulting model. We find a narrow low velocity anomaly, which is tilted to the WNW, extending from Yellowstone down to 660 km (see figure).

This regional tomographic model is supported by global seismological and geodynamical models, geoid and geochemical data, suggesting several possible scenarios. To evaluate the different hypotheses, we apply regional geodynamical modeling, testing viable mechanisms and geodynamical parameters.

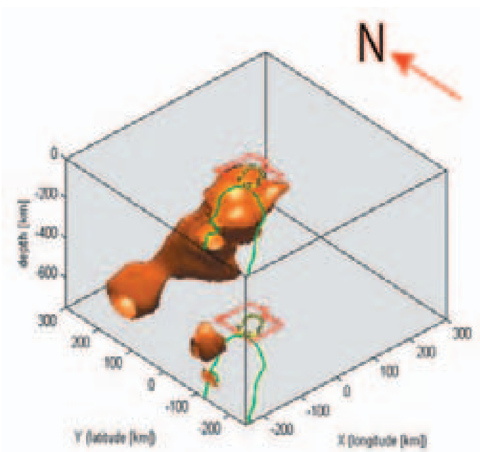
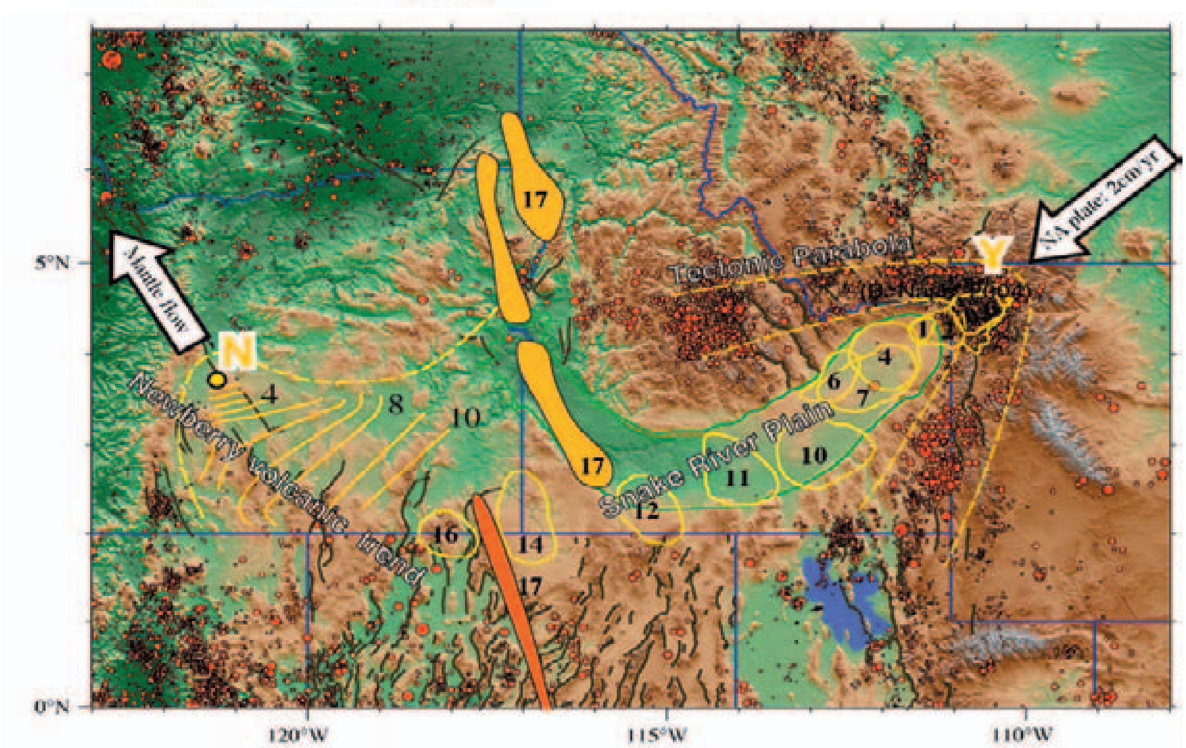


Figure a shows the 3D seismic compressional wave velocity perturbations beneath the Yellowstone Hotspot. The colored lines indicate the Yellowstone caldera (yellow), the Yellowstone National Park boundaries (red) and the Snake River Plain (green). Figure b displays the tectonic setting of the Yellowstone Hotspot and the Newberry volcanic trend. Included are ages of silicic volcanic centers and flood basalts.

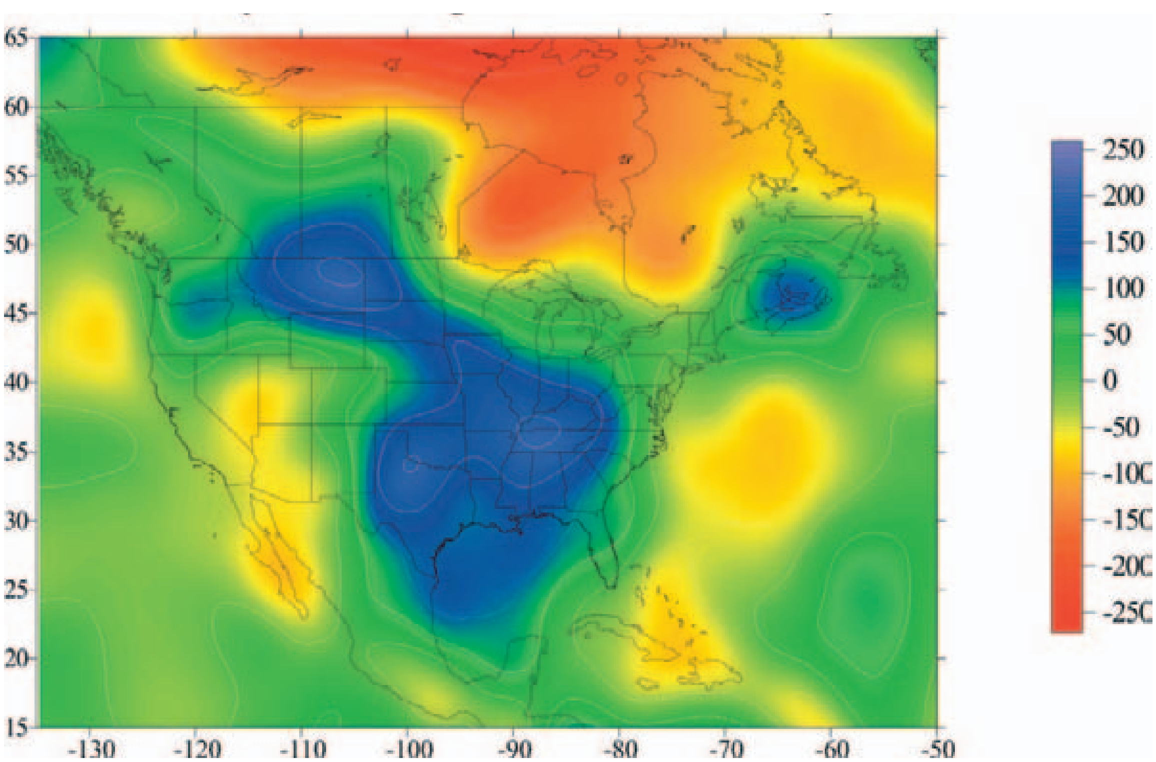


The North American Upper Mantle: Density, Composition, and Evolution

Mikhail Kaban
GeoForschungsZentrum Potsdam

Walter Mooney
U.S. Geological Survey

The upper mantle of North America (NA) has been well studied using seismic methods. Here we investigate the density structure of the NA upper mantle based on the Bouguer gravity anomaly map. The basis of our study is the removal of the gravitational effect of the crust to determine the mantle gravity field. The effect of the crust is removed in three steps by subtracting the gravitational contributions of: (1) topography; (2) low-density sedimentary accumulations; and (3) the 3D structure of the crystalline crust. Topographic data are taken from a standard data base; information regarding sedimentary accumulations, including thickness and density, are taken from published maps and summaries of borehole measurements of densities; the structure of the crust is from a recent publication (Chulick and Mooney, 2002), with layer densities estimated from compressional wave velocities. The resultant mantle gravity anomaly map shows a negative anomaly (-50 to -400 mgal) beneath western NA and the adjacent oceanic region, and positive anomalies (+50 to +350 mgal) to the east of the NA Cordillera. This division reflects the well-known division of NA into the stable eastern portion and the tectonically active western portion. A comparison of the mantle anomaly map with the topographic map indicates that a significant amount of the topographic uplift in western NA is due to buoyancy in the hot upper mantle, a conclusion supported by previous investigations. In order to separate the contributions of thermal expansion from mantle composition, we apply an additional correction for the thermal structure of the uppermost mantle. Our thermal model is based on the conversion of seismic shear-wave velocities to temperature, and is consistent with mantle temperatures that are independently estimated from heat flow and heat production data. The thermally-corrected map reveals mantle density anomalies that are solely due to compositional variations. These anomalies have a magnitude of +250 to –250 mgal. The upper mantle beneath the Canadian shield exhibits a negative anomaly (-50 to –200 mgal) that is consistent with chemical depletion that results in a mantle composition with lower density, also referred to as the mantle tectosphere. The strongest positive anomaly is co-incident with the Gulf of Mexico, and indicates a positive density anomaly in the upper mantle. Two linear positive anomalies are also seen in the eastern USA and beneath Texas, New Mexico, and Colorado. These anomalies are interpreted as either (1) due to the presence of the Farallon slab at a depth below 300 km; or (2) due to mantle density anomalies associated with the accretion of Proterozoic terrains along the southern margin of Laurentia. The evolution of the NA upper mantle is depicted in a series of cartoon that display the primary processes that have formed and modifies the crust and lithospheric upper mantle.



Residual Gravity after removing the Crust and Mantle Temperature Effects.

Opportunities and Challenges for EarthScope-leveraged 3D Super-experiments to Resolve the Nature of Mantle Velocity Domains and the Heterogeneous Structure and Polyphase Evolution of the Continental Lithosphere: Case Study from the Southern Rocky Mountains

Karl Karlstrom
University of New Mexico

Rick Aster
New Mexico Institute of Mining and Technology

The more than decade-long deployment of the EarthScope USArray Transportable Array (400 simultaneously deployed broadband seismographs with a mean station spacing of 75 km), in conjunction with the Flexible Array (200 broadband, 200 short period, and 2000 single-channel instruments) offers unique opportunities and challenges for pioneering lithospheric-scale imaging experiments. Important opportunities exist to: 1) design 3-D imaging experiments that go well beyond present imaging studies in 3-D resolution, and 2) resolve the nature and origin of mantle heterogeneity. Challenges involve creating multidisciplinary experiments that truly integrate diverse geologic, geochronologic, and geophysical data sets into a master model for lithospheric history, evolution, and dynamics.

The lithospheric structure of the western U.S. represents an interaction of structures that formed during Proterozoic arc accretion and structures that formed or were extensively modified during Laramide and post-Laramide tectonism. The Rocky Mountain region, especially, preserves an interaction between old structures and young driving forces and provides a set of ongoing lithospheric scale natural laboratories that can be used to understand geodynamics of continents. Based on the tantalizing and remarkably high resolution recent 2-D images of the lithosphere achieved by the CD-ROM and RISTRA experiments, one of the most fundamental observations is the abrupt nature (over several km) of very large lateral velocity contrasts in the upper mantle. A fundamental question for EarthScope concerns the extent to which these mantle velocity domains and provinces are old and influenced by ancient lithospheric structure of North America, as opposed to young upwellings of asthenosphere and displacement of lithosphere due to small scale mantle convection. Although the CD-ROM and RISTRA images are higher resolution than those that will be produced by the Transportable Array, their resolution and interpretation has been fundamentally limited by their primarily 1-dimensional deployment and 2-dimensional imaging geometries. Greater understanding (in association with 3-D EarthScope tomographic images) will require multidisciplinary studies involving a range of complementary geophysical studies, geologic studies (of old and young tectonics) that add ground truth and the time dimension, and geodynamic models that test realistic physical models.

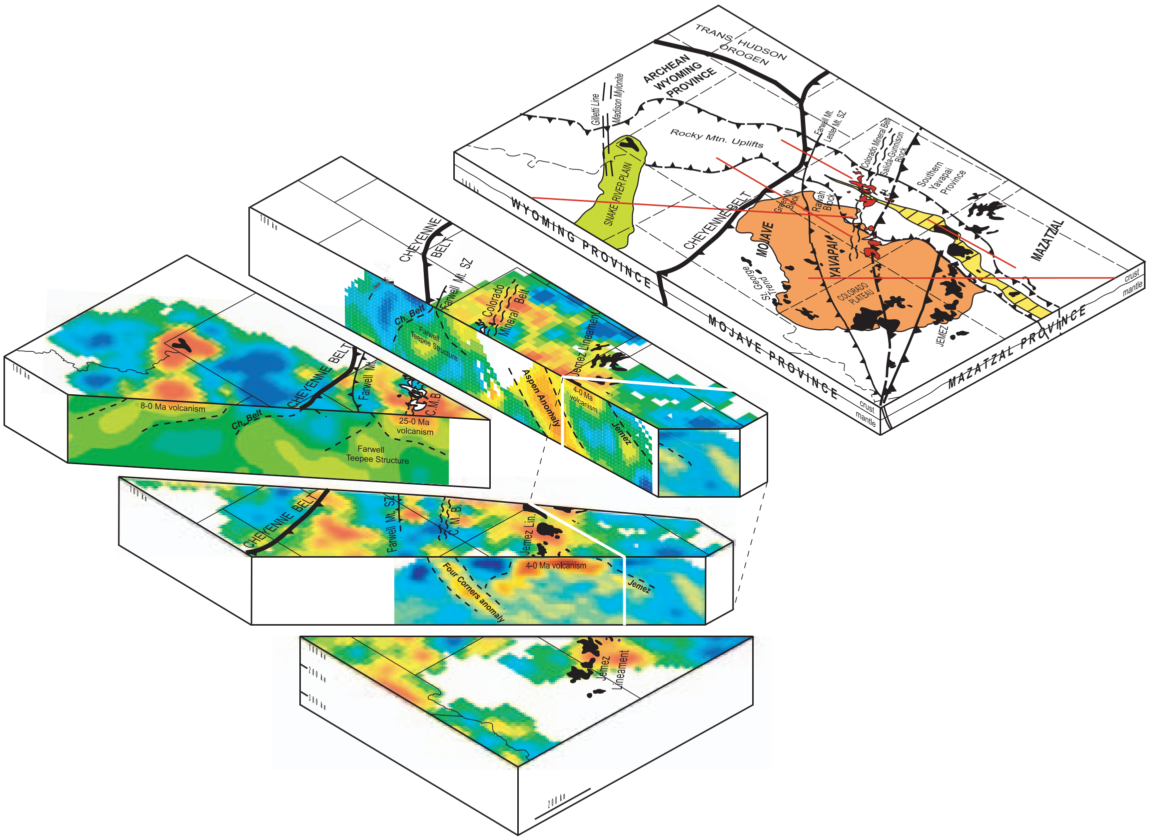
A working hypothesis is that the mantle velocity variations represent original differences in bulk composition, thickness, and state of hydration of the Proterozoic lithosphere that have been activated differently by Laramide hydration followed by Cenozoic to ongoing asthenospheric upwelling. This hypothesis views the velocity domains as zones that have different composition, fertility, and partial melt content that reflect an as-yet unresolved combination of old and young features. Figure 1 shows a block diagram that drapes surface geology on the 100 km depth tomographic image of (Dueker et al (2001) and shows the recent CD-ROM and RISTRA tomographic cross sections on the vertical faces. Based on along-strike correlations, two mantle velocity boundaries were apparently imaged by both lines: 1) The Four Corners- Aspen anomaly that appears to coincide with the Colorado Mineral belt, a Proterozoic tectonic boundary that was reactivated as a Cenozoic zone of magmatism, and 2) The Jemez lineament, which also coincides with a Proterozoic province boundary and a zone of Quaternary volcanism. The narrowness (several km), inferred tabular geometry, abrupt and profound velocity contrasts across them, south dipping geometry, correlation with Proterozoic crustal structures, and extent to the base of the crust are compatible with both zones originating as reactivated Proterozoic subduction scars that are now embedded in North American lithosphere. An alternative hypothesis is that Cenozoic magmatic reactivation, the presence of partial melt along the zones, and their depth extent to > 300-400 km could record ascent of superadiabatic mantle asthenosphere, and these features could hence be part of a small-scale active mantle convection system.

The moving deployment of US Array across the conterminous United States offers an unprecedented opportunity during the next decade for associated densification deployments of flexible array and other instruments at heretofore unapproachable scales, and in novel configurations, in areas of targeted special interest. An example is a 2-dimensional deployment/3-d imaging project in the southern Rocky Mountains that could, in association with the archived data from previous experiments, produce 3-dimensional images that resolve the true geometric complexities of these major but enigmatic mantle structures. The most ambitious possibilities would extend well beyond the capabilities of the Flexible Array alone and open the door for significant international partnerships. Pioneering seismic imaging experiments, combined with multidisciplinary geophysical and geologic studies such as this will be needed if EarthScope is to achieve its goal of providing breakthroughs in understanding the structure and evolution of the continent.

Figure on Page 163 >

Karl Karlstrom
University of New Mexico

Rick Aster
New Mexico Institute of Mining and Technology



Synergy Between Active and Passive Seismic Techniques in Integrated Studies of Lithospheric Structure

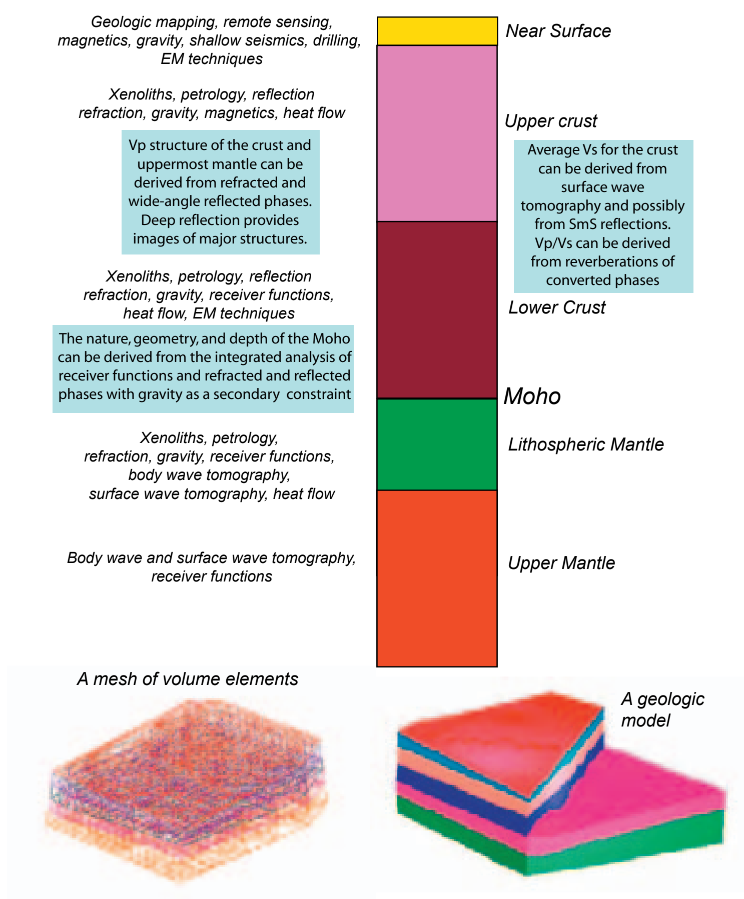
Randy Keller
University of Texas El Paso

Aaron Velasco
University of Texas El Paso

A fundamental goal of geophysical studies of the lithosphere is to characterize the 3-D structure of a region of interest in order to address key scientific questions. This could be accomplished by determining physical properties such as V_p, V_s, density, magnetic properties, electrical properties, anisotropy, attenuation (Q), temperature, etc. for volume elements that could take several forms. In addition, interfaces that represent features such as the Moho, faults, magmatic bodies, etc. must also be be mapped in order to properly characterize a region. This goal can only be achieved through a highly integrated approach that takes advantage of all of the geological and geophysical constraints available. In most cases, controlled source and passive seismology have the potential for providing the greatest resolution, but generally are the mostly costly approaches. Furthermore, many diverse techniques are available for each data type collected. Thus, developing an integration scheme for seismic results is an important first step in reaching our fundamental goal.

Each data type has its own sensitivities and resolution, and when used alone can constrain some aspects of the lithospheric structure. However, when used together with other data sets, the joint data sets have the potential for constraining fundamental aspects of the lithospheric structure. For example, controlled source experiments can yield the V_p structure, and sometimes V_s structure, of the crust and uppermost mantle with the analysis of refraction/wide-angle reflection data. In particular, analysis of the PmP phase (Moho reflection) yields a good estimate of the average V_p of the crust for the crust. Passive source experiments can constrain the V_p/V_s ratio with a receiver function analysis that utilizes full-crustal reverberation(s) from teleseismic earthquakes. Thus, a simple form of integration involves using the V_p/V_s ratio from receiver functions and the average V_p from refraction measurements, to solve for the average V_s of the crust. When refraction/ wide-angle reflection data and several receiver functions nearby are available, full 2-D models can be derived.

Potential field data can also help constrain our lithospheric models. For example, gravity data are available in most regions and, due to the approximate physical relationships between density and seismic velocity, have long belong employed as at least as a qualitative check on seismic results particularly in the lithosphere. Formal integration has been attempted in many ways over the years, but some recent 3-D approaches are ideally suited for at least joint modeling that provides better overall models of lithospheric structure. These approaches are a significant step towards mapping 3-D volumes comprehensively, and fit into an idealized integration scheme as shown in Figure 1.

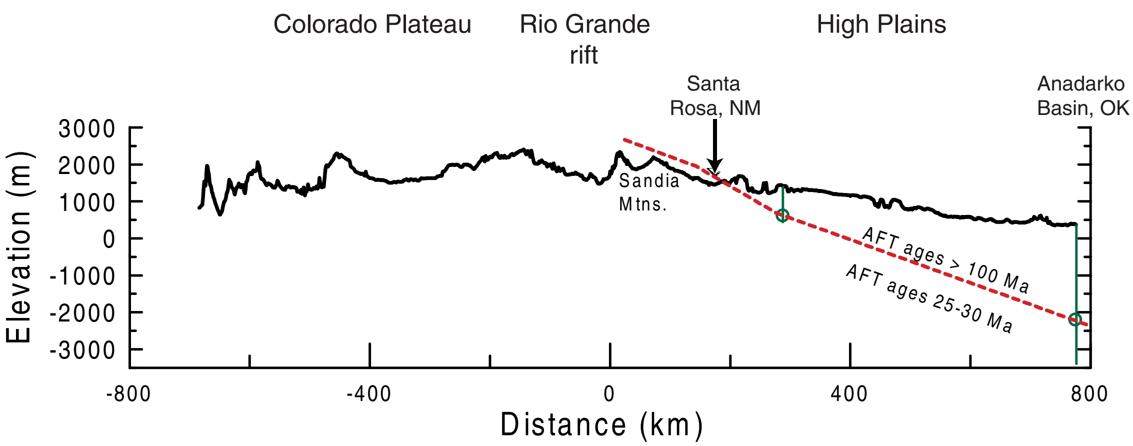


A schematic depiction of how different techniques could contribute to a highly integrated analysis. The goal is to create a 3-D model of the study area where each volume element is attributed with as many physical properties (time stamped) as possible.

Elevated Regional Heat Flow during Late Oligocene Time on the Southern High Plains

Shari Kelley
New Mexico Institute of Mining and Technology

Apatite fission-track (AFT) analysis of core samples from seven deep oil wells in Oklahoma, Texas, and northeastern New Mexico indicates that the base of a middle Cenozoic apatite partial annealing zone (PAZ) is preserved in the subsurface. The base of the PAZ, which approximately corresponds to the 110°C paleoisotherm, is at a subsurface depth of ~3000 m in the Anadarko Basin, at ~825 m at the NM-TX stateline and emerges from the subsurface, projecting into the air, near the Pecos River in eastern New Mexico. The AFT cooling age just beneath the base of the PAZ is ~27 Ma in northeastern New Mexico and ~38 Ma in the Anadarko Basin. Triassic sandstones exposed at the surface between Santa Rosa, NM, in the Pecos River valley, and Albuquerque, NM, on the eastern margin of the Rio Grande rift, yield AFT ages of 25 to 30 Ma. Thermal modeling indicates that a heat flow >84 mW/m^2 and at least 2 km of denudation prior to the deposition of the 12 to 5 Ma Ogallala Formation are needed to explain the distribution of AFT ages. A basaltic heat source at the base of the crust that extends from the eastern margin of the Colorado Plateau to a point ~100 km east of the present-day manifestation of the Rio Grande rift is required to produce the observed tilt of the PAZ. A well-crafted geophysical experiment should be able to test whether such a heat source existed.



Plot of the middle Cenozoic apatite fission-track partial annealing zone with respect to modern topography across the southern High Plains-Rio Grande rift-Colorado Plateau boundary.

Visualizing EarthScope Data for All Stakeholders

Michael Kelly
MMKAA Incorporated

Computer visualizations will be one of the most profound and instructive ways that the methods, processes, data, interpretations and results of the EarthScope experiment will reach the general public as well as the education community. While the EarthScope researcher community generally comprises spatial experts able to go from 2-dimensional data streams to 3-dimensional geologic interpretations, the other non-scientists stakeholders will need carefully crafted representations to gain a sufficient understanding. The EarthScope stakeholders as defined by the planning group EON are certainly not homogenous and include "The General Public", "Formal Educators and their Students", Informal Educators and their Audiences, Partner Organizations and Technical Specialists and other Professionals. Likewise there is a broad range of potential interactions between the stakeholders and the individual project activities that can take place between project initiation and termination. Potential computer visualizations for use in some of these predicted stakeholder-project interactions include digital images, animations and interactive simulations, and could be delivered through the web or on media. In some venues, visual content may require the use of supportive pedagogical mechanisms such as those found in electronic curriculum delivery systems such as WebCT and Blackboard. Collaborations with visualization development experts need to be planned as a regular project component and can be facilitated through existing networks such as the Association of Computing Machinery or the GeoWall Consortium.

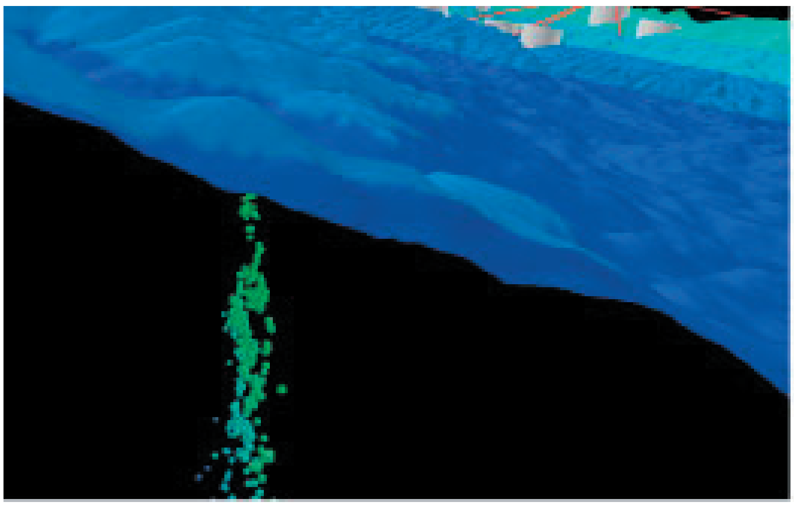
Seeing is Believing: 3D Interactive Visualization Tools That Include the Juxtaposition of Multivariate Data

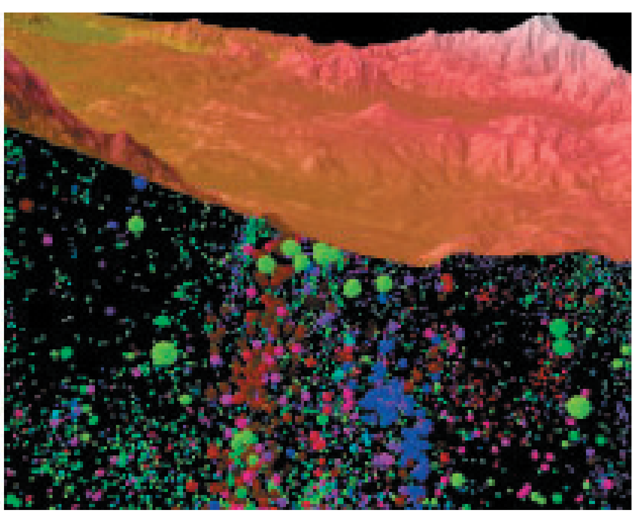
Debi Kilb
University of California San Diego

Graham Kent
University of California San Diego

Atul Nayak
University of California San Diego

If a picture speaks a thousand words, imagine what you could say with a wall-sized immersive visualization environment. At the SIO VizCenter (www.siovizcenter.ucsd.edu) we use such a system to present current seismological and geophysical research using images generated by an SGI® 3400 Onyx computer that is more powerful, by an order of magnitude in both speed and memory, than typical base systems currently used for data mining and analysis. This technology allows us to display multiple 3D data layers (e.g., seismicity, high resolution topography, seismic reflectivity, draped interferometric synthetic aperture radar (InSAR) images, etc.) simultaneously, render them in 3D stereo, and take a virtual flight through the data as dictated on the spot by the user. To extend many of these capabilities to the offices and desktops of the geoscience community, much of our focus has been on developing a library of visual objects (e.g., 3d interactive visual data that can be viewed with the freeware iView3d; http://www.ivs.unb.ca/products/iview3d/). These visual objects, which can be thought of as building blocks, form the foundation for 3D models that we archive and make available to scientists, educators and the general public via the web. Our visual objects library currently includes global seismicity, high-resolution topography and bathymetry spanning the entire Earth, data pertaining to noteworthy large earthquakes (e.g., 2004 Sumatra; 2004 Parkfield; 2003 San Simeon) as well as detailed studies of focus areas such as the San Jacinto fault zone, in southern California. We welcome suggestions on how we can help develop visualization tools and products specifically designed for EarthScope related projects.





Seismicity distribution. Contrast the knife-edge fault defined by seismicity in the Parkfield region (top) that drastically differs from the complex fault structure in Southern California (bottom). Both snapshots are from an interactive 3D interactive freeware visualization program (IVIEW3D) that is available for multiple platforms (e.g., Windows, MAC, SGI, Linux etc.).

Strategies for Estimating Coseismic Displacements with GPS: Test Cases from the Southern California Integrated GPS Network

Nancy King
U. S. Geological Survey

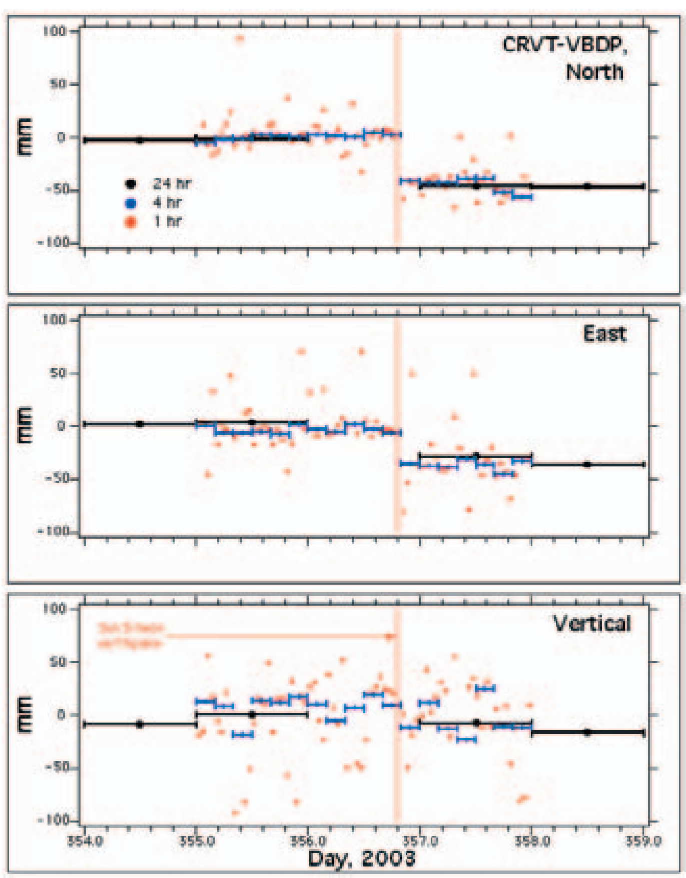
Keith Stark
Stark Consulting

Derik Barseghian
Stark Consulting

The Southern California Integrated GPS Network has detected significant coseismic displacements for three earthquakes, the M 7.1 Hector Mine earthquake of 16 October 1999, the M 6.5 San Simeon earthquake of 22 December 2003, and the M 6.0 Parkfield earthquake of 28 September 2004. In estimating coseismic displacements using data from continuously-operating GPS networks, there is a trade-off between latency and precision. The most precise methods require the best post-processed orbits and days or months of postseismic data. One approach requires time series analysis techniques to simultaneously estimate preseismic and postseismic secular trends, coseismic offset, and a postseismic transient. Such analysis requires several months of data, at least, after the earthquake. Another approach uses data from several days on either side of the earthquake. Scientists, surveyors, emergency responders, and the press require that estimates be available much more quickly, and the usual technique is to difference solutions from short time periods before and after the earthquake. Most automated processing systems produce daily solutions using 24 hours of data from the UTC day, so a good preseismic solution is usually already available. We want a good postseismic solution as quickly as possible, but it is acceptable for this initial solution to have sub-optimal precision. For near-field coseismic displacements which are on the order of tens of mm for our test cases, discrepancies of a few mm are acceptable in the preliminary solution required by the various user communities.

To quickly estimate coseismic displacements, it is necessary to quickly download sub-daily portions of postseismic data and process them with a less-than-optimal orbit. For San Simeon coseismic solutions using various orbits, mean differences between solutions are up to 10 mm for the horizontal and 20 mm for the vertical. Four-hour postseismic solutions are generally reliable, but 1-hour solutions are not. In the 1-hour San Simeon solutions, for example, there is a large outlier in the east and vertical components at the same hour of each day. This repeating pattern suggests a problem with satellite geometry or multipath, and depends on station location and environment.

Estimates of coseismic displacement can be improved within two weeks by using the most precise orbit and averaging several days of pre- and postseismic data. Unless the day before or after the earthquake is an outlier, averaging over various time intervals generally has little effect. Another complication is postseismic slip, which limits the amount of postseismic data that can be used without contaminating the estimate of coseismic displacement. Because various strategies for estimating trends, coseismic offsets, and postseismic transients may yield significantly different results, it is necessary to carefully investigate the different approaches.



USGS solutions before and after the 22 December 2003 M 6.5 San Simeon earthquake. The vertical red line shows the time of the earthquake. Black circles and bars show 24-hour solutions; there is no 24-hour solution for the day of the earthquake. Blue circles and bars show 4-hour solutions. Red circles show 1-hour solutions; several large outliers have been deleted from the east and vertical components.

SAFOD-3D: A Community Initiative for 3-D Seismic Reflection Imaging of the San Andreas Fault: Report of a Workshop at the EarthScope National Meeting

Simon Klemperer
Stanford University

John Hole
Virginia Tech

Biondo Biondi
Stanford University

Imhof Matthias
Virginia Tech

We will present a summary of the open SAFOD-3D Workshop held immediately prior to this National Meeting.

The SAFOD component of EarthScope seeks to better understand the earthquake process by drilling though the San Andreas fault to sample an earthquake in situ. If the scientific community is to capitalize fully on the opportunities presented by the unique but 1D drillhole into a complex fault zone, then we must characterize the surrounding 3D geology at a scale commensurate with the drilling observations. State-of-the-art 3D seismic-reflection imaging is necessary to provide the structural context to extrapolate 1D drilling results into the surrounding 3D volume and along the fault plane. Excellent active-source 2D and passive-source 3D seismic observations lack the detailed 3D resolution required. Only an industry-quality 3D reflection survey can provide c. 25 m subsurface sample-spacing horizontally and vertically.

A 3D reflection survey will provide subsurface structural and stratigraphic control at the 100-m level, mapping the major geologic units, their structural boundaries, and the subsurface relationships between the many faults that make up the greater fault system. In addition, a principal objective is a reflection-image (horizon-slice through the 3D volume) of the near-vertical fault plane(s) to show variations in physical properties around the drill-hole, and between SAFOD and the northern end of the Parkfield 1966 rupture zone. Without a 3D reflection image of the fault zone, we risk interpreting drilled anomalies as ubiquitous properties of the fault, or risk missing important anomalies altogether. However, such a survey should not be initiated without community involvement to ensure that such an expensive experiment is focused on the community's most important scientific issues and is designed based on the most complete information.

SAFOD-3D links the three components of EarthScope. Though physically located around SAFOD, SAFOD-3D would likely utilize the full USArray Flexible Array to collect long-offset/multi-component/broadband data in addition to that available in a typical industry survey, and SAFOD-3D will augment PBO by providing the 3D data that links the single SAFOD borehole with length scales commensurate with PBO observations, and contributing to PBO studies of fault mechanics at the plate boundary.

A workshop in advance of the EarthScope National Meeting will bring together academic and industry leaders to help evaluate the trade-offs for the community between cost, resolution and volume of the proposed data-set, and to begin to develop the full range of piggy-back experiments that could utilize the seismic sources available during a 3D experiment. A comprehensive design stage will subsequently be necessary, in which industry consultants will provide additional technical expertise on logistics of working in complex terrain and geology, industry crew capabilities, and cost. The scientific output of this project will be a community-vetted design for a community data set: a 3D reflection survey over SAFOD that is technically feasible, cost-effective, and most likely to yield the image and seismic-parameter measurements that will best constrain the physical properties of the fault zone and their spatial variation.

A New Look at Some Old Friends: A Workshop to Focus on the Greater Ancestral Rocky Mountains

Charles Kluth
Colorado School of Mines

Gerilyn Soreghan
University of Oklahoma

Randy Keller
University of Texas
El Paso

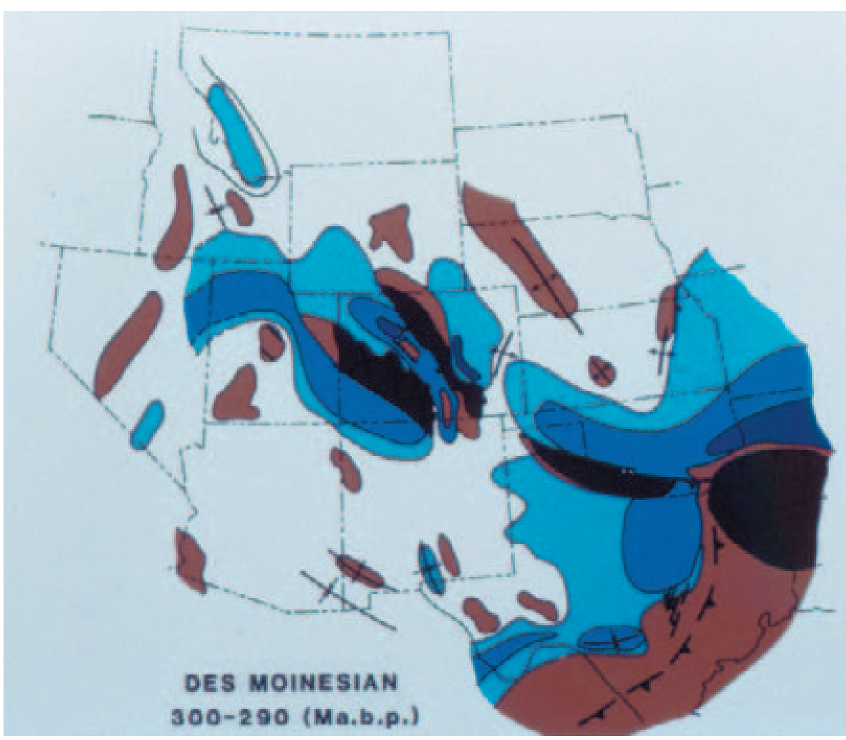
The Greater Ancestral Rocky Mountains are a region of enigmatic basement-involved uplifts and basins in the western and central North America that formed during the late Paleozoic in western Pangea. The basement block uplifts were adjacent to deep basins and formed up to 2000km from the nearest plate margin. The uplifts and basins are coeval with the assembly of Pangea, as the suture zone "zippered" close from east to west. The structures do not appear to have been highly folded, but they were internally faulted into blocks. Structural relief varies, but in some uplift-basin pairs exceeds 7 kilometers. The structural boundaries are complex; structural style sometimes changes along the strike of the boundary fault zones, and may include thrusts, high angle reverse faults and high angle normal faults. The complex geometry may represent more than one phase of deformation with differing styles. In addition, the Greater Ancestral Rocky Mountain region is located on the subducting plate of the collision that assembled Pangea, and the region is amagmatic.

Coarse arkosic sediments were eroded from the uplifts and deposited in the adjacent intermontane basins, and record the geologic events of the region. The arkosic sediments were deposited in deep water in some phases of the history of some of the basins. Other basins were dominantly fluvial. The distal clastics interfinger with shallow water marine carbonates, and the western basins in Colorado and Utah contain extensive evaporate deposits. Coal is found in some of the eastern basins in Colorado and toward the mid-continent. Glacial activity has been interpreted from some of the uplifts. There is some evidence therefore, that the uplifts had considerable topographic relief and influenced local climatic effects of the mega-monsoonal late Paleozoic subtropical climate.

A large area of the Greater Ancestral Rocky Mountains appears to have inherited its tectonic fabric from earlier, crustal structure, and provided an inhomogeneous framework for the later, Laramide Orogeny.

New data indicate that better, more detailed interpretations are possible. The correlations of regional unconformities along the western margin of North America suggest that it may be possible to correlate the unconformities through the basins of the Ancestral Rocky Mountains into the Mid-Continent. New work in Mexico suggests a revision is required in the interpretation of the southwestern margin of the orogen. Detailed stratigraphic work in the basins suggests revisions of the large-scale and small-scale interpretations of basin development may be required. The relationship of the classical Ancestral Rocky Mountain region to uplifts in the present mid-continent is becoming clearer.

We are convening a workshop, with a broad spectrum of participation, immediately following the Rocky Mountain GSA Section meeting in Grand Junction, Colorado, May 26-27, 2005. The workshop will bring the community of workers from industry, government and academia together to share and assess the current state of knowledge on several aspects of the Geology of Western Pangea.



Paleogeography of western Pangea during middle Pennsylvanian time. Brown areas are uplifts, darker browns are areas of most rapid development. Blues are basins, darker blues are areas of most rapid subsidence. New data from the western and southern margins and from the mid-continent, as well as from the classical Ancestral Rocky Mountain region, will allow improvements in our understanding and in this map interpretation.

Preliminary Analysis of Data From the PASO TRES Deployment: New Wavespeed Models and Earthquake Locations Near SAFOD

Jacqueline Krajewski
Rensselaer Polytechnic Institute

Steven Roecker
Rensselaer Polytechnic Institute

Cliff Thurber
University of Wisconsin Madison

Lee Powell
University of Wisconsin Madison

Since October 1, 2004, the PASO TRES deployment of short period seismic stations has been operating near the SAFOD Drill Site in Parkfield, CA. An initial RAMP deployment recorded about 150 events per day over a two week period. That original array was upgraded to a USArray type deployment in mid-October, and continues to record continuously at 200 sample per second. In November, we carried out a calibration experiment in which small explosives were discharged at six of our stations and recorded by the Duke University sonde in the SAFOD hole. We also recorded several larger shots that were detonated as part of an experiment performed by Li and other from the University of Southern California. We analyze this data, along with data recorded by previous deployments, to upgrade the wave speed model around the SAFOD drill site. We use this model, along with the results of the calibration study, to estimate the location capabilities of the PASO TRES network.

A Pre-PBO Strain Rate Model for the Great Basin

Corné Kreemer
University of Nevada Reno

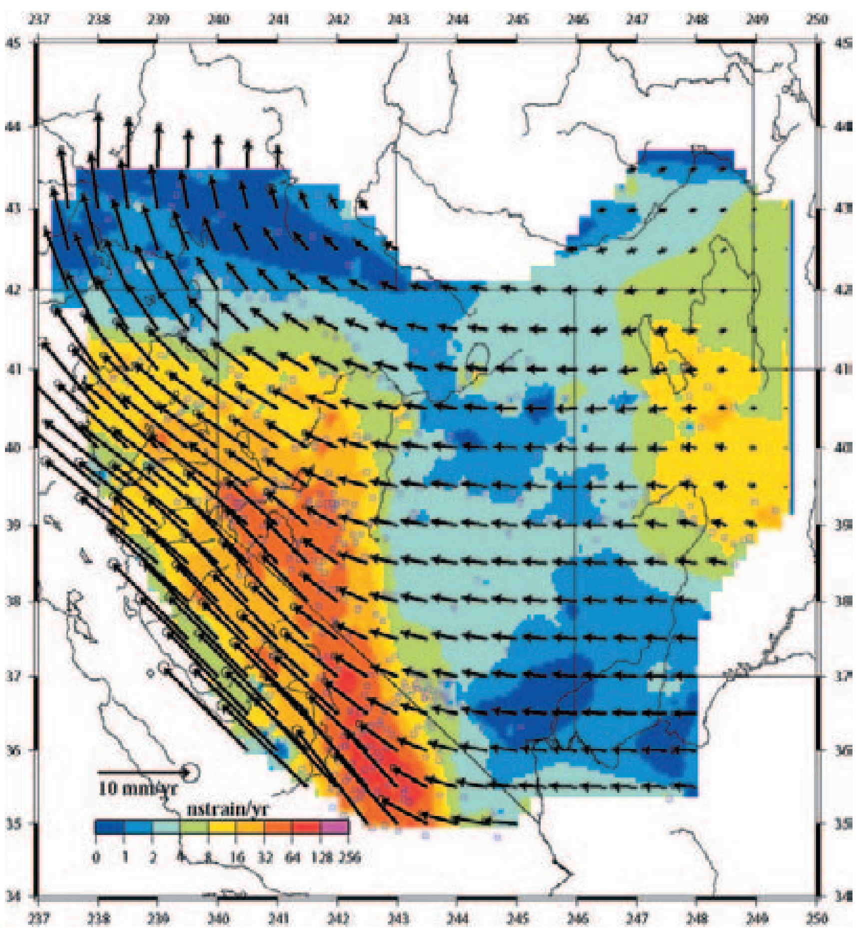
William Hammond
Nevada Bureau of University of Nevada Reno

Geoffrey Blewitt
University of Nevada Reno

The Great Basin in the western United States covers a large portion of the diffuse Pacific-North America plate boundary zone. Yet the seismic potential of its many faults, the evolution of the deformation field, and the underlying driving forces, remain largely unknown or disputed. To advance our understanding it is important to quantify the spatial distribution of the rate, style and direction of the present-day deformation field. GPS velocity estimates are uniquely suited to fulfill this objective, with many data sets now available from continuous and campaign style measurements. We use the Haines and Holt technique to present a new strain rate model that is greatly improved by use of the latest GPS solutions, which are more accurate and of higher resolution, allowing for a denser model grid. We obtained a 'master' GPS velocity solution through a reanalysis of data from the BARGEN, BARD, and PANGA networks, as well as from USGS campaigns. The uniform assessment of formal uncertainties and consistency in reference frame for this GPS solution is crucial for obtaining a reliable strain rate model, and therefore all solutions are derived from a consistent application of the GIPSY OASIS II software. Our strain rate model could serve as a starting model on which the contribution and impact of future Plate Boundary Observatory (PBO) data can be evaluated once future strain rate models based on PBO data become existent.

The release of the 2003 USGS fault database makes it possible to use geologic data (i.e., slip rate and/or fault geometry) either as an additional constraint in or as a comparison with models based on the interpolation of GPS velocities alone. The ultimate aim of this work is: 1) to compare present-day style and rate of deformation with finite strain markers and Quaternary fault slip rates in order to place constraints on the Quaternary evolution of deformation, particularly in the northern Walker Lane, 2) to identify zones of transient deformation, and 3) to improve geodynamic models. The latter will be achieved by a) comparing strain rate directions with finite strain orientations, stress directions, and gravitational potential energy gradients, and b) evaluating the dilatational strain rate budget in light of possible driving forces within the plate boundary zone.

We will show the latest results, discuss the non-uniqueness of the strain rate model, highlight the contributions PBO will make in constraining the deformation field, and discuss the challenges in the comparison and integration of the geodetic and geologic strain rates obtained from the presently available data.



Contour plot of the second invariant of the model strain rate field derived from GPS velocities observed at the locations indicated by the squares. The superimposed velocity field is the interpolated model velocity field on a regular grid. Vectors are with respect to stable N. America (which is set equal to the most eastern boundary in the model grid).

Seismic Reflection Crustal Structure and 3D Geometry of Cordilleran Metamorphic Core Complexes in Southeast and West-central Arizona

Joseph Kruger
Lamar University

Roy Johnson
University of Arizona

James Faulds
Nevada Bureau of Mines & Geology

Stephen Reynolds
Arizona State University

A grid of over 1000 km of 2-D oil industry reflection seismic data in west-central Arizona and about 120 km in southeast Arizona have been reprocessed and interpreted in order to develop a 3-D picture of crustal structures associated with Cordilleran metamorphic core complexes and highly extended terrains. Detachment faults, tilted upper plate strata, and uplifted zones of crustal reflectivity interpreted to have originated in the middle crust are imaged on these seismic lines. These reflections are correlated to detachment faults, tilted Tertiary volcanics/sediments, and mylonite zones, respectively, at the surface. Numerous sub-parallel reflections within the lower crust, which die out at the interpreted Moho, are also imaged on the seismic data.

In southeast Arizona, these reflective features are imaged beneath the Safford Basin and adjacent Pinaleño Mountains core complex (Fig. 1). These data show widespread middle and lower crustal reflectivity that is arched upward beneath the Pinaleño Mountains core complex to a depth of about 4 km (2 s) beneath the surface. The top of this reflective crust continues northeastward beneath the Safford basin into the Transition Zone along the Eagle Pass detachment fault (A and B in Fig. 1), which becomes a mylonite zone at about 15 km (5 s) beneath the Transition Zone. The mylonite zone associated with the detachment fault is responsible for the uppermost part of the reflective crust (A and B in Fig. 1), but most of the reflectivity is probably due to either widespread sub-horizontal intrusions and cumulates in the middle and lower crust, anastomosing mylonitic shear zones, partial melts or other fluids, ductile fabrics that stretch out pre-existing compositional variations, or a combination of these. Although this reflective fabric is widespread, it varies in amplitude and continuity, and in some areas is localized in layers or pods within the middle and lower crust (e.g. C, D, and E in Fig. 1), separated by areas of weaker crustal reflectivity such as the middle part of the lower crust. This suggests that intrusions, ductile processes, or other pre-existing compositional variations are not evenly spaced throughout the middle and lower crust laterally or vertically. The base of the crust is determined by 1) relatively strong reflections near the Moho that are likely due to underplating, cumulates, partial melts, or other fluids, or 2) reflectivity that dies out at the base of the crust due to lack of compositional layering below the crust (D and F in Fig. 1).

In west-central Arizona, the reflective features are particularly evident along the trend of the Buckskin-Rawhide, Harcuvar, Harquahala, and White Tank core complexes, and to the valleys southwest and northeast of them. These reflections are interpreted as being caused by similar geologic features as those responsible for crustal reflectivity in southeast Arizona. Somewhat unexpected on the west-central Arizona data though are elongated domes of crustal reflectivity interpreted beneath detachment faults that occur under the breakaway zones and detachment faults associated with the exposed core complexes, and which have breakaway zones of their own farther southwest. The reflective domes appear to be controlled by the Plomosa detachment fault and other low angle normal faults beneath it. These reflective crustal upwarps do not crop out at the surface, but have a northeastward elongated antiformal top similar to those imaged beneath exposed core complexes to the northeast. In light of their location, reflection geometry, and position beneath detachment faults, these buried upwarps are interpreted as incipient core complexes that have not experienced enough extension along the overlying detachment fault to bring mylonite zones to the surface.

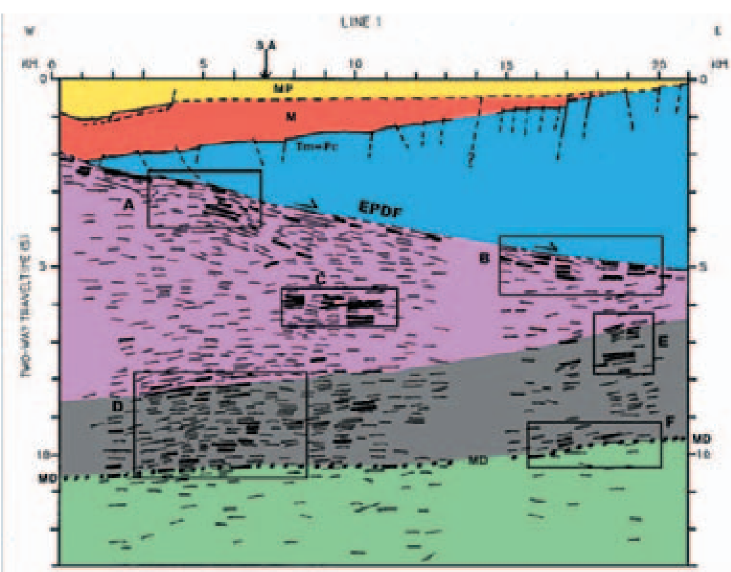


Figure 1. Line drawing interpretation of major reflections and crustal layers on a reprocessed west-east oriented oil industry reflection seismic line in southeast Arizona. The yellow layer (MP) and red layer (M) are Miocene and Miocene-Pliocene sedimentary units, respectively, separated by an unconformity beneath the Safford Basin. EPDF is the Eagle Pass detachment fault, and MD is the Moho discontinuity. The blue layer represents the part of the upper and middle Precambrian crystalline crust (Pc), including middle Tertiary volcanic, volcaniclastic, and highly indurated sedimentary rocks (Tm) lying unconformably beneath the Miocene sedimentary units, that have experienced brittle deformation. The pink layer represents the reflective middle crust that has undergone ductile to brittle deformation, and has been uplifted beneath the Pinaleño Mountains core complex to the west. The gray layer represents the lower crust and the green layer represents the upper mantle. Reflective areas A-F are referred to in the text.

NASA's Activities in Support of the Developing EarthScope Program

John LaBrecque
NASA

Craig Dobson
NASA

EarthScope is the centerpiece of US crustal dynamics research. NASA is firmly committed to the support of EarthScope and the development of Plate Boundary Observatory and InSAR - EarthScope's space geodetic and geodetic imaging components.

NASA's Restless Planet Program is developing four essential elements of the EarthScope InSAR component (1) Airborne and spaceborne InSAR observation instrumentation (3) Community organization and data systems for InSAR data distribution (2) Algorithms for the analysis of InSAR data, (4) New InSAR technology.

Progress to date in the development of the InSAR component includes:

- The development of an airborne repeat pass mini-InSAR for EarthScope applications in the 2008 time frame.
- Enhanced InSAR data access to international data sets for research purposes through the geohazards natural laboratory paradigm.
- Delivery of the SRTM InSAR data base at 30 meter resolution and other remote sensing data sets for the EarthScope region.
- Development of an interagency working group to advance the development of the InSAR component involving the USGS, NSF, and NASA.
- Several community based workshops to develop the structure and voice of the EarthScope InSAR community

Other NASA supported EarthScope development activities include:

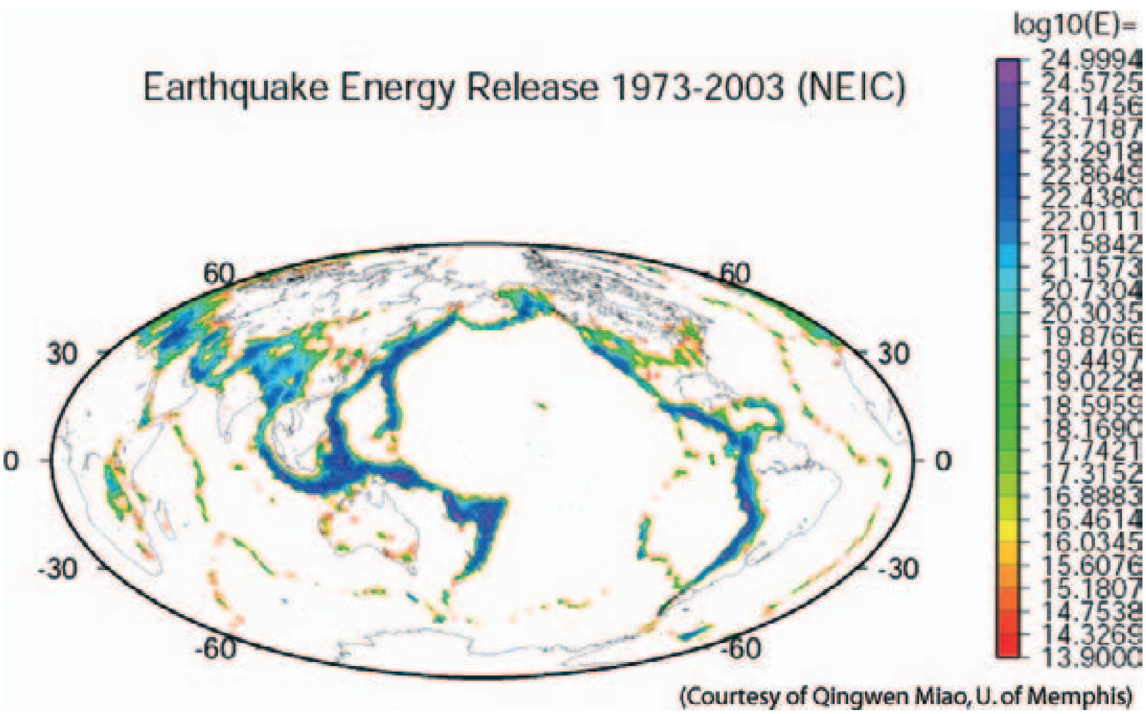
- Announcement of grant support for EarthScope related efforts in the ROSES announcement of opportunity for solid Earth in the Earth Surface and Interior Focus Area (http://nspires.nasaprs.com/external/solicitations).
- GPS technology development for PBO within the SCIGN and global networks for high value end user products and precision real time positioning.
- GIS support for the development and deployment of PBO, USArray, and SAFOD.
- Optical and geodetic imaging data sets for the EarthScope region including the lidar surveys of the northern San Andreas Fault and the Pacific Northwest and the MASTER thermal imaging data of the Southern California fault systems.

The InSAR component was designated a critical component of the EarthScope program by the National Research Council. NASA is working with its sister agencies to develop a vibrant and strong InSAR program. The significant cost of an InSAR measurement system requires the strong and sustained support of the entire EarthScope community.

The Science of Intraplate Earthquakes

Charles Langston
University of Memphis

Earth Sciences only integrative theory, plate tectonics, provides the operating scientific framework for understanding the genesis of earthquakes along plate boundaries. Time-dependent strain accumulation at the edges of the plates produces characteristic deformation that gives rise to subduction and transform fault hypotheses with further predictive physical hypotheses involving locked and slipping portions of the major faults and heterogeneous lithospheric structure. Time-dependent strain is a clear observable through GPS and VLBI geodesy but is, in itself, not fully explained by a physio-chemical theory of relative plate motions. North America is famous for its large historical intraplate earthquakes that do not seem to be related to plate tectonic processes. Although it is generally accepted that intraplate earthquakes are not fundamentally different from interplate earthquakes – they occur on faults – there is a sense that intraplate earthquakes must operate by other, unknown physical rules outside of plate tectonic theory or occur due to secondary physical processes associated with plate motion. The basis of any operating theory of intraplate earthquakes will reside in the usual physical ideas of earth sciences. Slip on intraplate faults will be due to loading of lithospheric strength heterogeneity that will, in turn, be related to material heterogeneity and geometry, and strain history. However, it may be that intraplate earthquakes are telling us something fundamental about plate tectonic processes in North America. As the accompanying figure of seismic energy release shows, central and eastern North America appears as seismically active as other divergent plate boundaries. Based on the geological history of the eastern margin, perhaps an operating plate tectonic hypothesis for intraplate events is that they indicate strain accumulation at the beginning of another Wilson cycle. EarthScope facilities can make a significant contribution towards the solution of the intraplate earthquake mystery in North America by allowing mapping of the geometry and heterogeneity of the lithosphere from fault scales to continent scale and through regional geodetic observations.



World-wide earthquake energy release from 1973 to 2003 computed using the Gutenberg magnitude-energy relation for NEIC data. Note that there is significant seismic energy release along the southern and eastern margins of North America. Perhaps these intraplate earthquakes indicate the beginning of another Wilson cycle and may be placed in a plate tectonic hypothesis to be addressed using the EarthScope facility. (Figure courtesy of Qingwen Miao, U. of Memphis)

The Increasing Costs of Natural Disasters

Richard Lease
Princeton University

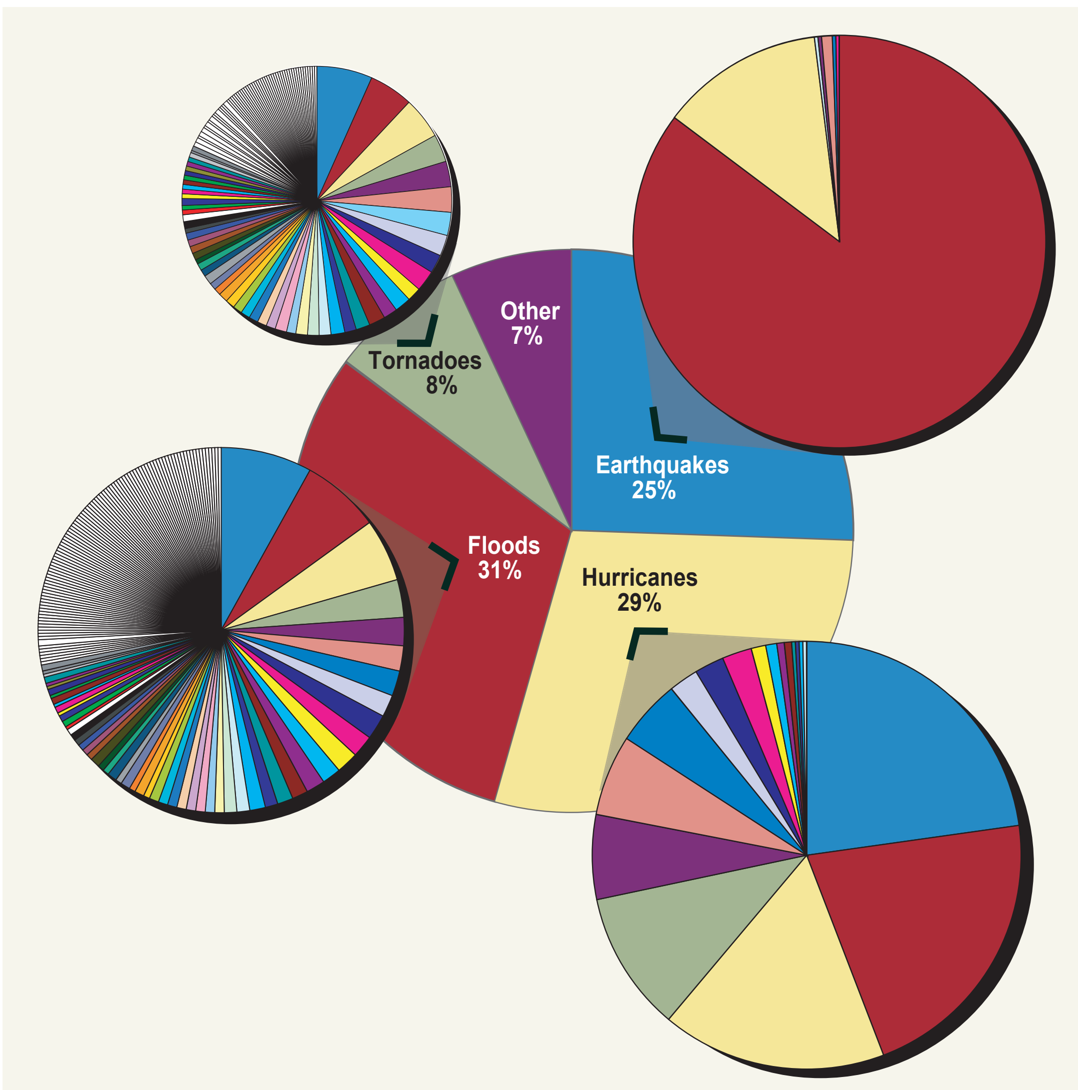
Lisa Newman-Wise
Princeton University

Margee Prat
Princeton University

Ashley Prescott
Princeton University

Despite mitigation efforts, natural disasters have an increasingly large financial impact on the United States, though neither the average size nor the frequency of events is rising significantly. A small number of disasters are responsible for the majority of costs to the federal government: the ten costliest disaster events account for nearly half of the Federal Emergency Management Agency's 1989-2004 total relief and recovery costs. Over the last four decades, FEMA spending as a percentage of GDP has more than tripled. As population and wealth densities of disaster-prone areas increase, disaster costs will continue to rise. FEMA cost is generally proportional to the population density of the disaster affected area. Though there are outliers, this is true for the most expensive earthquakes, category 3+ hurricanes, and floods, though there is no such correlation for tornadoes.

Analyzing low cost, high frequency disasters such as tornadoes and floods shows that the costliest events are those that are the most unusual in relation to the severity of the event or the preparedness of the location where it strikes. Analyzing high cost, low frequency disasters such as earthquakes and hurricanes shows that severe events (magnitude 6.5+ for earthquakes and category 3+ for hurricanes) occurring in areas of high population density (> 200 people/square mile) tend to cost FEMA the most money out of all natural disasters. Since the United States is experiencing growth in earthquake-prone California and the hurricane-prone Eastern seaboard, we can expect the relief costs of natural disasters to continue escalating.



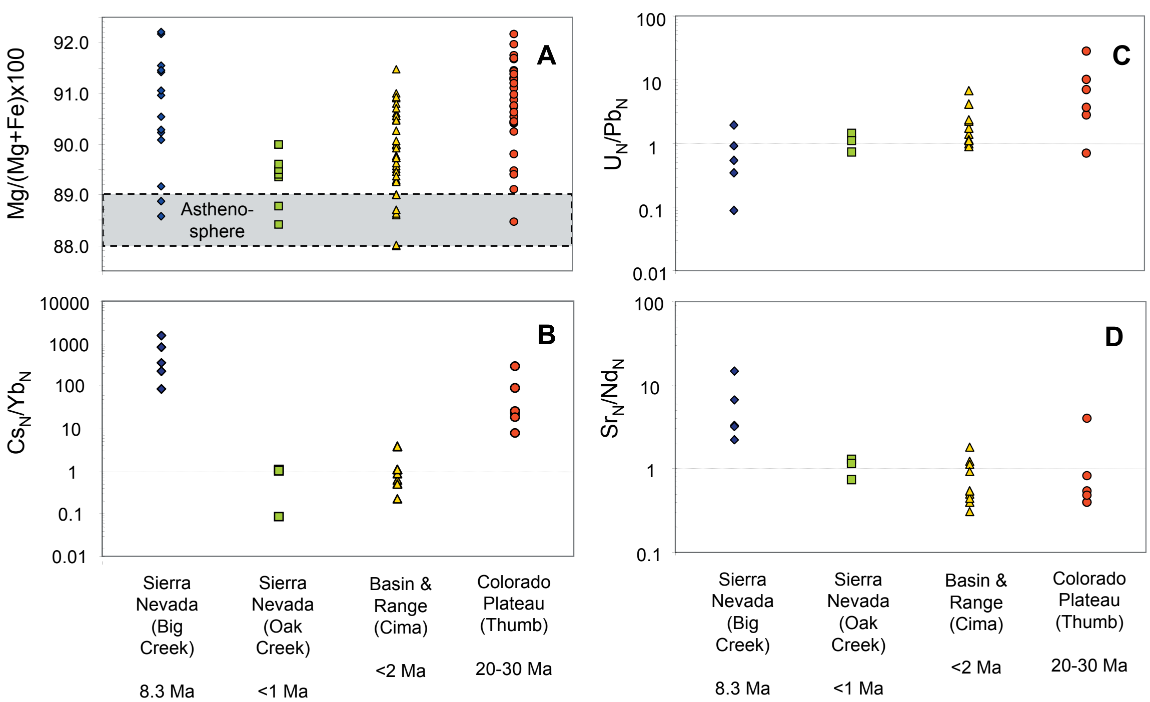
FEMA Cost Breakdown for All Disasters 1989-2004. SOURCE: Federal Emergency Management Agency

Trace-element Evidence for Hydrous Metasomatism of North American Lithosphere by the Farallon Slab

Cin-Ty Lee
Rice University

The North American Cordillera is a broad region of intracontinental deformation. The origin of diffuse orogenic belts and how deformation is internally distributed is an important question. It seems reasonable that the distribution of deformation is controlled by lateral variations in integrated lithospheric strength, which depends on the lithosphere's thermal and compositional structure. One compositional parameter that is of interest is the concentration of water in the lithospheric mantle as the presence of water decreases effective viscosity. Thus, two important objectives are to 1) determine the distribution of water in the lithospheric mantle and 2) constrain the origin of this water. Towards these ends, we are investigating the metasomatic history of lithospheric mantle beneath the North American Cordillera.

We show that pre-Miocene lithospheric mantle beneath the Sierra Nevada is highly enriched in fluid-mobile elements, such as Cs, Pb, U, and Sr, suggesting an origin almost solely from aqueous fluids derived from dehydration of altered oceanic crust. Lithospheric mantle beneath the Colorado Plateau, lying ~1000 km inboard, is also enriched in these elements. However, the extent of enrichment is lower, the U/Pb ratios are high, the Sr/Nd ratios are low, and there is a strong enrichment in the light rare-earth elements but negligible enrichment in the heavy rare-earths. Unlike the Sierran case, these features suggest that although the metasomatic component beneath the plateau involved an aqueous component, an additional component could have been partial melts of eclogitized oceanic crust, previously stripped of Pb relative to U and Sr relative to Nd by earlier dehydration in the subduction factory. The aqueous component in the plateau metasomatic agent is suggested here to have originated from dehydration of serpentinites preserved in the colder core of the subducting slab rather than from the oceanic crust itself. Fluxing of such fluids could have facilitated partial melting of the overlying eclogitized oceanic crust. These observations are consistent with the compositional evolution of fluids/melts derived from prograde metamorphism of altered oceanic lithosphere. The simplest explanation is that the base of the Cordilleran lithosphere, extending as far as the Colorado Plateau, was metasomatized by hydrous fluids derived from the shallowly subducting Farallon plate during the Laramide orogeny. Tectonic implications of these hydration processes will be discussed.



A) Mg# (Mg/(Mg+Fe)x100) in olivines from Big Creek, Oak Creek, Cima and the Colorado Plateau; B) Cs/Yb ratios normalized to primitive mantle Cs/Yb ratio. C) Primitive mantle-normalized U/Pb ratios. D) Primitive mantle-normalized Sr/Nd ratios. Shaded region in A) represents range for fertile asthenospheric mantle. Dashed lines in B-D represent nominal primitive mantle estimates.

Velocity Model from the 2004 Stanford University Seismic Experiment: A 260 km Refraction/Reflection/Teleseismic Survey in the Northwestern Basin and Range

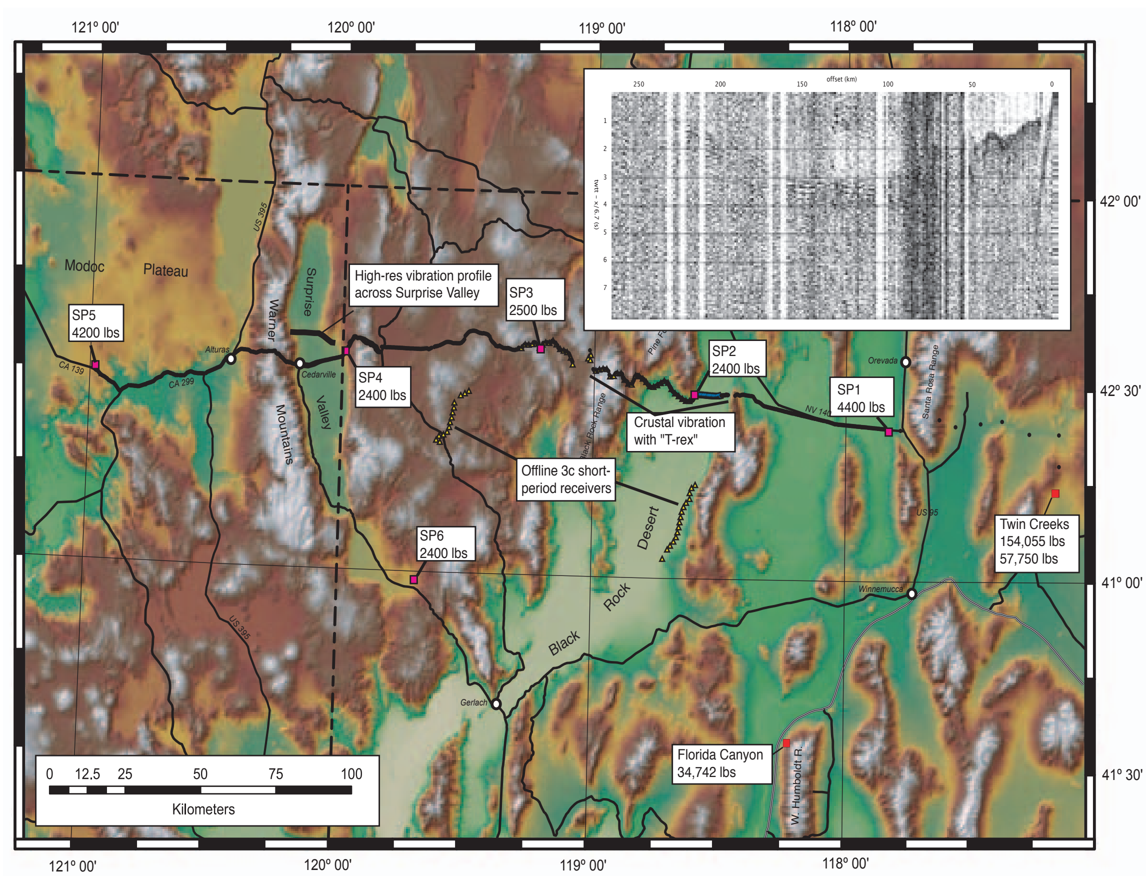
Derek Lerch
Stanford University

Simon Klemperer
Stanford University

Elizabeth Miller
Stanford University

Joseph Colgan
Stanford University

Velocity modeling results from the 2004 Stanford University seismic experiment across the northwestern Basin and Range transition zone will be presented. Our EarthScope-funded survey, a 260 km seismic refraction/reflection/teleseismic experiment, offers new constraints regarding the crustal structure of this relatively unstudied corner of the Basin and Range Province. This region was the locus of intense mid-Miocene (ca. 17-15 Ma) volcanism and subsequent high-angle extensional faulting, and is often thought to be the breakout region of the Yellowstone hotspot. Today the region is characterized by high heat flow and relatively thin crust (~30 km), with little known about the overall structure of the crust and how it relates to magmatism and extensional faulting. Our seismic experiment collected information on the crustal thickness, velocity structure, and reflectivity of this area, and consisted of 2 parts presented here: (1) A 260 km crustal refraction profile, with 5 in-line shots, one fan shot to the south, and three nearby mine-blasts, with ~1100 receivers spaced 100-300 m apart, determining crustal thickness and overall velocity structure. (2) During the deployment for the refraction experiment, we collected reflection data from both P and S-wave sweeps with the tri-axial "T-Rex" vibrator truck operated by the Network for Earthquake Engineering Simulation (NEES) and the University of Texas at Austin, assessing the capability of this vibrator in crustal-scale reflection surveys. Our 2-D velocity model indicates both lateral velocity heterogeneities and significant westward crustal thickening, providing new resolution of the northwestern Basin and Range transition zone.



Experiment configuration showing receiver locations, shotpoints, and areas of vibrator work. Inset shows reduced gather from Shotpoint 1.

Images of the Upper Mantle: A Cratonic Root, a Subducting Slab, and Basalt Extraction Structures

Alan Levander
Rice University

Fenglin Niu
Rice University

Sangwon Ham
Rice University

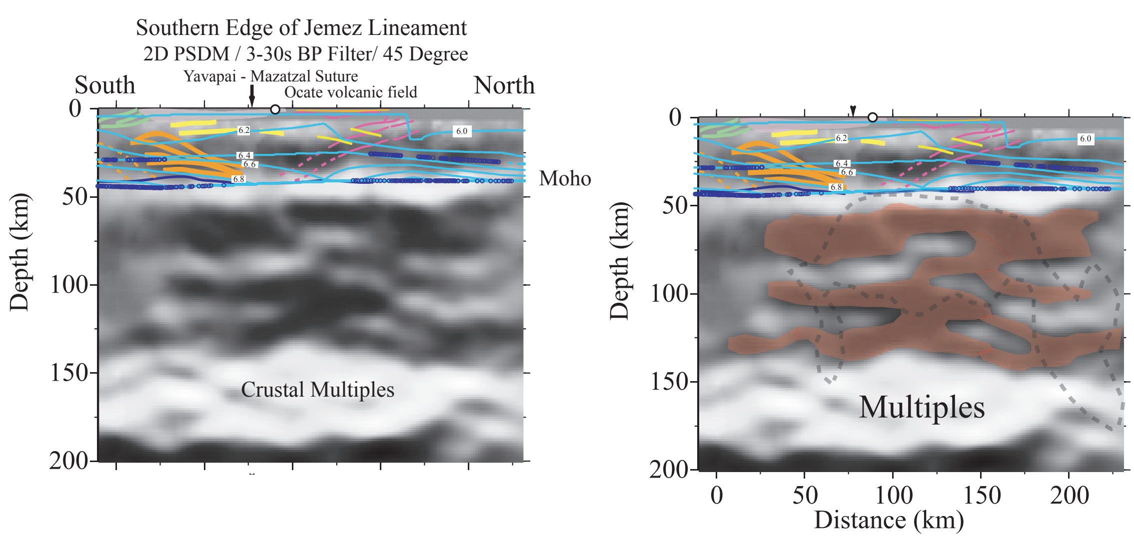
Maria Beatrice Magnani
Rice University

We present pre-stack Kirchhoff depth-migrated receiver function images of the upper mantle from the Kaapvaal craton, the Japanese subduction zone, and the Jemez lineament of the western U.S. orogenic plateau. In all three cases we have made use of local 2D tomography models for the migration velocity models.

The Kaapvaal image, made with receiver functions from 9 earthquakes recorded on the L~2000 km long array (dx~35 km), shows that the transition zone discontinuities are almost flat under the craton, and close to the global average in depth. The relative amplitudes between the 410 and the 660 in the images are in agreement with predictions from global models, as is the relative abruptness of each phase change boundary. Between the 410 discontinuity and the end of the crustal multiple reflections at ~225 km depth are a series of moderate amplitude events which extend laterally for 100's of kilometers that we interpret as being from the base of the craton. Geodynamic modeling of thrust stacking as a means of craton formation suggest similar lateral scales.

In the Japan subduction zone we have used receiver functions from 5 earthquakes recorded by more than 400 of the short-period stations of the HiNet array (dx ~ 3 km, L ~ 1200 km) to make an image of the Pacific plate subducting beneath Honshu. The image shows the dipping slab pass through the 410 discontinuity, producing the upward deflection predicted from the Clapeyron slope, and pass through the transition zone to the top of 660 discontinuity. At the base of the transition zone the slab appears to stagnate, although data coverage is poor in this vicinity. The image shows a complicated internal slab structure both in the upper mantle and in the transition zone.

The image crossing the Jemez lineament is made from 7 earthquakes recorded across one of the L~225 km CD-ROM arrays (dx ~ 15 km). The narrow aperture restricts imaging below the zone of the crustal multiples (~125 km depth). The image shows that the mantle under the Jemez lineament from the Moho to > 125 km depth consists of a series of subhorizontally-layered sill-like structures. The conversions from the sills are much stronger than and of opposite polarity to the Moho conversion. Using CD-ROM refraction data for calibration we estimate that the sills contain ~1% partial melt, and are acting as the source for recent local basalts and mafic dikes, as well as the likely cause of a geomorphically determined recent uplift.



Jemez Lineament pre-stack Kirchhoff depth migrated receiver function image made from data from 7 earthquakes shown without (left) and with (right) interpretation of the negative polarity events and the outline of the -3% S-velocity contour from the tomography. The receiver function data were bandpass filtered from 0.033-0.33 Hz, and the final image was made with dip-filtered subimages preserving scattered S-waves within 45° of the incident P-waves. The Moho is well imaged and corresponds well to the Moho determined from the CD-ROM reflection data (colored lines), refraction data (light blue contours), and wide-angle reflections (dark blue circles). The image shows large amplitude negative polarity sill like structures (solid red) that we interpret as zones of partial melt.

USArray Siting Outreach and Public Access to Data

Gayle Levy
IRIS

John Taber
IRIS

Russ Welti
IRIS

USArray Siting Outreach promotes the value to local communities of hosting a Transportable Array site, assists in finding potential sites, and provides a legacy for the local community after relocation of the Transportable Array. It will be closely linked to the broader Education and Outreach efforts to be undertaken at the EarthScope level. Siting Outreach is designed to precede and be integrated with the permitting process, creating community awareness and interest before the Transportable Array arrives. A key element is the involvement of local universities in the siting process, particularly in states where no regional seismic network exists. This will engage the wider Earth science community and will provide students with an opportunity to engage in a continental-scale scientific experiment. The universities will also help develop college and secondary school GIS-related exercises associated with learning about the process of siting. Siting Outreach activities also include creating a bi-annual newsletter to be distributed to landowners and other hosts of Transportable Array sites, and creating and updating information sheets for potential Transportable Array hosts.

The siting outreach effort implemented thus far has successfully sited Transportable Array stations in schools. Providing seismological data from the nearby Transportable Array station and associated teaching material has been successfully implemented in Washington State, and will be a model used for interacting with other schools. Data is provided via the online IRIS Data Management System, using tools developed for general audiences by University of South Carolina (Global Earthquake Explorer and Rapid Earthquake Viewer). However, Transportable Array stations are demobilized after 18-24 months, and so a legacy system consisting of inexpensive AS-1 seismometers will be left with the school. The AS-1 seismograph is a low cost seismograph capable of recording global seismicity and also demonstrating the mechanical components of a seismograph.

IRIS has found that there is a high level of interest in an engaging real-time seismology display. The Museum Lite display is a newly developed, simple to implement, and low cost way to provide real-time seismology and other information to a wide audience. The project evolved out of the online Seismic Monitor and the successful IRIS/USGS large-scale earthquake displays in use in major museums around the US. The Seismic Monitor allows for interactive or preset use for small museums, schools, visitor centers, etc, and its capabilities are very flexible. Customized implementations of the display can precede the Transportable Array to generate public interest, then provide local information while the array is in place, and finally act as part of the USArray legacy after the Transportable Array is removed.

The Museum Lite display operates on a PC and touch-screen display connected to the Internet. It provides a customizable and low cost way to provide real-time seismology and other EarthScope-related information to a wide audience.

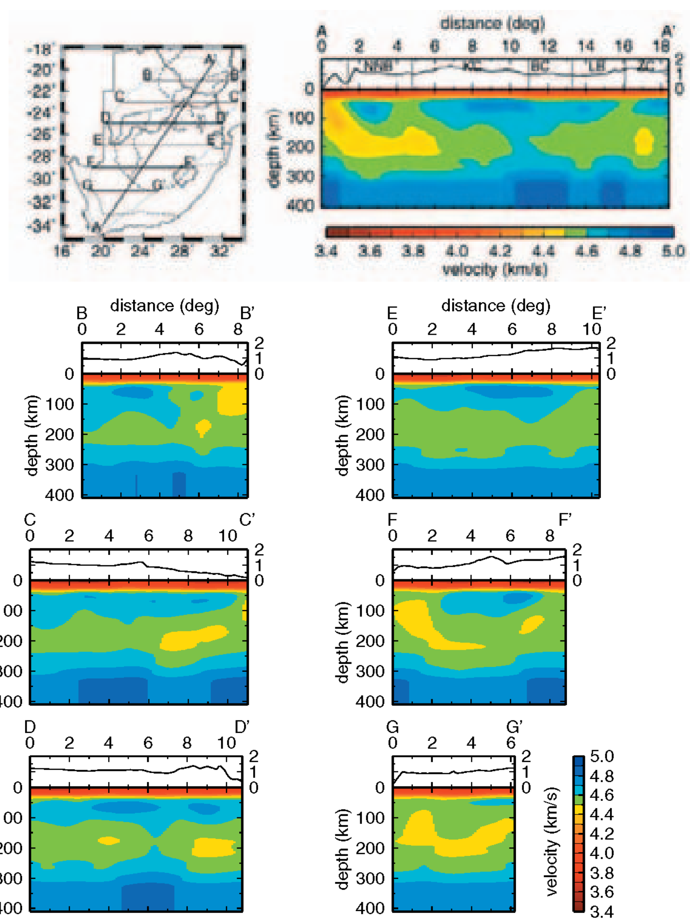
A Shallow Low Velocity Zone Beneath Old Continental Lithosphere in Southern Africa

Aibing Li
University of Houston

Kevin Burke
University of Houston/ Carnegie Institute of Washington

Southern Africa, the Archean Kaapvaal and Zimbabwe cratons and several Proterozoic mobile belts, is characterized by high average surface elevation of between 1 and 2 km. Current explanations of the high elevation in southern Africa include: (1) That it represents dynamic topography supported by upwelling and low velocities in the lower mantle (2) That is a response to hearting in the upper mantle associated with the Mesozoic Karoo and Tristan plumes and (3) That it represents a response to part of a plate-wide pattern of shallow mantle convection. 3-D seismic images may help in distinguishing among these hypotheses.

One of us (Li) has constructed 3-D shear-wave models for southern Africa from Rayleigh waves recorded at the Southern Africa Seismic Experiment (a deployment of 82 broadband seismic stations that operated from April 1997 to July 1999). A fast lithospheric lid extending to ~160 km depth has been imaged beneath the Kaapvaal craton but under the Zimbabwe craton and the Limpopo and Namaqua mobile belts the corresponding fast lid is only about 100 km thick. Relatively low shear wave velocities have been found in the Cape-Fold belt, and at the tectonic boundaries between the Namaqua belt and the Kaapvaal craton as well as between the Limpopo belt and the Zimbabwe craton. For a first time a low shear wave velocity layer has been observed beneath the high velocity lid of southern Africa in three dimensions. The slowness and thickness of this low velocity layer vary from ~2% and ~100 km beneath the Kaapvaal craton to ~4% and ~150 km beneath the Limpopo and Namaqua mobile belts. Complex morphology at the base of the lithosphere and at the base of the low velocity layer is consistent with the idea of active small-scale, vigorous convection in the upper mantle beneath southern Africa. Cratonic lithosphere may have been eroded. If the low velocities reflect from high temperatures the average 3% velocity reduction corresponds to a roughly 1% density reduction that would support a ~1 km elevation of the surface. In summary, Rayleigh wave tomography models indicate that the high elevation in southern Africa is dominantly associated with heating in the upper mantle that might be related to shallow convection and/or Mesozoic plume eruptions but cannot rule out contributions to southern Africa's dynamic topography from the deep mantle.



Shear-wave velocity profiles across southern Africa constrained from Rayleigh wave data recorded at the Southern Africa Seismic Experiment. The locations of the profiles are shown in the top-left diagram.

Spatio-temporal Characterization of Damaged Zone on the San Andreas Fault Near the SAFOD Drilling Site, Parkfield from Fault-zone Trapped Waves

Yong-Gang Li
University of Southern California

John Vidale
University of California Los Angeles

We deployed dense linear seismic arrays of 45 PASSCAL RT130 three-component seismometers across and along the San Andreas fault (SAF) near the SAFOD drilling site in the fall of 2003 to record fault-zone trapped waves (FZTW) generated by local earthquakes and explosions detonated by the USGS in Hole/Ryberg's refraction profiling. The FZTW data have been used to characterize the low-velocity structure on the SAF to seismogenic depths [Li et al., 2004]. Immediately after the 2004 September 28 M6 Parkfield earthquake, we installed dense seismic arrays of 45 RT130s across and along the SAF near the town of Parkfield, co-sited with our previous experiment in 2002, to record FZTW generated by aftershocks. The array site was located in the middle of a high-slip part of the surface rupture in this earthquake. We recorded ~1000 aftershocks in three months. Locations of aftershocks indicate that the fault zone near-vertically across seismogenic depths to ~12 km. During the experiment, we detonated two 300-pound explosions within the fault zone; one shot at Middle Mountain was co-located at the shot-hole site in 2002. We observed prominent FZTW with large amplitudes and long-duration wavetrains after S-waves for events located within or close to the fault zone. The dominant frequencies of FZTW are 2-4 Hz for shots and 4-6 Hz for earthquakes. Observations and 3-D finite-difference simulations of FZTW show an ~150-m wide low-velocity waveguide along the SAF, in which seismic velocities are reduced by 30-45% from the wall-rock velocities and Q values are 10-50. The data from on-fault events occurring at different depths and with small epicentral distances from the array show that the duration of FZTW wavetrains after S-waves increases from 1 to 2 s as the focal depth increases from 3 to 10 km progressively, indicating that the low-velocity waveguide on the SAF extends across seismogenic depths likely to 10 km, although the waveguide on the deeper fault zone shows smaller velocity reduction and narrower width due to the larger confined stress at greater depths. We interpret that the distinguished low-velocity waveguide on the principle slip plane delineated by FZTW is a intensely fractured zone due to major earthquakes, brecciation, liquid-saturation and possibly high pore-fluid pressure near the fault. We also find some seismic trapped energy partitioning in the branch faults, which may connect the main strand at depth and experienced minor damage due to strong shaking during earthquakes on the main fault.

The waveform cross-correlations of P, S, and trapped waves recorded at the same stations for the repeated shots show several percentage decrease in seismic velocities within the fault zone between the fall of 2002 and December 2004, most likely due to the coseismic damage of fault-zone rocks during the 2004 September 28 M6 Parkfield earthquake. However, seismic velocities recovered with time after the mainshock. Waveform cross-correlations of identical aftershocks recorded at our array shows ~1% increase in velocity within the rupture zone in the early stage after this earthquake, indicating that the fault is healing and regaining the strength due to the closure of cracks in the damaged zone with time. The observed co-seismic and post-seismic variations in seismic velocity on the SAF at Parkfield is consistent with the conceptual model of damage and healing progression presumed from our previous FZTW study on rupture zones at Landers and Hector Mine [Li et al., 1998; 2003; Vidale and Li, 2003]. We find that the healing rate decreases with time in earthquake interval, but may also depend on the magnitude of slip, stress drop, pore-pressure and rock types.

Figures on Page 183 >

Yong-Gang Li
University of Southern California

John Vidale
University of California Los Angeles

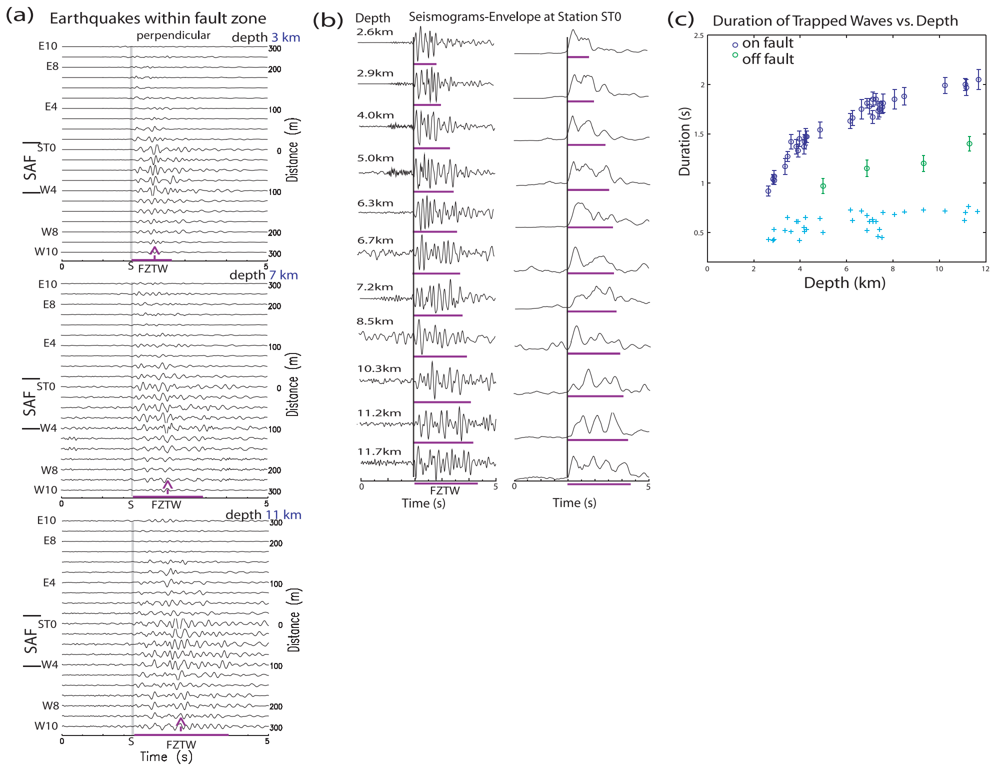


Fig. 1 (a) Horizontal-component seismograms at across-fault Array 2003 for 3 microearth earthquakes at different depths within the San Andreas fault near the SAFOD drilling site at Parkfield, Seismograms have been <5 Hz filtered. Fault-zone trapped waves (FZTW) appear at stations between E2 and W4, indicating that the width of low-velocity waveguide on the SAF near Parkfield is ~150 m. Vertical lines are alinged with S arrivals. The duration of trapped wavetrains (denoted bybars) following S waves increases with event depths. Arrows denote the maximum amplitudes of FZTW at dominant frequency. (b) Raw seismograms and envelopes at station ST0 of Array 2003 located on the SAF trace for 13 on-fault earthquakes occurring at depths between 2.6 km and 11.7 km show increase in the length of trapped wavetrains after S waves, indicating that the low-velocity waveguide on the SAF extends across seismogenic depths. (c) Measurements of the time duration of FZTW wavetrains versus depth for 37 on-fault quakes with epicentral distances from the array smaller than 3 km. The data show the long wavetrains at stations close to the fault (dark blue circles), but short wave trains at stations far away from the fault (light blue circles). Each data point is an average of measurements at 5 stations. Error bar is the standard diviation of measurements for each data point. The data from 4 away-fault events show shorter wavetrains after S waves at all stations (green circles).

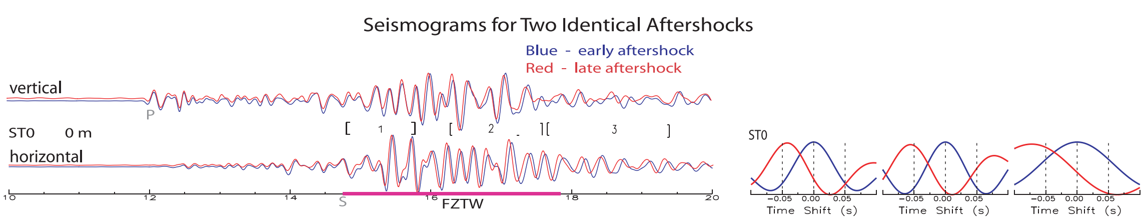


Fig.2 left: Vertical-and parallel-fault component seismograms recorded at station ST0 of Array 2004 across the San Andreas fault near the town of Parkfield for two identical aftershocks occurring at the same location within the fault zone at 6 km depth and about 10 km northwest of the array. The early aftershock (blue line) and the late aftershock (red line) occurred one week and one month after the September 28 mainshock. Seismograms have < 6Hz filetered and are plotted in trace-normalized. Fault-zone trapped waves (FZTW) appeared clearly after S arrivals. P arrivals for these two events are aligned at the same time. S and trapped waves advanced for the late aftershock, showing the shear velocity within the rupture zone increased between one week and one month after the mainshock, indicating the post-earthquake fault healing. right: Auto-correlation (blue line) and cross-correlation (red line) between seismograms for the two events in 3 time time windows, including S, and early and late parts of trapped waves, show traveltime advances for the late aftershock. The peak auto-correlation curve is at zero lag time in each window. The negtive time shift of cross-correlation indicates time advance.

The 2004-2005 Eruption of Mount St. Helens, WA

Michael Lisowski
U.S. Geological Survey

Michael Poland
U.S. Geological Survey

Daniel Dzurisin
U.S. Geological Survey

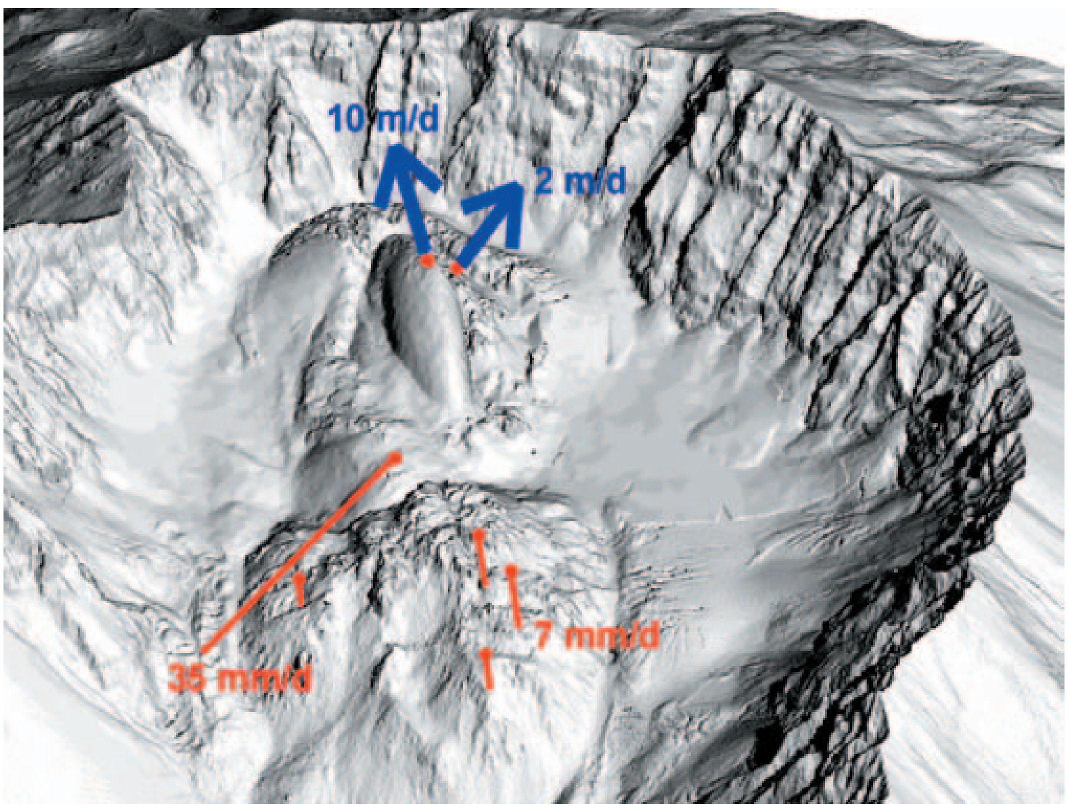
Richard LaHusen
U.S. Geological Survey

Mount St. Helens is one of three Cascade volcanoes targeted for PBO magmatic systems instrument clusters. UNAVCO conducted site reconnaissance and initial contacts with USFS land managers during the spring and summer 2004. The volcano, however, does not wait for permits. A small, shallow earthquake swarm on September 23, 2004, signaled the start of the current episode of unrest. The number and size of shallow earthquakes increased dramatically before a series of phreatic explosions on October 1 to 5. Extrusion of a new lava dome at a rate of ~10 m^3/s began a few days later and has continued to the present. The growth of the dome is accompanied by several small earthquakes per minute and occasional ash emissions. The total volume of the new dome, deformed crater floor, and deformed glacier ice was about 40 million m^3 in mid-February, 2005.

No apparent anomalous deformation preceded the unrest, and little ground deformation has occurred outside of the crater during the eruption. The USGS surveyed a 50-station GPS network in 2000 and 2003 and found no significant deformation around Mount St. Helens, except for slow subsidence of the old lava dome. No anomalous change occurred before the eruption at a continuous dual-frequency GPS station (JRO1 - 8.3 km to the north) nor at a continuous L1 GPS (SOFO - 3.5 km to the west). Recovery of many campaign GPS stations on the flanks of the volcano in late September and early October showed surprisingly little ground deformation during the first few weeks of the eruption. The continuous GPS station JRO1 moved 1 cm towards the crater between September 23 and October 5, suggesting volume loss at depth, and it has moved an additional 1 cm through February.

UNAVCO and USGS installed a monitoring network of 10 continuous GPS stations by mid-October, 2004. UNAVCO added two far-field PBO GPS stations in November, 2004 and two edifice PBO GPS stations in January, 2005. A systematic pattern of deformation is not yet apparent from analysis of the continuous GPS data. One station high on the SE flank of the volcano moved 4 cm SE between mid-November 2004 and January 2005, likely due to impingement of the new lava dome against the SE crater wall. InSAR results have shown no significant surface displacements before or during the eruption.

To monitor deformation within the crater, the USGS used a helicopter to sling expendable L1 GPS and seismic instrument packages (nicknamed “spyders”) on or near the growing lava dome. As illustrated in the accompanying figure, the surface of the growing dome moved at rates of several m/day while those on the old dome were relatively stable (cm/day). Together with time-lapse photography, these measurements demonstrate that the velocity of lava extrusion declined slowly between November 2004 and February 2005.



Comparison of L1 GPS station velocities during December, 2004, on growing lava dome (blue) and old dome (red) within the crater of Mount St. Helens.

What is a "Good" Model? A Comparison of Regularization Methods with Examples Using InSAR Data

Rowena Lohman
Woods Hole Oceanographic Institution

Mark Simons
California Institute of Technolog

We compare three different regularization techniques applied to the problem of inversions of geodetic data for fault slip: Spatial smoothing, minimum moment and spatial compactness. Each regularization method defines what constitutes a "simple" model in a different way, creating inversions that balance the fit to the data vs. solution simplicity. Each inversion method results in different best-fitting models and model covariance matrices. We compare the inferred slip distributions and resulting coulomb stress changes for the 1995 M_w 8.1 Antofagasta, Chile, and 2003 M_w 8.1 Tokachi-Oki, Japan, subduction zone earthquakes, using InSAR and GPS data.

Towards a Geophysical Investigation of Rio Grande Rift Extension

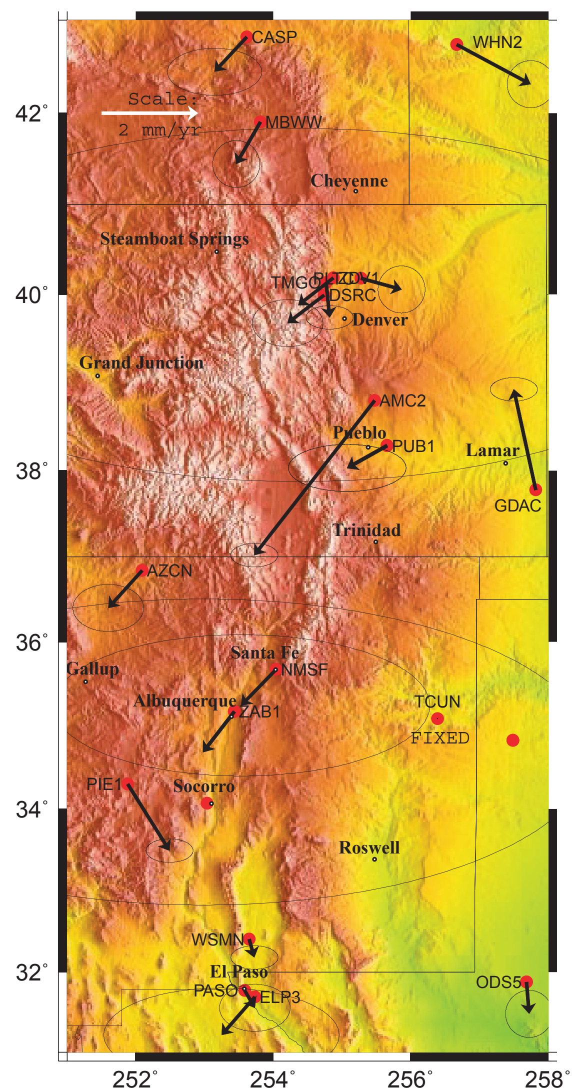
Anthony Lowry
University of Colorado

Anne Sheehan
University of Colorado

Mousumi Roy
University of New Mexico

Steve Nerem
University of Colorado

The Rio Grande rift is perhaps the most important actively deforming province in the western United States to be left off the list of Plate Boundary Observatory focus deployments. Geological data and existing continuous CORS network GPS sites suggest extension of about 1 mm/yr with tantalizing evidence for an additional few mm/yr of left-lateral strike slip. However, uncertainties in these data are large and, while the PBO backbone sites will improve the picture, the combined existing and proposed sites are far too sparsely distributed to address questions regarding the dynamics and mechanisms of extension. We suggest that a focused deployment of quasi-continuous, quasi-campaign GPS sites could address some of these questions in a cost-effective manner. This presentation will review what we already know about the rift, including the range of hypothetical mechanisms for rifting, and assess what kinds of geodetic information will be needed to achieve a better understanding. It will also discuss monumentation and occupation strategies for minimizing cost, as well as the technical and other advances that must be made in order to achieve high accuracy estimates of GPS velocity in low-strain-rate locales such as the Rio Grande rift.



Velocities of Continuously Operating Reference Station (CORS) permanent GPS sites relative to station TCUN (Tucumcari, NM), for the period 1994-2003. Error ellipses represent 95% formal uncertainties of the solution, scaled by a factor of 10. Although spatial sampling is poor and the monumentation is not optimal for tectonic studies, the data suggest ~1 mm/yr of extension and ~1 mm/yr sinistral strike slip across the Rio Grande rift. Answering questions about the width and processes of rifting posed by ambiguous seismic, gravity and topographic constraints will require a denser network of accurate measurements than will be provided by PBO backbone sites.

InSAR Studies of Alaskan Volcanoes

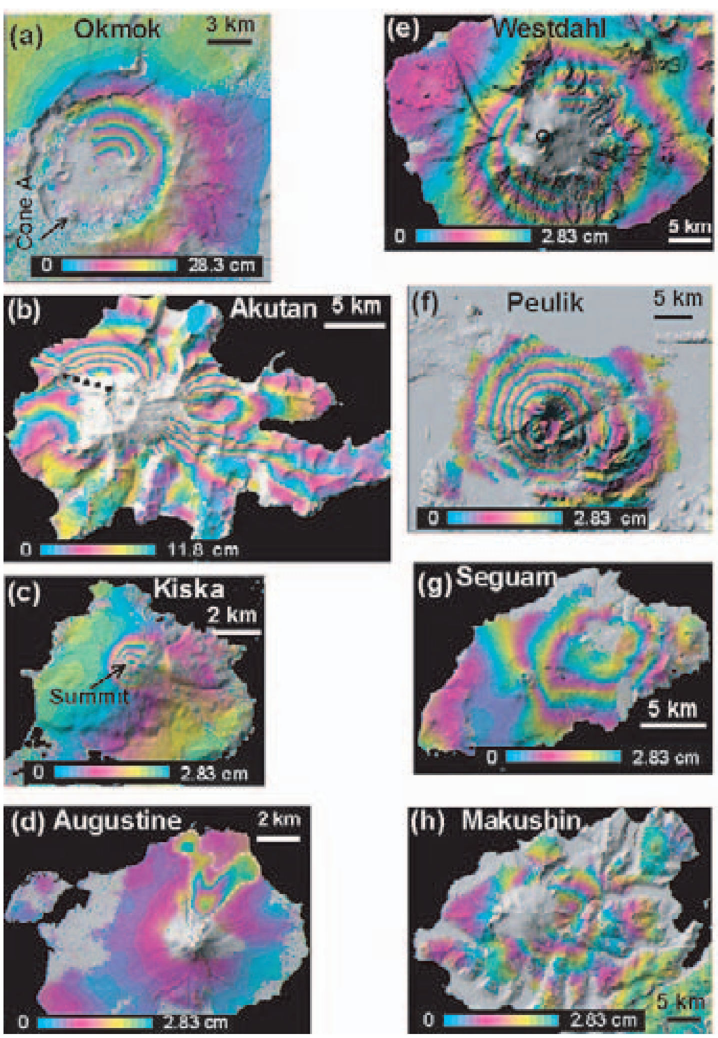
Zhong Lu
U.S. Geological Survey

Chuck Wicks
U.S. Geological Survey

Dan Dzurisin
U.S. Geological Survey

John Power
U.S. Geological Survey

Interferometric synthetic aperture radar (InSAR) is capable of measuring ground-surface deformation with centimeter to subcentimeter precision and spatial resolution of tens-of-meters over a relatively large region. With its global coverage and all-weather imaging capability, InSAR has been an important measurement technique for constraining magma dynamics of volcanoes along the Aleutian islands. The spatial distribution of surface deformation data, derived from InSAR images, enables the construction of detailed mechanical models to enhance the study of magmatic and tectonic processes. This paper highlights our recent InSAR studies of Alaskan volcanoes, associated with both eruptive and non-eruptive activity: the pre-eruption inflation, co-eruption deflation, and post-eruption inflation at Okmok volcano; magmatic intrusion and the associated tectonic stress release at Akutan volcano; progressive aseismic inflation of Westdahl volcano; magmatic intrusion at Mount Peulik volcano and its relation to an earthquake swarm 30 km away; magmatic intrusion at Makushin volcano associated with a small eruption in 1995; complex patterns of transient deformation during and after the 1992-1993 eruption at Seguam volcano; surface subsidence caused by decrease in pore fluid pressure in an active hydrothermal system beneath Kiska volcano; compaction of young pyroclastic flow deposits at Augustine volcano; persistent volcano-wide subsidence at Aniakchak volcano; and a lack of expected deformation associated with recent eruptions at Shishaldin, Pavlof, Cleveland and Korovin volcanoes. The InSAR results are derived from a broad spectrum of volcanism over the Aleutians, and can provide guidance for the development of EarthScope instrumentation. Integrating InSAR results with continuous GPS measurements from PBO will enhance our understanding on how the Aleutian volcanoes work.



InSAR deformation images of selected volcanoes in Alaska. (a) Deformation interferogram (Oct. 1995 – Sep. 1997), bracketing the Feb. – Apr. 1997 eruption of Okmok volcano, shows the volcano deflated more than 1.4 m due to magma withdrawal. The location of the 1997 vent, Cone A, is labeled. (b) Deformation interferogram of Akutan volcano, spanning the March 1996 seismic swarm, shows uplift of more than 60 cm on the western part of the island and subsidence of similar magnitude on the eastern part of the island. The dashed line represents a zone of ground cracks created during the 1996 seismic swarm. (c) Deformation interferogram for Kiska volcano shows subsidence of the volcano summit during Aug. 1999 and Aug. 2000. (d) Interferogram (1992-1993) of Augustine volcano depicts the subsidence associated with the compaction of the 1986 pyroclastic flow deposits outlined by the white dashed line. (e) An InSAR image (1993-1998) shows aseismic inflation of Westdahl volcano. The circle represents the horizontal position of the shallow magma reservoir beneath the Westdahl Peak. (f) Interferogram (Oct. 1996 – Oct. 1997) shows about 17 cm of uplift of Peulik volcano. The aseismic inflation occurred before the May 1998 earthquake swarm about 30 km northwest of the volcano. (g) Interferogram of Makushin volcano shows about 7 cm inflation associated with a possible eruption in Jan. 1995. (h) Interferogram of Seguam volcano shows uplift of the island from Jul. 1999 to Sep. 2000. All these interferograms are draped over the DEM shaded relief images and areas without interferometric coherence are uncolored.

InSAR Time Series Analysis of Surface Deformation for the Metropolitan Los Angeles and San Francisco, California Areas

Paul Lundgren
Jet Propulsion Laboratory

Riccardo Lanari
IREA-CNR

Mariarosaria Manzo
IREA-CNR

Francesco Casu
IREA-CNR

The Los Angeles and San Francisco, California, metropolitan areas are tectonically active regions with surface deformations that are a combination of fault related tectonics plus a variety of natural and anthropogenic signals, most notably aquifer changes and oil extraction. We produce interferometric SAR (InSAR) time series analyses for these areas for 1993 into 2002 and determine space-time maps of surface deformation at each ERS epoch for which we have data. The results are space-time deformation products that can be exploited to view not only the mean or smoothly varying long-term surface motion, but also its time varying patterns (Fig. 1, top). Large seasonal oscillations of the Santa Ana aquifer observed in Southern California Integrated GPS Network (SCIGN) data are accurately matched in the InSAR time series, moreover, correlations of the InSAR time series with an annual sinusoid reveals amplitude and delay-time patterns that reflect the dynamics of the hydrologic system (Fig. 1, bottom). Similar patterns can be found for the San Francisco area. We will explore these features and their implications for detecting earthquake related transient deformation. Future work will encompass significant areas of that are the focus of EarthScope.

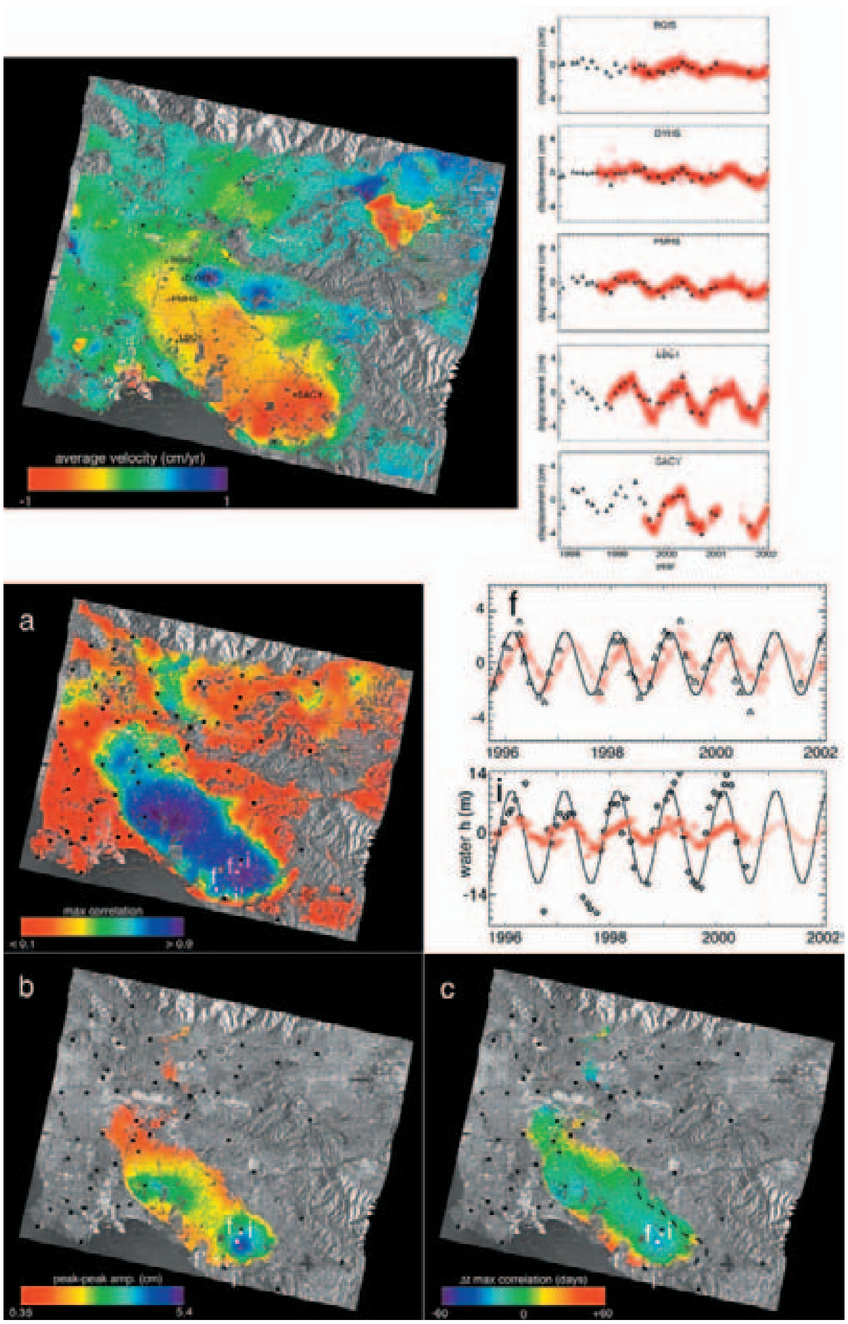


Figure 1: (Top panels) On the left, average surface velocities of ground in the satellite line-of-sight (LOS). Right, comparison of InSAR (black diamonds) and SCIGN GPS (projected into LOS direction, red), times series. (Bottom four panels) Correlation of InSAR time series with an annual sinusoid peaking in the first half of the year (a), the amplitude (b), and phase delay relative to March 10 (c), of points where the correlation in (a) is greater than 0.6. Point time series examples at points f, f' (black and red, respectively), and nearby well height data (l, l').

Dating Sinter Deposits in Dixie Valley, Nevada: A Record of Hot Spring-Fault Interaction in the Great Basin

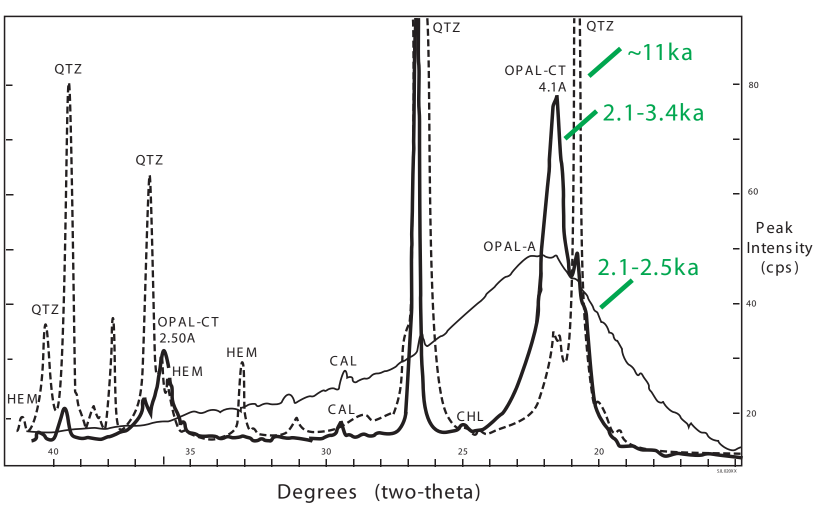
Susan Lutz
University of Utah

S. John Caskey
San Francisco State University

The Dixie Valley geothermal field occurs in an area known as the “Stillwater seismic gap”, a 45 km-long section of the Dixie Valley fault that lies between the 1915 (M_s 7.7) Pleasant Valley and 1954 (Ms 6.8) Dixie Valley fault rupture zones to the north and south, respectively. Fossil hot spring deposits are exposed at the Stillwater range front just south of the producing geothermal field, at the northern extent of a late Holocene rupture zone along the Dixie Valley fault. These deposits are composed of both travertine and siliceous sinter that have trapped pollen and other organic materials during their formation. Radiocarbon dates on the organic material indicate that the youngest hot spring deposits in the Section 10/15 sinter area are between 3.4 and 2.5 ka. Clasts of quartz sinter in diatomite at the Dixie Comstock hot-spring gold mine yielded a 14C age of 10,722 +/- 70 years BP, approximately coeval with pluvial Lake Dixie that filled Dixie Valley at 11-12 ka. The mineralogy and texture of the siliceous sinters are consistent with their age. The youngest deposit consists of hyaline “geyserite” that likely formed from actively spouting eruptions of boiling fluids along the fault zone at about 2.5 ka. X-ray diffraction analyses (Fig. 1) indicate that the sinter is composed of original opal-A which has not undergone the transition to the more crystalline opal-CT or cristobalite (opal-C). Slightly older (2.2 to 3.4 ka) sinters appear to be admixtures of opal-CT, and microcrystalline quartz. Sinter clasts at the Dixie Comstock mine have completely transformed to quartz. The process of maturation or “aging” of the sinter (the transformation from juvenile opal-A to crystalline quartz) appears to occur within 11,000 years.

There are three parts of the geyserite-sinter deposit: the upper geyserite, steeply-dipping outflow channels that mantle the range front, and a shallowly-dipping apron terrace where the sinter is interbedded with marsh deposits at the base of the slope. The lower sinter terrace is broken by a fault that has vertically displaced the footwall from the hanging wall by about 3 meters. Radiocarbon dating of sinter samples from both sides of the fault yielded ages of about 2.5 ka, indicating a maximum age for the surface-rupturing earthquake. Trench studies previously bracketed the age of the earthquake (“The Gap” M_w7 event) between 3.7 and 2.0 ka (Caskey, 2002). This portion of the Dixie Valley fault, just a few kms southwest of the producing geothermal field, appears to have been actively discharging geothermal fluids until about 2.5 ka when fault rupture and associated stress changes related to The Gap earthquake effectively put an end to the hot spring activity. The 3.4-2.5 ka spring activity may have been related to a period of increasing tectonic stress and fracture dilatancy preceding The Gap event.

Steam now emanates from the fault zone and small fumaroles occur locally along The Gap surface rupture. The transition from hot spring activity before the earthquake to fumarole activity after the earthquake suggests deeper boiling at a lowered water table within the fault zone, and fluid pressure reduction and stress drop as a result of the surface rupture (Caskey and Wesnousky, 2000). The present-day stress regime based on borehole studies in nearby well 66-21 (Hickman et al., 1997; Barton et al., 1998), indicate that fractures and faults near the well are not critically stressed for frictional failure. Even though the faults and fractures in well 66-21 were found to be optimally oriented for normal faulting, a high ratio of Shmin to Sv appears to have a great effect on the fracture permeability in this nonproductive well. The observed sequence of hot spring and faulting activity at Dixie Valley is consistent with modern earthquake theory and fracturing dynamics in normal fault zones (Sibson, 1986; Parry and Bruhn, 1990; Bruhn et al, 1994) which predict a period of dilatancy before frictional failure and earthquake rupture. This period of dilatancy may to relate to periods of high permeability and hot spring activity along the Dixie Valley fault. The episodic nature of the hot spring activity is revealed by the range of ages of the thermal spring deposits in the area, as well as the variation in silica mineralogies and maturation.



X-ray diffraction (XRD) patterns of three sinter samples, illustrating characteristic silica mineralogies and the general age of each deposit based on radiocarbon dating. The thin black line is the XRD pattern of a young geyserite sample that is composed of noncrystalline opal-A with traces of calcite (CAL). The thick black line represents a sinter sample that contains paracrystalline opal-CT, crystalline quartz (QTZ), and traces of chlorite (CHL) and calcite (CAL). A stratigraphically lower sinter terrace (dashed line) is predominantly composed of crystalline quartz with minor amounts of opal-CT and hematite (HEM).

EarthScope and National Park Service – Partners in Education and Outreach

Linda Lutz-Ryan
National Park Service

Judy Geniac
National Park Service

Phil Zichterman
National Park Service

EarthScope (ES) and the National Park Service (NPS) have been working together since the summer of 2002 to find ways to make the general public, educators, and other scientists aware of this remarkable geological experiment. Though changes have occurred in the education/outreach community of ES, the NPS in the Intermountain Region has endeavored to supply continuous support to the program.

As instrumentation is placed in parks it would be very helpful for scientists and the parks to have access to a predetermined selection of venues and educational materials, that would best tell the story of the science that is being done for ES and the individual parks. It is essential that NPS and ES have a coordinated message and identity. In order for that to occur planning documents for proposal writing and educational/interpretive media should be in place to help guide both parks and scientists.

Scientists who are seeking funding from ES are well acquainted with proposal writing and what the benefits of their work will be to the scientific community. Over the last 80 years the NPS has developed best practices for planning and designing educational/interpretive media for the general public and the educational community. Many times scientists do not have this expertise or the time to develop materials to be used by the general public or the educational community. Each unit of the National Park System has a division devoted to the interpretation of natural and cultural resources for the general public. Many also work directly with local schools to develop curricula based programs. In August of 2003, scientists from ES and rangers from the NPS met to develop a long-range plan for education and outreach. Though much has changed in ES since the development of that plan, the core ideas are still valid and being reshaped to apply to the current structure of the ES education and outreach program.

Millions of people visit national parks in the west each year. In September, 2003 the Social Science Program of the NPS compiled data that had been gathered over a number of years and produced a report titled “Visitor Use and Evaluation of Interpretive Media.” That report found 54% of park visitors surveyed between 1997 and 1999 used visitor center exhibits. In 2004 roughly 266,000,000 people visited a national park. Of those approximately 77,000,000 went into a park visitor center (roughly 30%). Through the use of simple publications and more complex media, such as kiosks with 3D modeling, ES can reach these same millions with their message. Flagstaff parks have used their design expertise to develop an exhibit prototype for ES. It is presently being displayed in the Sunset Crater National Park visitor center. This exhibit could be adapted for use in a number of visitor centers throughout the region. These kinds of exhibits could also be modified for community centers, schools, or other venues that ES proposes to have as partners.

NPS education programs reached 3,587,000 students throughout the nation in FY2004. With distance learning scientists and parks can directly communicate with even more students during the next decade. As ES education outreach proceeds, the NPS will be able to provide a direct connection to educational communities that they already serve.

Computational Infrastructure for Geophysical Simulations – Building an EarthScope Community Modeling Environment

Philip Maechling
University of Southern California

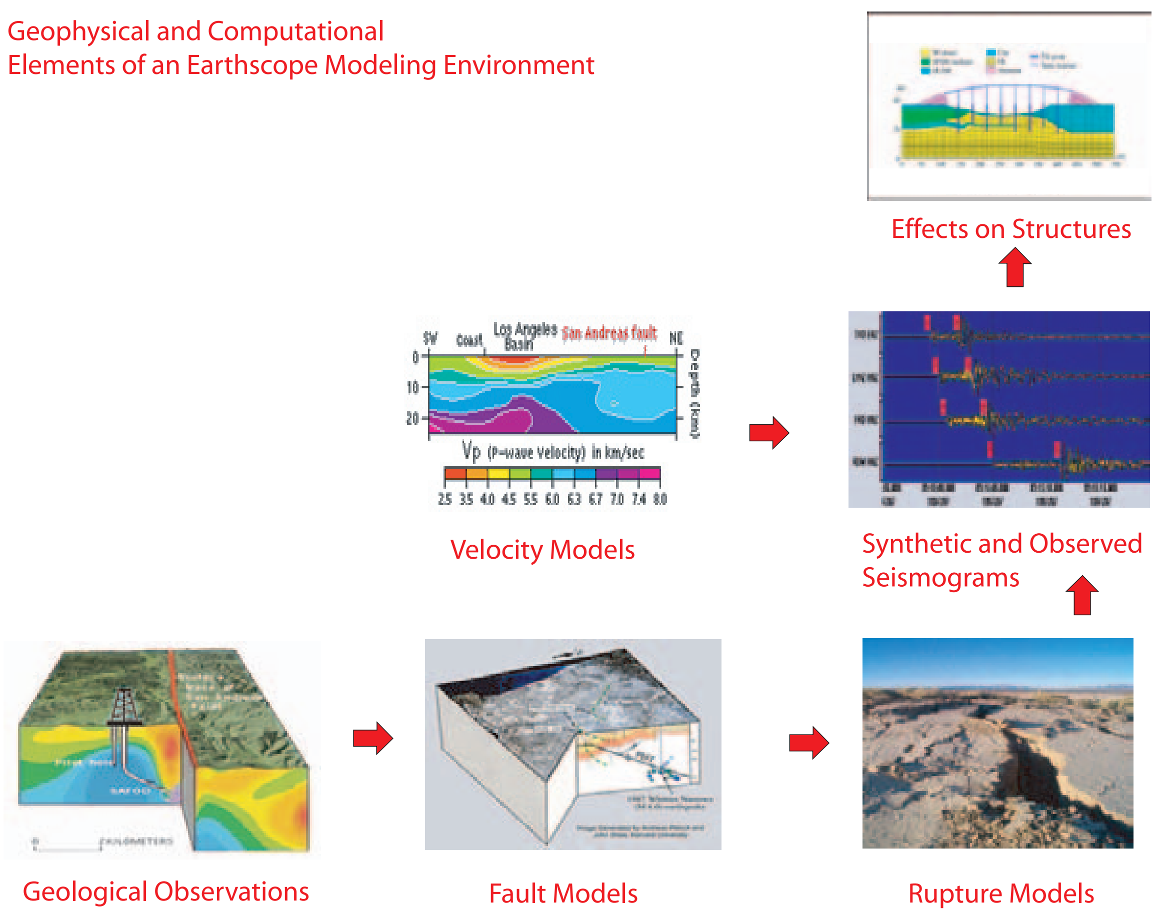
Thomas Jordan
University of Southern California

Bernard Minster
Scripps Institution of Oceanography

We anticipate that the analysis, application, and synthesis of EarthScope seismic, geodetic, and geological data will lead to the development of high-level data products such regional or national 3D velocity models, mantle tomography models, and crustal motion models. These models can then be used as parameters in further geophysical products such as empirically-derived attenuation relationships, scenario ShakeMaps, probabilistic seismic hazard analysis, earthquake wave propagation simulations, and other socially relevant geophysical information.

The computational infrastructure needed to run geophysical simulations using geophysical models is significantly different than the existing EarthScope data acquisition infrastructure. The computational infrastructure for running geophysical simulations is likely to include grid computing software for sharing computing and storage resources, digital library tools for maintaining large, file-based data collections and associated metadata, and a library of well-verified and validated geophysical simulation software.

The Southern California Earthquake Center has developed a Community Modeling Environment for Southern California-oriented earthquake research. The SCEC Community Modeling Environment (SCEC/CME) is an integrated geophysical simulation modeling framework that automates the process of selecting, configuring, and executing models of earthquake systems. The SCEC/CME integrates SCEC geophysical models with geophysical simulation software to allow scientists to perform a wide variety of geophysical simulations. The SCEC/CME utilizes grid-based workflow tools to facilitate running a sequence of processing steps. It also utilizes digital library tools to facilitate the data and metadata management issues associated with archiving the results of many large simulations. The computational infrastructure and the geophysical simulation capabilities of the SCEC/CME may be a useful prototype for a future EarthScope Community Modeling Environment.



A computational infrastructure for performing geophysical simulations will help to develop socially relevant data products from the EarthScope data.

Seismic and Geomorphic Evidences for Rejuvenation of Topography in the Southern Rocky Mountains

Maria Beatrice Magnani
Rice University

Frank Pazzaglia
Lehigh University

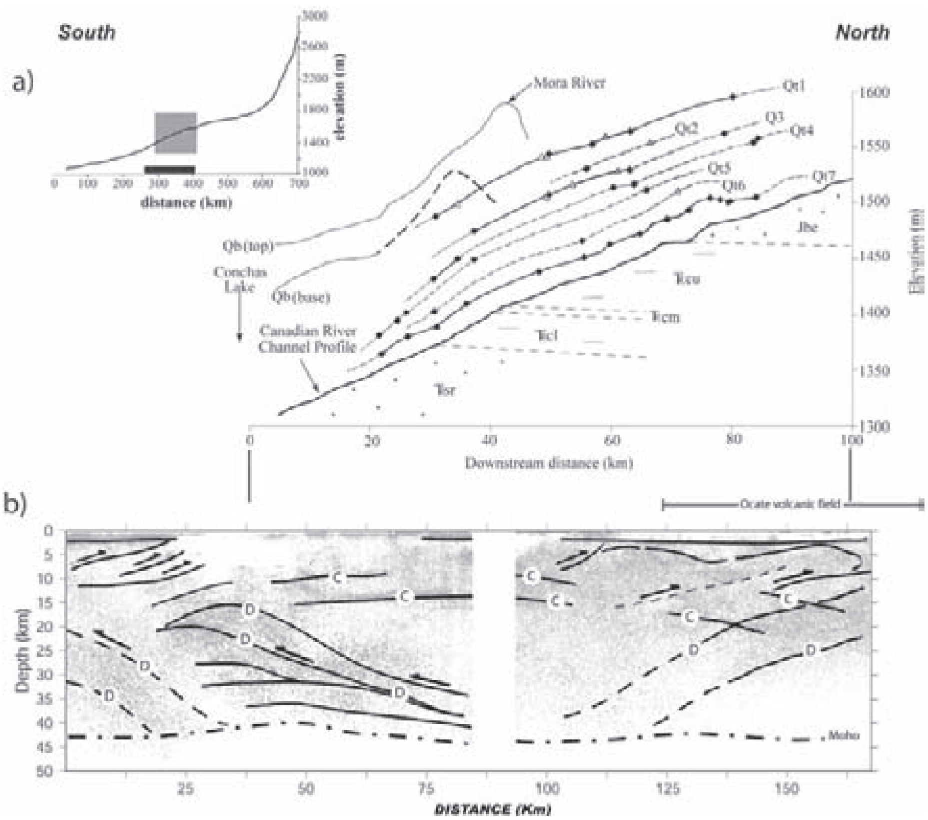
Alan Levander
Rice University

Mousumi Roy
University of New Mexico

We merge the diverse approaches of seismology, geomorphology and geodynamics to argue for a mantle driven Tertiary uplift of the Southern Rocky Mountains in western North America. We use two different bandwidth seismic probes to determine the crust and the mantle geometry, geomorphology to estimate modern uplift, and geodynamics to model the influence of mantle thermal properties on surface uplift.

The cause of the high elevations of this area, part of one of Earth's great orogenic plateaus, are still a matter of debate because neither the timing nor the causes driving the uplift are clear. Unlike most of the orogenic belts we study today, the Rocky Mountains appear to deviate from the normal topographic decay that usually follows the end of the compressional phases of mountain building that is consistent with the consumption of the low-density root. Subsequent to the Laramide orogeny, only part of the North American Orogenic Plateau experienced orogenic collapse, and today, ~50 Ma afterward, the Rocky Mountains, the inboard edge of the plateau, show no evidence of subsiding. In fact the entire region currently appears to be slowly uplifting.

Our results suggest that Neogene tectonics and ancient lithospheric heterogeneities preserved in the crust and in the mantle are controlling the uplift in this region and that the modern topography is responding to processes taking place in the mantle as shown by the rates and the distribution of rivers incision. Based on geophysical and geomorphologic observations we suggest that such processes variably affect the lithosphere of the Southern Rocky Mountains due to heterogeneities inherited from Proterozoic continental assembly that continue to influence present-day landscape evolution.



a) Vertically exaggerated longitudinal profile of the Canadian River and its terraces (Qb, Qt1-Qt7) on a straight line stretching 100 km upstream from Conchas Lake, across the Canadian Escarpment, parallel to the Canadian River valley and the seismic reflection line. Inset map shows 700 km of the Canadian River long profile from its headwaters in the Sangre de Cristo Mountains across the Canadian Escarpment (gray box) and out onto the High Plains of New Mexico and Texas. The dark narrow rectangle shows the projected location of the reflection profile onto this long profile. Rock type symbols below the Canadian River long profile are Trsu = Santa Rosa Sandstone, Trcl = lower formation of the Chinle Group, Trcm = middle formation of the Chinle Group, Trcu = upper member of the Chinle Group, Jbe = Bells Ranch – Entrada Formation. (b) Depth migrated seismic reflection profile across the Jemez lineament. The N-S 170 km long profile shows a complex crustal architecture characterized by oppositely dipping reflectors (D) overprinted by subhorizontal high amplitude seismic events (C). Reflections D define a Paleoproterozoic bivergent suture between the Mazatzal and the Yavapai provinces. The suture provided a pathway for the Neogene mafic sills (reflectors C) to penetrate the crust and reach the surface along the volcanic centers that make up the Jemez lineament (Magnani et al., 2004).

Secure Earth: A National Cross-cutting Initiative for the Geosciences

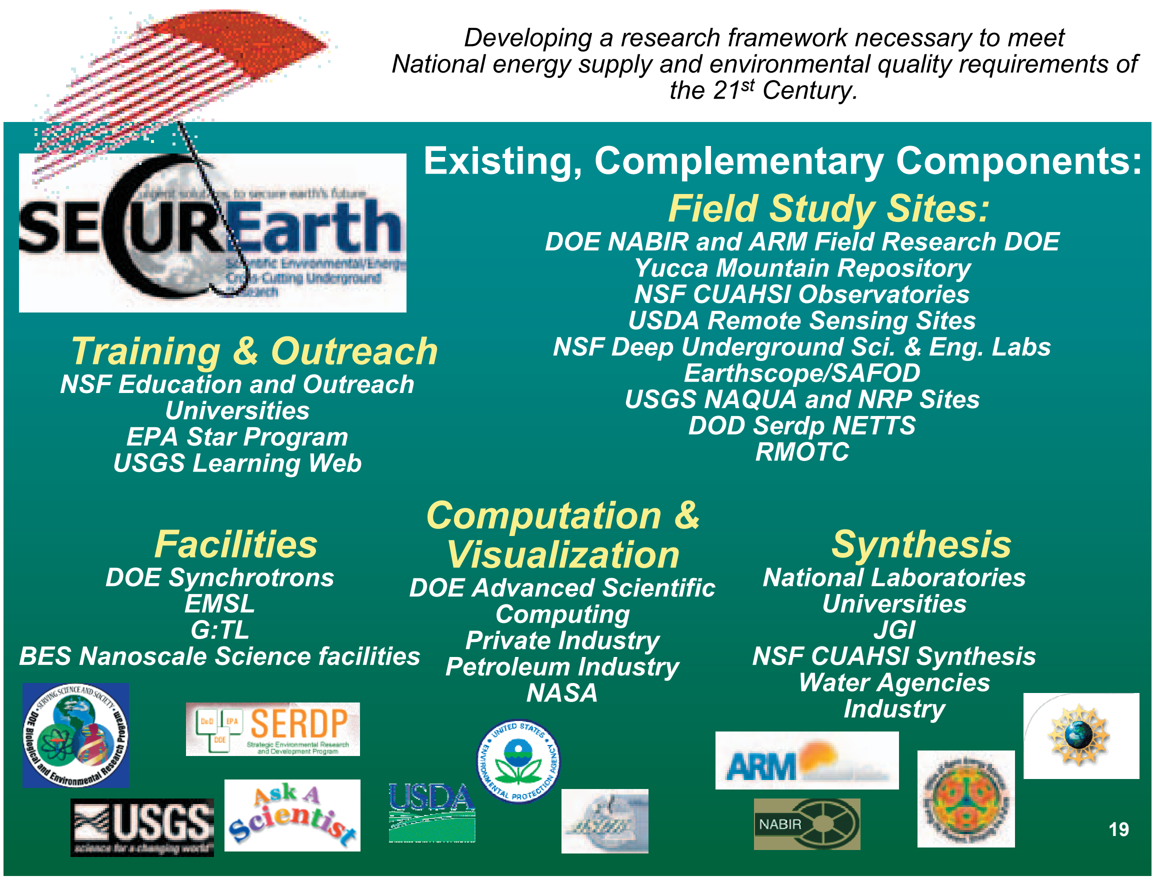
Ernest Majer
Lawrence Berkeley National Laboratory

Bo Bodvarsson
Lawrence Berkeley National Laboratory

Rick Colwell
INL

Phil Long
Pacific Northwest National Laboratory

Presented will be a description of a large new initiative for the geoscience community addressing Scientific Environmental/Energy Cross-Cutting Underground Research in the Earth, or SECUREarth. An outline of the initiative was presented to a diverse group of funding agencies at a National Research Council workshop in July of 2004 in Washington D.C. and is in the formative stage. The motivation is based on the premise that the current pace of geoscience research will not meet our energy and environmental needs in a timely fashion to prevent severe societal impacts, i.e., optimizing energy extraction (conventional as well as alternative), sequestering CO^2, disposing of nuclear waste, providing cost-effective environmental remediation, and protecting our water supply. We envision that the SECUREarth effort will build a large but focused research activity to integrate and augment existing research programs and facilities at universities, labs and industry to overcome key geoscience related environmental and energy roadblocks. Because subsurface imaging and process monitoring will be a corner stone of the initiative it is envisioned that such efforts and facilities as EarthScope will play a central role in the effort. In the next year a science plan will be developed by involving a wide segment of the geoscience community. It is anticipated that upon completion it will be submitted for review by the National Academy of Sciences as part of a larger review the earth sciences currently being planned.



An example of the anticipated links to existing programs and facilities.

High-resolution 3D Anisotropic Structure of the North American Upper Mantle from Inversion of Body and Surface Waveform Data

Federica Marone
University of California Berkeley

Barbara Romanowicz
University of California Berkeley

Seismic anisotropy is not only required to correctly interpret 3D tomographic models at least down to 400 km, but is also a very powerful tool for gaining insight into paleo and recent deformation processes and therefore mantle dynamics. Hence, the investigation of seismic anisotropy is important for addressing unresolved geophysical questions such as the nature and strength of lithosphere/asthenosphere coupling, the depth extent of continental sub-regions and the relation of imaged seismic anisotropy to present-day asthenospheric flow and/or past tectonic events recorded in the lithosphere.

To date, our knowledge of the North American anisotropic structure arises mainly from global tomographic models or *SKS* splitting studies which lack horizontal and vertical resolution respectively, and are limited to either radial or azimuthal anisotropy. Our goal is a high resolution model for the North American upper mantle incorporating both radial and azimuthal anisotropy. We hope to achieve unprecedented lateral and depth resolution by improving both current methodology and data coverage. We invert long period waveform data in the framework of normal mode asymptotic theory (NACT), a normal-mode perturbation approach, which takes into account coupling between modes both along and across dispersion branches, and thus distinguishes itself from standard studies based on wave dispersion and path average approximation. The resulting 2D broad band sensitivity kernels allow us to exploit the information contained in long period seismograms for body, fundamental and higher mode surface waves simultaneously. For the moment, we have considered only radial anisotropy and we invert the waveform dataset simultaneously for perturbations in the isotropic *S*-velocity structure, the anisotropic parameter $\xi = \frac{V_{SH}^2}{V_{SV}^2}$ and the depth to the Moho, starting from a 3D anisotropic global model, which is perturbed only in the region of interest, while it is used to correct the data for the heterogeneous structure outside the target region. For areas with an optimal data coverage, our approach will allow us to go a step further and invert for a more complete model of anisotropy that will include azimuthal information as well. Until now, this approach has only been applied at the global scale, with a lateral parametrization in terms of spherical harmonics. Here, we have adapted the NACT algorithm for the regional case by implementing a lateral parametrization in terms of spherical splines on an inhomogeneous triangular grid of nodes, with the finest mesh for North America.

The inverted dataset consists of more than 100,000 high quality 3 component body, fundamental and overtone surface waveforms, recorded at broad band seismic stations in North America from teleseismic events and provides a fairly homogeneous path and azimuthal coverage. In the future, we expect to further improve the data coverage, in particular by taking advantage of the broad band dataset that will be collected under the USArray effort within EarthScope. We will devote a particular attention to *SKS* waveforms because of their information about azimuthal anisotropy, which will be important when we will invert for a more complete model of anisotropy.

Our preliminary model (Fig. 1) shares the large scale features of previous regional studies for North America. In particular, we confirm the pronounced difference in the isotropic velocity structure between the western active tectonic region and the central/eastern stable shield, as well as the presence of subducted material (Juan de Fuca and Farallon plate) at transition zone depths. Concerning the anisotropic signature, we observe a positive ξ anomaly in correspondence of the cratonic areas, within the lithosphere and deeper, while a negative ξ anomaly beneath the Basin and Range province suggests possible mantle upwelling.

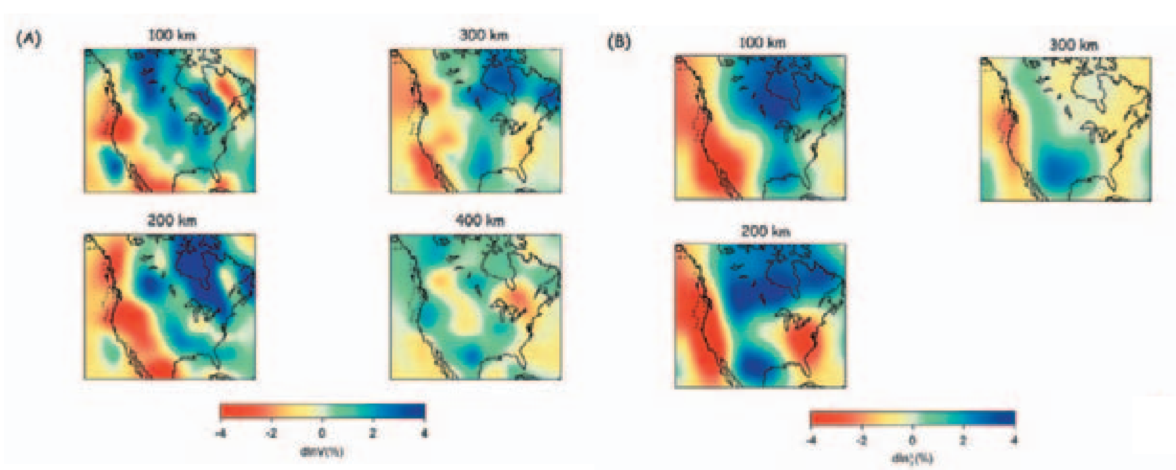


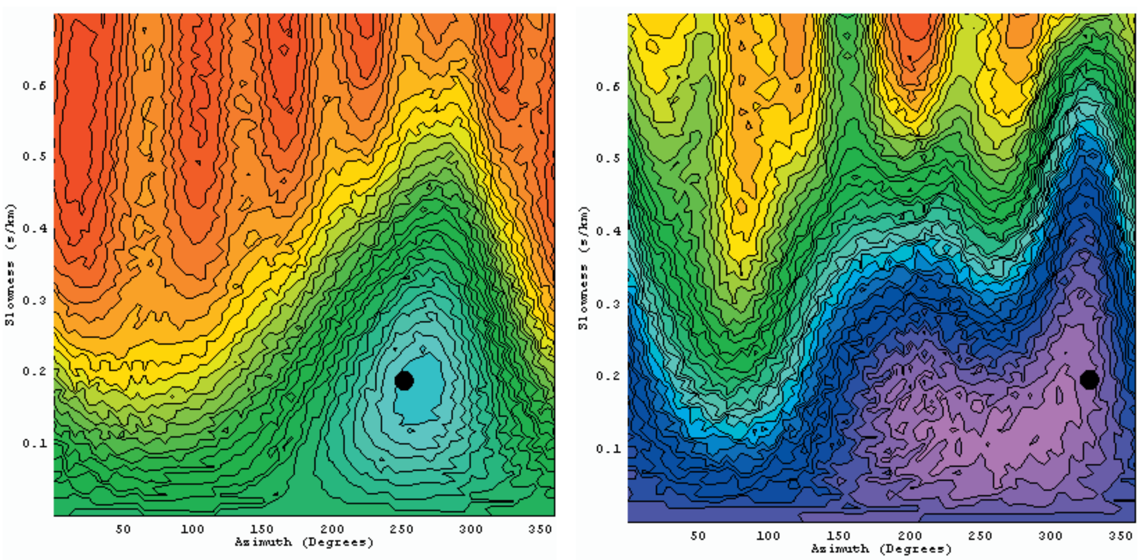
Figure 1: Horizontal slices at different depths through our preliminary model. Anomalies are relative to PREM - (a) Perturbations in the isotropic \textit{S}-velocity structure, (b) Perturbations in the anisotropic parameter ξ.

Resolving Multiple Simultaneous and Continuous Deep Tremor Sources Using Three Small Aperture Seismic Arrays

Wendy McCausland
University of Washington

Steve Malone
University of Washington

One of the most interesting recent discoveries in seismology and geodesy has been the cyclic concurrence of slow slip earthquakes and deep tremor along the Nankai and Cascadia subduction zones (Obara, 2002, Rogers and Dragert, 2003; McCausland and Malone, 2003, 2004; Kamaya et al, 2004). The tremors occur as emergent bursts of energy lasting on the order of two to four minutes and as a low-level relatively constant background signal. At any given time there can be a more than one active tremor source. Three azimuthally distributed small aperture seismic arrays (diameter ~600m) recorded the episodic tremor and slip event of July 2004. The arrays have proven extremely useful by providing a continuous record of the back-azimuth and slowness that resolves multiple sources as well as constant low-level tremor. Traditional seismic network stations can only locate isolated bursts. There are still many unanswered questions about deep tremor and slow slip events. Particularly, we do not yet know what the source of the tremor signals is. Nor do we know if the tremor and slip are two different manifestations of the same source process, or if they are separate processes that can be excited by similar source condition(s). A coordinated deployment of seismic arrays as part of the planned facilities of EarthScope to capture another episodic tremor and slip event would provide the detailed seismic and geodetic information required to begin to answer these questions.



Lopez North **Sequim East**

Beamforming results from a 2-second bandpassed window of array data from July 15, 2004. The left figure shows one resolved source on the Lopez array. The figure on the right shows two resolved sources on the Sooke array.

Principles of GPS and GPS-determined Velocity Fields for the Non-geodesist – And a Peek at the Latest Gear

Charles Meertens
UNAVCO

Frederick Blume
UNAVCO

Mike Jackson
UNAVCO

We will offer an overview of GPS geodesy techniques and applications and a hands-on introduction to the new EarthScope/PBO campaign receiver pool managed by UNAVCO. This mini-course is aimed at all users, and potential users, of GPS and will demonstrate the varied capabilities of the state-of-the-art hardware available to the community.

The uses and applications of GPS are expanding rapidly as precision continues to improve, survey receivers become more affordable and available, and supporting infrastructure is enhanced. A ubiquitous technology, GPS is widely used for mapping and measuring nearly everything that moves over a fantastic range – from millimeters/year to kilometers/sec – global plate tectonics to seismograms of large earthquakes. Whereas determining your position on a map at the meter level is relatively simple with a hand-held GPS unit, pushing the precision to the highest levels requires specialized equipment, careful technique, and relies on a developed global infrastructure. Continuously operating global GPS networks, under the umbrella of the International GPS Service (IGS), provide a framework for the determination of the global reference frame, GPS orbits, earth orientation parameters, and global plate motions.

The global network supports regional studies of plate boundary deformation, such as the EarthScope Plate Boundary Observatory (PBO). Campaign surveys using portable GPS equipment are less costly and enable the researcher to conduct detailed measurements over more local scales including fault zones, basin subsidence, tectonics, magmatic deformation, or ice motions. Portable GPS can also be used to perform precise mapping, provide control for aerial surveys and LIDAR, and can be integrated into ground based LIDAR and Ground Penetrating Radar systems.

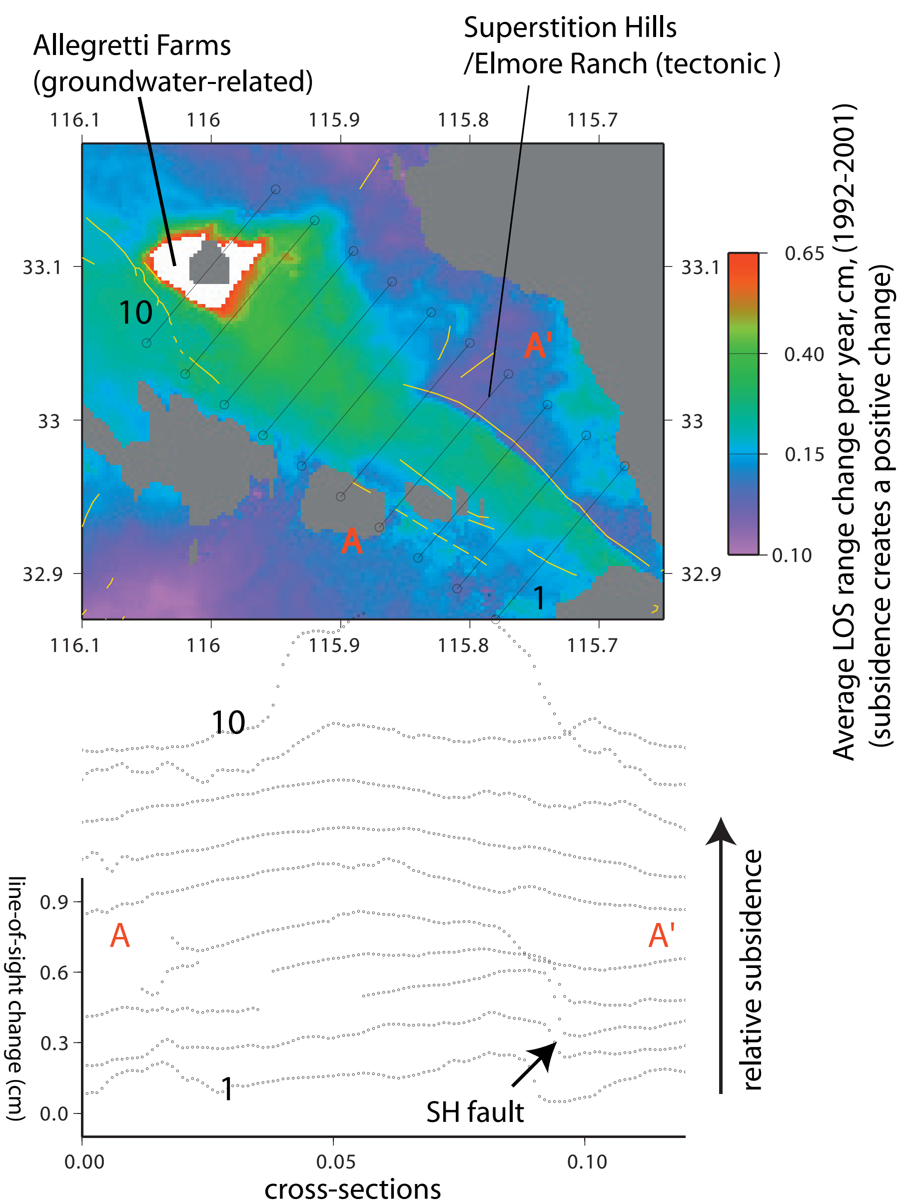
Kinematic GPS survey conducted by Chuck Kurnik (UNAVCO) in support of environmental remediation efforts at Cape Hallett Antarctica. Photo by Geoff Gilbert, Raytheon Polar Services Company.

Deformation in the Western Salton Trough During 1992-2000 as Observed by InSAR

Robert Mellors
San Diego State University

Afton Van Zandt
San Diego State University

Data from 83 ERS-1 and ERS-2 interferograms (descending orbit, track 356, frame 2943) covering the Western Salton Trough and spanning a time period from 1992 to 2000 are analyzed to measure surface deformation. Several areas of apparent deformation are observed: along the Superstition Hills/Elmore Ranch faults, near the southern end of the Coyote Creek segment of the San Jacinto fault, in the Borrego Valley, and near the northwest shore of Salton Sea. Comparison with groundwater data and surface geology suggests that the deformation signals along the southern Coyote Creek fault, near Borrego Springs, and along the northwest shore of the Salton Sea are primarily related to groundwater extraction and resulting subsidence. Faults in the area appear as barriers to groundwater flow. The deformation along the Superstition Hills/Elmore Ranch fault appears to be tectonic in origin. We invert the InSAR data to determine deformation as a function of time and compare with field observations and other geodetic data.



Stacked interferogram showing average line-of-sight range change for the period 1992-2001 over the Western Salton trough. Units are in cm. Cross-sections of the range change are shown below, going from SE (bottom) to SW (top). Gray represents areas of no data and white represents clipped color scale in order to show fine details. Known faults are in yellow.

The PBO Data Communications Network

David Mencin
UNAVCO

Jim Wright
UNAVCO

Erik Persson
UNAVCO

Greg Anderson
UNAVCO

One of the major technical hurdles for the Plate Boundary Observatory (PBO) is the design and construction of the communications network. Historically GPS permanent station networks (as well as strain networks) have been serial based schemes unique to a group or cluster of sites and the sites have either been low in number or constrained geographically. PBO is a very large number of stations spread out over two million square miles. PBO has also adopted many modern communication schemes such as IP based communications and standard embedded operating systems. This has presented some unique challenges both in terms of technology adoption, network control, network monitoring and remote diagnosis and repair. This presentation will review the technologies adopted, the successes and failures of these technologies, and current progress and strategies for network monitoring (both communication devices and the instrument itself), control, diagnosis and repair.

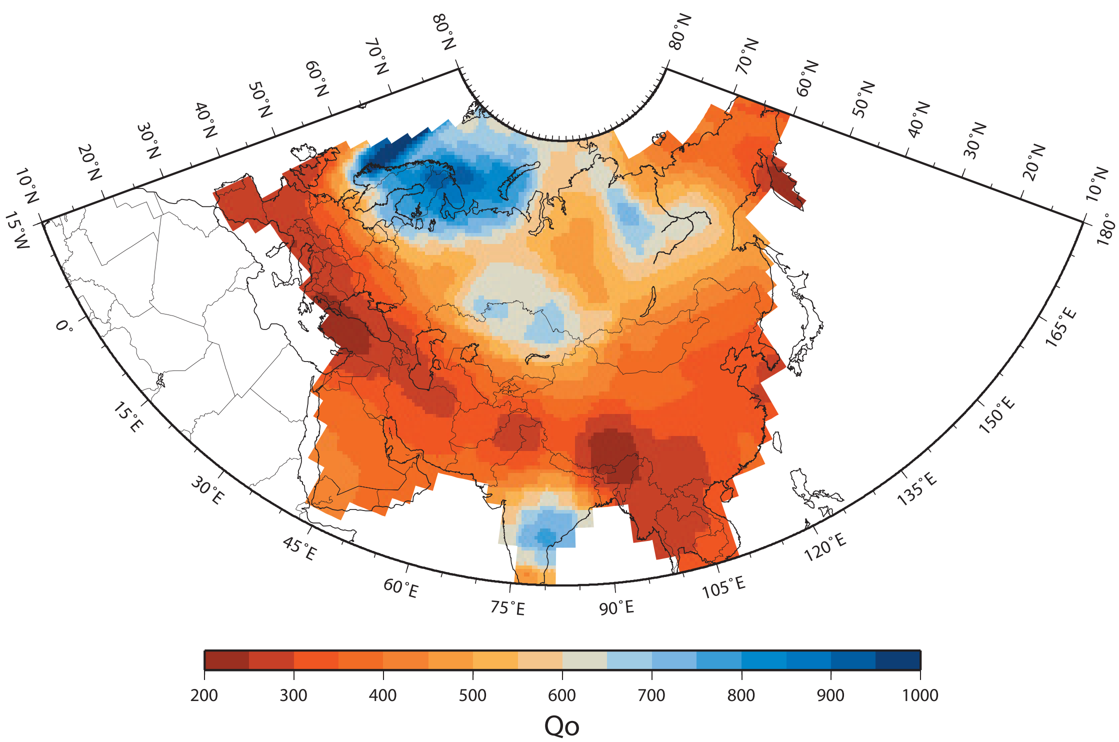
Lg Coda Q and the Evolution of Continents: New Results for Eurasia

Brian Mitchell
Saint Louis University

Lianli Cong
Yunnan University

In recent years it has become possible to produce continent-wide tomographic maps of Lg coda Q. The first such maps, for all continents except Antarctica, even though limited in their ability to resolve detail, have revealed stunning correlations between Q and recent tectonics and a clear relationship between the value of Q in any region and the time elapsed since the most recent tectonic/orogenic activity there. Of all continents studied, North America currently has, by far, the largest gaps in coverage and the greatest need for further study.

An illustration of the power of Lg coda Q mapping, where dense path coverage is available, is illustrated by Eurasia where we have made 943 new determinations of 1-Hz Lg coda Q and its frequency dependence. The new values provide coverage for four previously unsampled regions and greatly improve the density of sampling for three others. Values are high, 700 or more, in most cratons but are surprisingly low in the Arabian craton (300 – 450), in the Siberian trap portion of the Siberian Craton (about 450) and in the Deccan traps of the Indian craton (450-650). They are generally low in the active Tethysides belt of southern Eurasia but also vary in value (150-500) there. Lowest values coincide with four of the five most seismically active regions of Eurasia – Turkey, northern India and Pakistan, southwestern China, and Kamchatka. The exception is the Zagros belt where Lg coda Q is low but similar in value to surrounding regions. Lg coda Q variations are best explained by variations in the volume of fluids of hydration in permeable crust that traveled there after release from subducting lithosphere or other upper mantle heat sources. They approximately correlate with at least three other geophysical parameters. They correlate directly with Rayleigh-wave velocities and inversely with upper mantle temperatures and crustal strain. Anomalous values for all four quantities extend well northward of presently subducting slabs and cannot be explained if mantle convection is restricted to the southern Tethysides. Possible explanations may that they are due either to unexpectedly large lateral movements of fluid through weakened and permeable upper mantle that extends northward from currently subducting lithosphere or to earlier subduction that occurred in northern portions of the Tethysides. Support for both possibilities can be found can be found in recent literature.



New Lg Coda Q Map of Eurasia.

Analysis of Seismic Data from the Northern San Francisco Bay Area

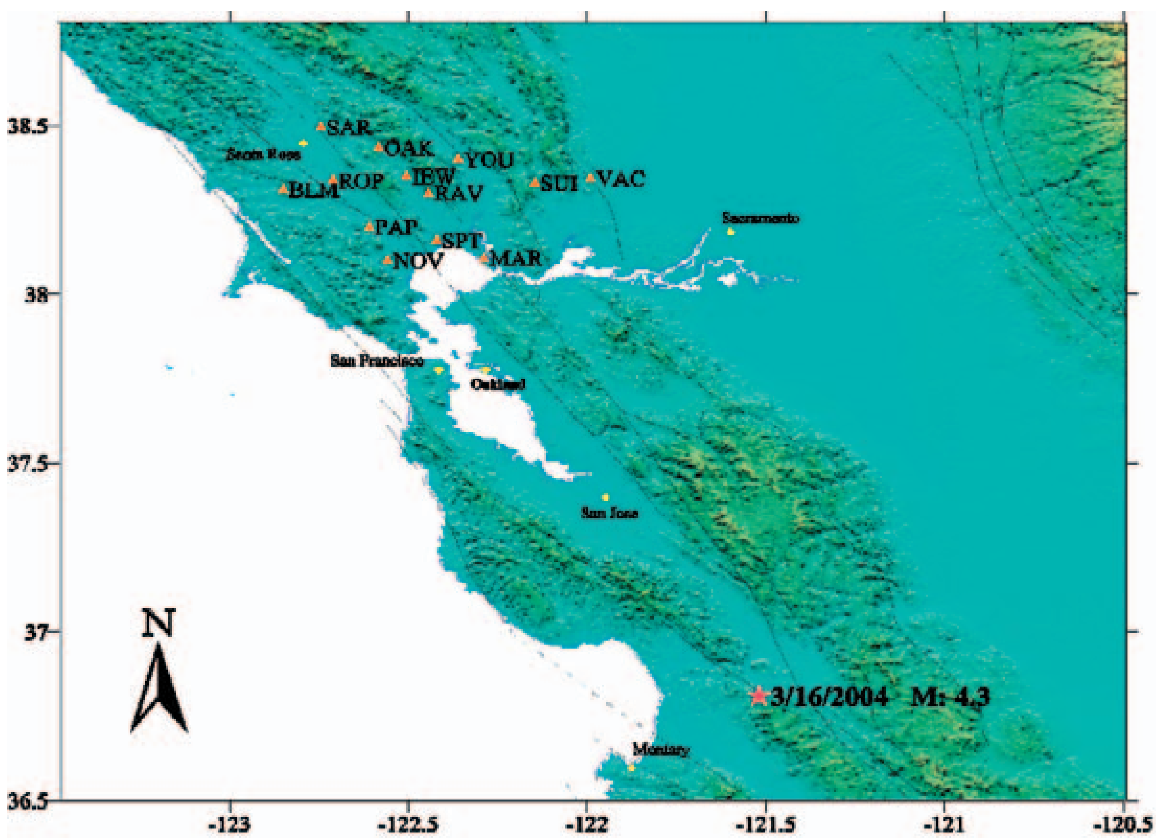
Walter Mooney
U.S. Geological Survey

Matthew Coble
U.S. Geological Survey

Shane Detweiler
U.S. Geological Survey

Joe Fletcher
U.S. Geological Survey

Seismic hazards in the region north of the San Francisco Bay area have been less studied than the areas around San Francisco and Oakland. In order to address this deficiency, we have instrumented the region around Santa Rosa, Napa, and Sonoma and recorded regional events, including the September 28, 2004, M = 6 Parkfield earthquake (Fig. 1). These data have allowed us to assess site responses and local structure in the study area. It is well known that waves diminish in size and change character as they propagate from source to surface. This field project seeks to record such waves as they propagate both from regional and teleseismic distances, and to use this information to determine the velocity structure of the upper crust. Once known, the velocity structure can be used to model synthetic seismograms to get an estimate of ground shaking and site response. We deployed 13 intermediate-period seismometers in the Northern California region, with most stations located on unconsolidated soils. Data from these stations were downloaded approximately every three months, and significant events were examined. The two most interesting events we have analyzed to date were the M=4.3 Pinnacles event of November 24, 2004 and the September 28, 2004 M=6.0 Parkfield event. We have analyzed three-component records from these events using a method for the calculation of full-wavefield synthetic seismograms. One of our principal interests is whether large amplifications are found at sites in the various valleys as have been found elsewhere. Thus far, we find significant discrepancies between the observed data and what is expected from purely theoretical considerations. Our observed data show remarkable and unexpected regional and local site effects in the northern Bay Area. We find a strong, long duration resonance at a period of 1.5 s. Surprisingly, strong surface wave trains are not observed. We find strong evidence for the conversion of P-wave energy into scattered S-wave energy, as is evident in the comparison of Fig. 4 and 5. Specifically, we observe significant energy on the transverse component (black lines) prior to the arrival of the direct S-wave. These and future observations will provide a firm basis for quantifying seismic hazards in this highly-populated region. Also noteworthy is that the two earthquakes that we used for modeling purposes were both located on the opposite side of the San Francisco Bay. It appears that the three-dimensional structure of the crustal blocks around the Bay dampened the signal reaching the instruments, causing very little surface wave energy to be recorded. This decrease in shaking in the North Bay was also noted during the 1989 Loma Prieta earthquake. This will be an interesting challenge for efforts to model the region.



Location map for 13 seismic stations located to the North of the San Francisco Bay. Also shown is the March 16th, 2004 M=4.3 event used for analysis in this study.

Precambrian Evolution of the Northern Rocky Mountains: From Precambrian Evolution of the Northern Rocky Mountains: From Laurentia to North America

Paul Mueller
University of Florida

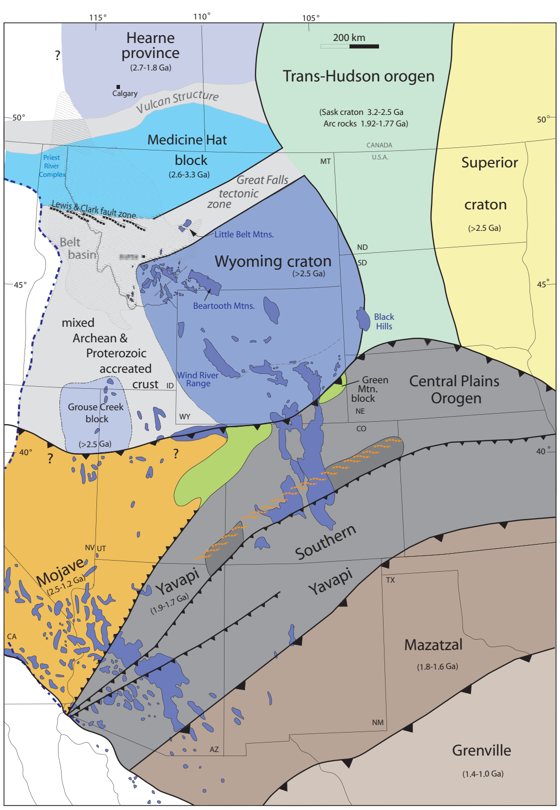
David Foster
University of Florida

David Mogk
Montana State University

Joseph Wooden
U.S. Geological Survey

A large section of SW Laurentia consists of a poorly constrained mosaic of Archean and Proterozoic crust that accreted to the Wyoming craton (WC) subsequent to its incorporation into Laurentia at ~1.86 Ga. The western margin of the Wyoming craton is dominated by crust formed during two distinct Archean cycles. The earliest is represented by the Montana metasedimentary terrane (MMT), which is distinguished because of the age of the basement gneisses (3.2-3.5 Ga) and widespread occurrences of supracrustal assemblages dominated by metasedimentary lithologies (particularly marble). To the south, TTG suite rocks of the Beartooth-Bighorn magmatic zone (~2.9 Ga) and the Wyoming greenstone terrane (2.5-2.8 Ga) constitute the western boundary of the WC. Collectively, this crust acted as a rigid and impenetrable lithospheric buttress to the repeated juxtaposition of younger Archean and Proterozoic crust that accumulated to form the adjoining Selkirk terrane, which extends westward to the Neoproterozoic rifted margin. Geo- and thermochronologic data clearly indicate significant, widespread events in the Selkirk terrane involving magmatic additions to the crust, metamorphism, and crustal melting at 2.2-2.5 Ga. Evidence for these events are found within the western Great Falls tectonic zone (MT-ID) and as far south as the Farmington Canyon complex (UT). Younger Proterozoic events are not as widespread, but include burial and crustal melting of the NW margin of the WC at 1.77 Ga and a widespread tectono-thermal event at ~1.65 Ga that is recorded from UT to southwestern MT/eastern ID. Crust of intermediate ages (e.g., 1.81, 1.83, 1.91) and indeterminate origins has also been documented in this terrane. Because none of the currently recognized tectono-thermal events associated with Proterozoic accretion resulted in the formation of magmatic systems with the Wyoming craton, we propose that 1) crust accumulated along a transpressional margin that stretched from at least the Uinta reentrant to the northern margin of the Great Falls tectonic zone and that 2) any coeval subduction was directed outboard from the Wyoming craton. Unraveling the spatial and temporal distribution of this crust is critical to understanding the overall plate tectonic regime that characterized Proterozoic accretion along the southern margin of Laurentia and for identifying the specific terranes that may have been joined to Laurentia prior to Neoproterozoic rifting.

In addition, the distribution of Precambrian structures and lithosphere strongly influenced the Phanerozoic tectonic and geochemical evolution of the crust-mantle system of western North America. For example, a major component of the Paleoproterozoic lithosphere extends west to the Neoproterozoic rifted margin along the trend of the Great Falls tectonic zone. This lithosphere was relatively enriched in incompatible elements and proved more fertile for partial melting than areas underlain by Archean lithosphere. The Idaho batholith, Cretaceous SW Montana granitic province (including the Boulder and Pioneer batholiths), the Eocene Challis volcanics, the Absaroka volcanics, and the Montana alkaline province are mainly restricted to the Great Falls tectonic zone and other areas known to contain Paleoproterozoic lower crust. This suggests that the relative fertility of the lithosphere controlled the distribution of Phanerozoic partial melting and led to the wide range of compositions and specific spatial distributions of Phanerozoic igneous rocks in the northern Rocky Mountains. Delineation and characterization of these Precambrian crustal components through space should be a first order goal of EarthScope experiments in the northern Rocky Mountains.



Schematic depiction of Precambrian terranes of the northern Rocky Mountains. The Selkirk terrane (gray) includes crust of the Great Falls tectonic zone and underlies the SW Laurentian margin, including the Belt basin.

Slip on the San Andreas Fault at Parkfield, CA Through Two Earthquake Cycles

Jessica Murray
U.S. Geological Survey

John Langbein
U.S. Geological Survey

Robert Simpson
U.S. Geological Survey

Paul Segall
Stanford University

With the occurrence of the M6 earthquake at Parkfield, CA on September 28, 2004 there are now geodetic data spanning the three most recent M6 earthquakes on the San Andreas fault at this locale. Here we use these data to evaluate the persistence of slip deficit on the fault and the applicability of a simple earthquake recurrence model.

Inversion of Global Positioning System (GPS) offsets for the slip distribution of the 2004 event shows that slip was concentrated over the 25 km northwest of Gold Hill. Previous studies have shown that slip in the 1934 Parkfield M6 earthquake was confined northwest of Gold Hill (Segall and Du, 1993), while in 1966 a substantial amount of slip took place southeast of this point (Segall and Harris, 1987). We examine the geodetically-estimated accumulation of slip on the Parkfield segment of the fault over the last two earthquake cycles, accounting for aseismic slip during the interseismic period and a transient increase in fault slip during the early 1990s.

Due to insufficient data for the 1934 – 1966 interseismic period, we assume the same slip-rates as those inferred for the 1966-1991 period. Over two earthquake cycles about half the fault plane has kept up with the long-term slip, largely aseismically. In contrast, the southeastern end of the fault shows a slip deficit of >1.5 meters.

The time-predictable earthquake recurrence model states that the time between two earthquakes is the time required to rebuild the strain released in the earlier of the two events. In contrast, the slip-predictable model states that the size of an earthquake can be calculated as the product of the slip-deficit rate on the fault and the time since the most recent earthquake. The time-predictable model did not accurately forecast the occurrence of a subsequent event on the rupture plane of the 1966 Parkfield earthquake (Murray and Segall, 2002). We find here that the moment of the geodetically imaged slip for the 2004 Parkfield earthquake, even when postseismic slip is considered, is far less than would be expected if this earthquake followed the slip-predictable model.

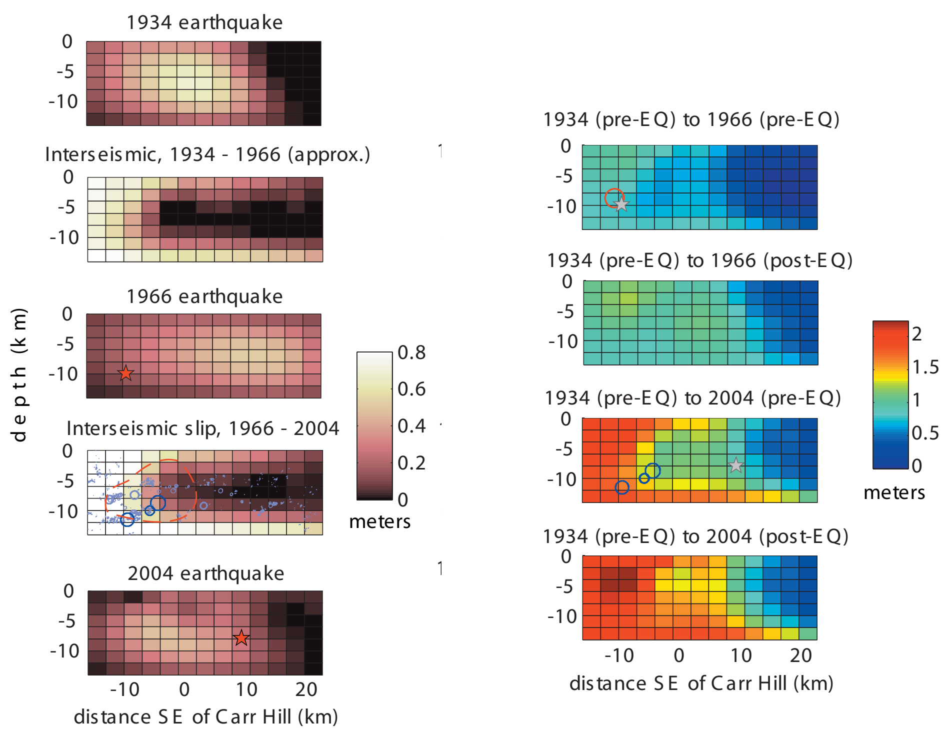


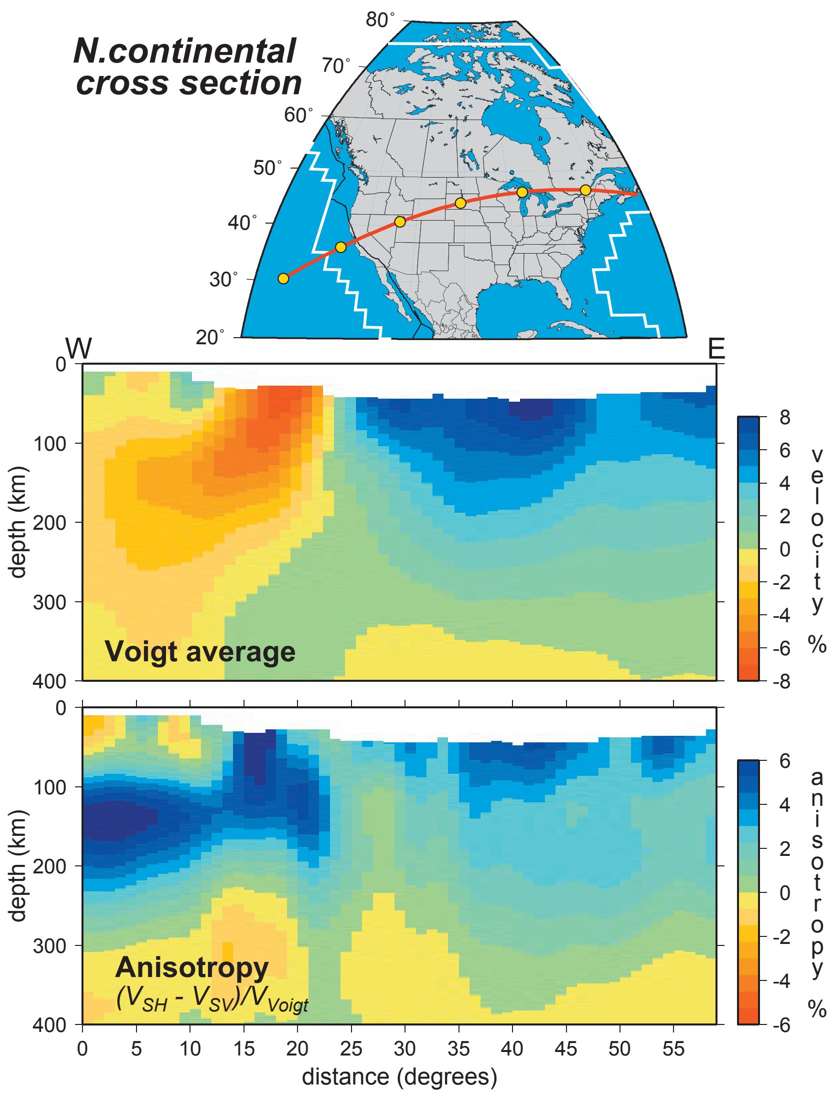
Figure caption: Evolution of slip on the San Andreas fault near Parkfield, CA over two earthquake cycles. Left: Slip in the three most recent earthquakes, and the cumulative slip during the two intervening periods. The slip distribution for the interseismic period between 1966 and 2004 is a weighted average of the slip-rates estimated from trilateration data collected between 1966 and 1991, campaign GPS data collected between 1991 and 1998, and continuous GPS data from 1998 – 2004. There is strong evidence for a transient increase in slip rate on the San Andreas near Parkfield between 1993 and 1996, associated with three M 4.5 – 5 earthquakes near the 1966 hypocenter. These earthquakes are shown in dark blue on this plot, and the area of transient slip inferred from two-color laser data is outlined in red. The slip rate estimated from GPS data collected between 1991 – 1998 is higher on this part of the fault than that estimated from the trilateration data. The distribution of background seismicity relocated by Waldhauser and Ellsworth [2004] is shown in light blue, and the hypocenters of the 1966 and 2004 earthquakes are shown by the stars. There are insufficient data to estimate the interseismic slip-rate distribution between 1934 and 1966; it is assumed to be similar to that between 1966 and 1991. Right: Cumulative sum of the slip shown on the left. The gray stars show the location of subsequent mainshocks that occur at the end of the time periods covered by the corresponding figure, and the red circle in the upper right plot is the location of the 17-minute foreshock of the 1966 event. The peak slip color on the right hand plots is what would be expected if the fault slipped at the long-term rate of 32 mm/yr estimated from GPS data and consistent with geologic estimates.

Tomography of the North American Upper Mantle Using Global and Regional Datasets

Meredith Nettles
Harvard University

Adam Dziewonski
Harvard University

The velocity structure of the upper mantle under North America is of great interest as the USArray project's deployment of a dense grid of broadband seismographs begins. The data from the stations of USArray will provide a regional-scale complement to the large volume of high-quality seismic data now available from the Global Seismographic Network of the Incorporated Research Institutions for Seismology. We use a hybrid global-regional approach to combine currently available regional and global datasets for tomography of the North American upper mantle, incorporating data from the GSN with data from the U.S. National Seismic Network (USNSN), the Canadian National Seismograph Network (CNSN), and several IRIS PASSCAL deployments, including the MOMA, BEAAR, RISTRA, and FLED arrays. We use a large dataset of surface-wave phase-delay measurements at periods of 35-350 s to determine a regional model of the three-dimensional radially anisotropic shear velocity structure under North America that is consistent with long-wavelength, global models of the upper mantle. The model we retrieve resolves structure on a wavelength of a few hundred kilometers throughout most of the continent. The correspondence between major geological features and those imaged in our mantle model is generally good. Radial anisotropy is observed to vary regionally, with systematic differences in anisotropy between oceanic and cratonic provinces. Radial anisotropy is observed to be strong under the Basin and Range, where the amplitude of the anisotropy reaches 4-6%.



Cross section through the upper mantle under North America shows isotropic (top) and anisotropic (bottom) velocity structure. Note the rapid transition between slow and fast wavespeed in the isotropic structure, and the difference in anisotropic structure under the Pacific plate and the Canadian craton.

Xenowhiffs – The Link Between Mantle Tectonism and Groundwater

Dennis Newell
University of New Mexico

Laura Crossey
University of New Mexico

T.P. Fischer
University of New Mexico

David Hilton
Scripps Institute of Oceanography

Karl Karlstrom
University of New Mexico

B.M. Kennedy
Lawrence Berkeley National Laboratory

Xenowhiffs are mantle-derived volatiles entrained within groundwater systems. Travertine–depositing cool springs, hot springs, and gas fields of western North America have RA values ($^3He/^4He$ ratios relative to air) indicating the presence of mantle-derived helium. We hypothesize that mantle-helium is traveling with CO_2 and other mantle-derived fluids from the mantle to the upper crust using deeply penetrating faults and volcanic conduits driven by magmatic and seismogenic processes. Elevated RA values correspond to slow mantle seismic velocities at 100 km (Fig. 1), and the regional trends in RA values appear to mimic the heterogeneity observed in mantle tomography. These relationships indicate that xenowhiffs may be a tool for describing the nature of mantle heterogeneity.

Mantle-derived fluids do not make the ascent through the crust unaltered. Rather, they acquire and impose unique geochemical characteristics due to fluid-rock interaction (e.g., mineral alteration and dissolution) and mixing with basement fluids, basin brines, and shallow groundwater. The geochemical character of travertine-depositing cool springs in the Colorado Plateau and Rio Grande rift appears to correlate with local tectonic provinces, and these springs often have poor quality water (elevated salinities and trace element content). Inputs of mantle-derived fluids may help describe the degraded water quality found in many aquifers of the western U.S., ultimately linking mantle tectonism to groundwater chemistry.

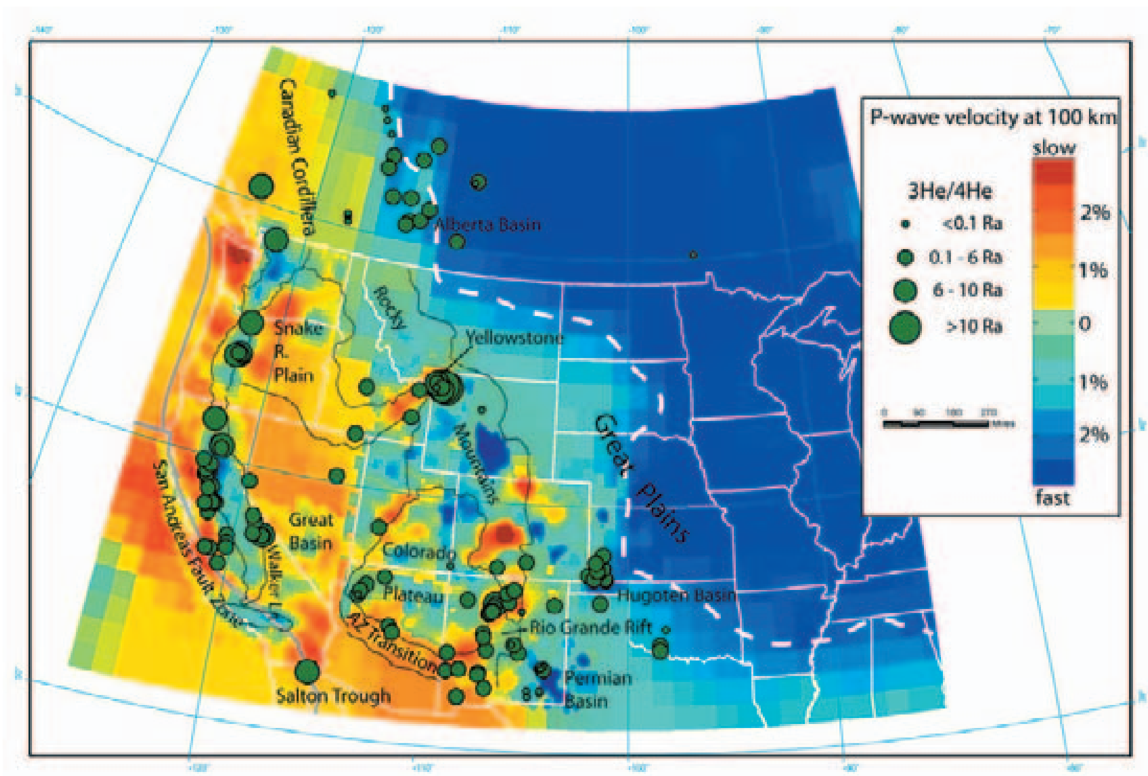


Figure 1. $^3He/^4He$ values (literature and this study) reported relative to air (RA) for travertine-springs, hot springs, geothermal fields, CO_2-fields and groundwater overlain on mantle P-wave velocity at 100 km (after Grand et al., 1997; Humphreys and Dueker, 1994). The white dashed line marks the transition from the tectonically active, seismically slow western U.S., to the tectonically quiet, seismically fast mid-continent.

Temporal Variations in the Scattered Wavefield Associated with the 1993 Parkfield Aseismic Transient Event: A Comparison Between Borehole and Surface Instruments

Fenglin Niu
Rice University

Xin Cheng
Rice University

Paul Silver
Carnegie Institution of Washington

Robert Nadeau
University of California Berkeley

Extracting subsurface deformation information from temporal changes in the seismic properties of the crust has been a long-time pursuit of seismologists. One of the more promising approaches to this problem has been the comparison of the codas of similar events occurring at different times and recorded at the same station. If one forms a cross correlation, C(t), within a time window centered on elapsed time t, the lag time τ at the maximum of the cross correlation Cm(t) and the decorrelation index D (defined as 1-Cm(t)) are both measures of the temporal change in the medium, if the contribution from differential event location is negligible. The variation can be due either to a temporal change in velocity, or a change in the location or amplitude of scatterers that produce the coda. This approach has been successfully applied to similar events that have followed major earthquakes. The change appears to reflect the gradual post-seismic healing of cracks in the shallowest crust. We have previously applied this approach to a repeat-earthquake dataset recorded by the High Resolution Seismic Network (HRSN) along the Parkfield segment of the San Andreas Fault (Niu et al., 2003). We found a systematic difference in the S-wave coda between earthquakes that occurred before and after the onset of the 1993 Parkfield aseismic transient, which was observed on a variety of geodetic and seismic instruments in the region. We additionally found that the difference can be explained by the motion of scatterers located very close to the initiation region of the aseismic transient. Given the close correspondence between the change in the medium and the aseismic event, we hypothesized that the observed structural change was due to a change in the stress field induced by the aseismic event.

While low-noise borehole networks are particularly well suited to the task of detecting small variations in the scattered wavefield, their spatial distribution is presently limited. We have thus begun to evaluate the utility of the noisier, but far more numerous surface stations that would provide greater density and spatial coverage. To address this issue, we have conducted a comparison between the borehole (HRSN) and surface network (NCSN) stations at Parkfield to examine whether the temporal change observed with the HRSN can be successfully performed with data recorded by surface instruments. We find that in general, the signal-to-noise ratio of the NCSN data is about 2 orders of magnitude lower than that of the HRSN data, even in the case where the NCSN and HRSN stations are very close to each other (< 0.1 km). The resulting decorrelation index between repeat seismograms for the surface stations is ~0.1, which is about a factor of 20-100 higher than those calculated from the borehole stations (~0.001-0.005). Despite the high noise level of the NCSN data, however, we are nevertheless able to confirm the changes between the pre- and post 1993 seismograms. The two datasets also generate very consistent scattering field that changed during the aseismic event. We are currently apply our techniques to other sections of the San Andreas fault system to identify consistent changes in scattering field induced by tectonic events.

Finite Frequency Sensitivity in Crustal Environments

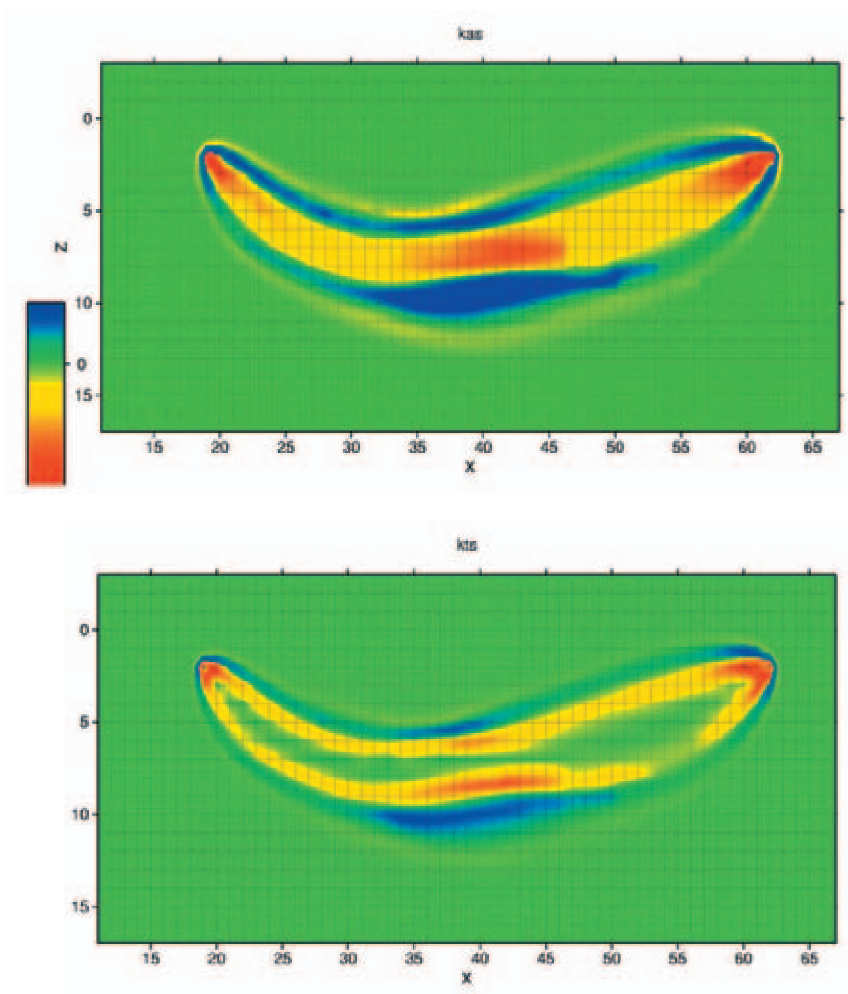
Guust Nolet
Princeton University

Stéphanie Gautier
Université Montpellier II

Jean Virieux
Geosciences Azur

Travel times and amplitudes of seismic body waves in crustal environments show a complicated dependence on perturbations in the elastic parameters that very often defies human intuition as guided by ray theory. Even waves with a high dominant frequency have sensitivities (Frechet kernels) that may be many kilometers wide. The complexities found in many crustal environments create caustics in the wavefield that in turn may lead to sensitivity of opposite sign: a geological unit that is 'fast' in lab tests with ultrasonic waves may actually slow down the cross-correlation travel time of a body wave at seismic frequencies of, say, several Hertz. Nonzero Maslow indices may make the location of the ray theoretical path sensitive to velocity perturbations, which is not the case normally. This, and multipathing of seismic waves may create sensitivities that differ substantially from the now familiar 'banana-doughnut' shape found for teleseismic P and S waves. The differences with ray theory are profound, and we strongly advocate that crustal tomography experiments use finite-frequency theory to interpret travel time delays and/or amplitude anomalies.

We developed an efficient and ultra-stable 3D raytracing method to compute accurate sensitivities in complicated 3D crustal environments. Graph theory is used to generate a set of rays from a source or receiver location to every node in a (Cartesian) model grid. These rays are bent to minimum travel time, after which we use paraxial ray tracing along the bent ray to determine geometrical spreading and Maslov index. To compute Frechet kernels for travel time and amplitude we interpolate the fields of travel time and geometrical spreading calculated on the nodes of the model grid. An application is under way to interpret travel time data from an array around the Gulf of Corinth in Greece.

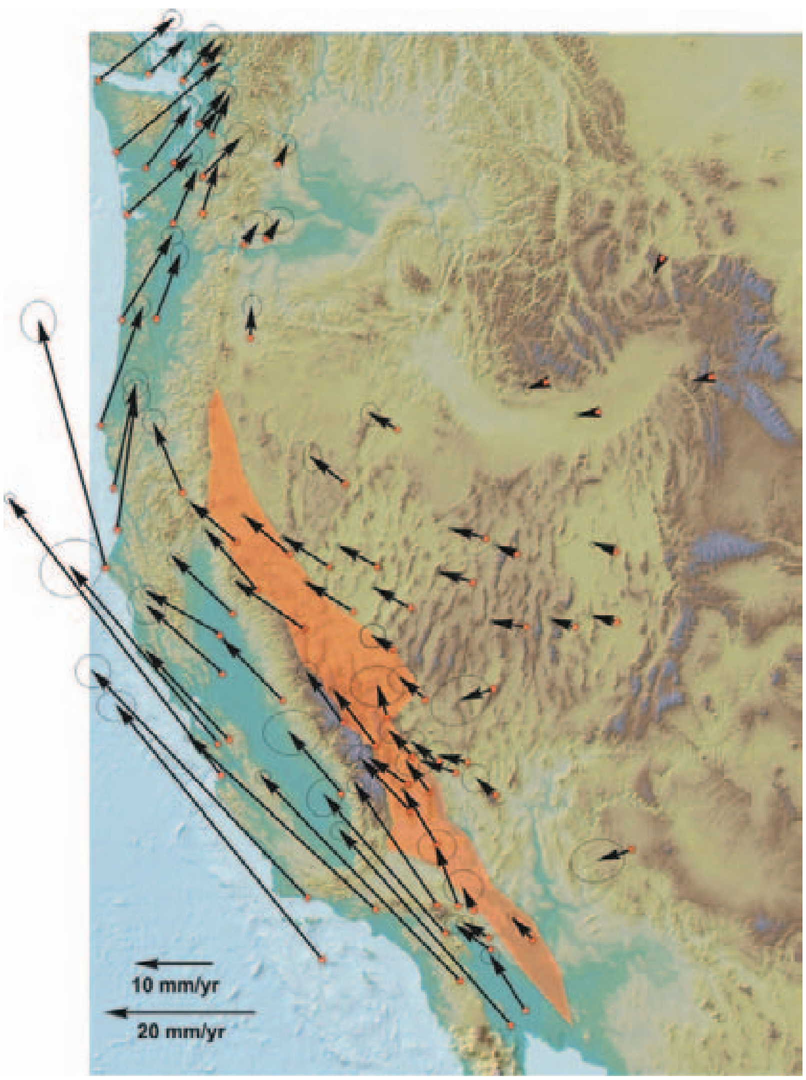


Examples of sensitivity kernels for P wave amplitude (top) and travel time (bottom), traveling in a highly heterogeneous crustal structure beneath Corinth (Greece). The dominant period of the wave is 0.3s. Depth z and horizontal distance in the source-receiver plane x are in km. Note the enhanced areas of sensitivityvisible in both kernels, as well as the narrowing down of the doughnut 'hole' (the area of zero sensitivity) in the travel time kernel. Clearly, interpreting data like this with ray theory, or even with idealized banana-doughnut kernels, would lead to wrong results.

The Role of Crustal Anisotropy in the Development of Transtensional Strain Partitioning in the Western Great Basin

John Oldow
University of Idaho

Northwest displacement of the Sierra Nevada block is accommodated by a system of kinematically linked structures localized along the western margin of the Great Basin. Active deformation is expressed by an east to west increase in regional velocity field, recorded by a dense array of GPS sites, and by belts of seismicity. The regional velocity increases from 2-3 mm/yr in the central Great Basin to ~14 mm in the Sierra Nevada and exhibits a clockwise rotation from WNW to NW. Incremental strain axes determined from earthquake focal mechanisms and fault-slip inversion show an east to west anticlockwise rotation of 50° from parallel to the velocity trajectory in the central Great Basin to nearly orthogonal to the velocity field along the eastern flank of the Sierra Nevada. The progressive divergence between strain- and velocity-field trajectories marks the transition from plane to nonplane strain conditions of deformation. The regional velocity field is oblique to the eastern margin of the Sierra Nevada block and many structures within a NW-trending boundary zone separating the Sierra Nevada and the central Great Basin and results in constrictional strain during transtensional deformation. East of the southern Sierra Nevada, the boundary zone forms the northern extent of the Eastern California Shear Zone, which has an eastern margin that coincides with an abrupt east to west increase in the regional velocity. Farther north, the belt of active deformation bifurcates into the NW-trending Walker Lane and NNE-trending Central Nevada Seismic Belt. From south to north, the velocity boundary steps east across a NNE-trending structural stepover that kinematically links faults of the Eastern California Shear Zone and central Walker Lane and continues northeasterly along a series of dog-leg steps and ultimately follows the eastern margin of the Central Nevada Seismic Belt. Interaction of the regional velocity field and pre-Tertiary crustal anisotropy produced displacement partitioning on NNW, ENE, NW, and NNE structures and the local development of nonplane strain conditions. The crustal anisotropy was developed during late Proterozoic continental rifting and formation of the lower Paleozoic miogeocline and during younger Mesozoic backarc and intra-arc deformation.



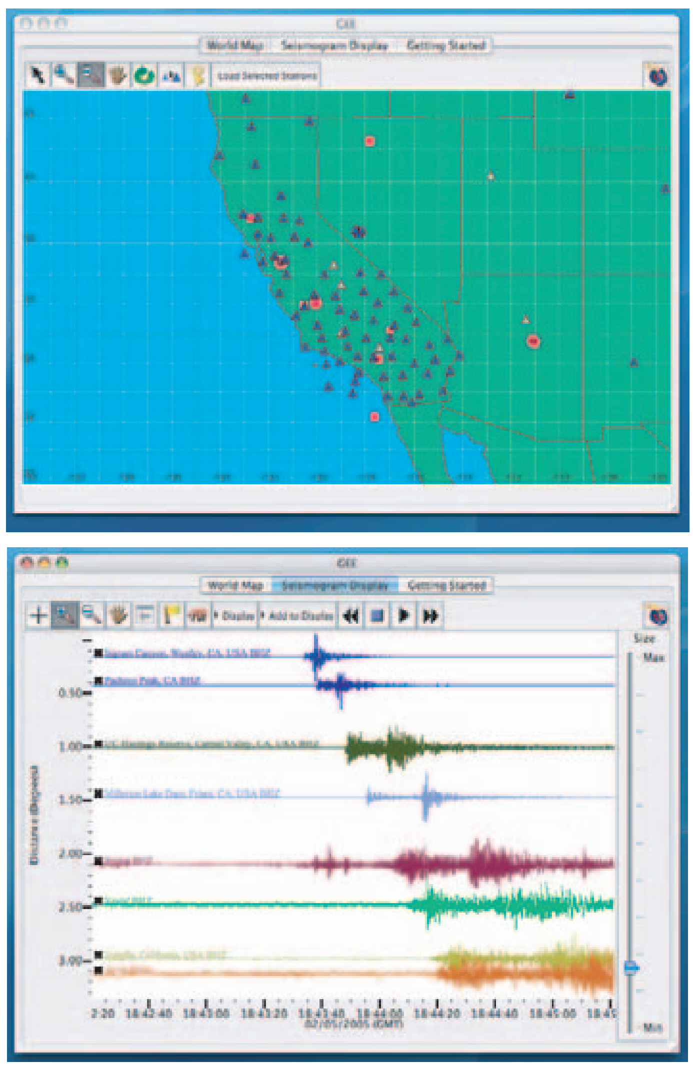
Shaded relief map of the western United States showing a representative sampe of the regional GSP velocity field in a stable North American reference frame. The boundary zone (orange) between the central Great Basin and the Sierran Nevada block and southern Cascade Range is undergoing active transtensional deformation (constrictional strain) produced by the interaction of crustal anisotropy and the regional displacement field.

Access to USArray Data for Education and Public Outreach

Thomas Owens
University of South Carolina

Philip Crotwell
University of South Carolina

User-friendly access, suitable for an educational environment, to the vast EarthScope data holdings has been a stated goal of the Education & Outreach community for some time. The Global Earthquake Explorer (GEE) utilizes advanced data access technology hidden by an intuitive map-based interface to provide educational users with full access to seismological data from the IRIS Data Management Center. Within minutes of a significant earthquake anywhere in the world, seismograms of that earthquake are transmitted to center recording facilities for analysis. Designed with education in mind, GEE can access these same data sources used by professional seismologists through a clickable map interface that allows users to easily select the earthquake and seismograph stations of interest and then receive the seismograms over the Internet with a single click of a mouse. With GEE, users can then view and analyze these seismograms on their local computer. GEE is also a teaching tool. It offers teachers a simple and fun way to introduce their students to earthquakes, earth structure, and wave properties. GEE includes several structured Learning Modules that help develop an elementary understanding of physical principles behind earthquakes and seismology. Recent and future enhancements and extensions to GEE are creating interfaces suitable for public outreach as well. USArray is featured in the GEE as a "Regional Hot Spot" to allow simplified viewing of Transportable Array data within GEE. In response to a request from USArray, we have created the USArray Monitor (http://roo.seis.sc.edu/USArrayMonitor) to allow landowners and the interested public to quickly look at USArray data. A more rich environment that combines education and public outreach needs is REV (The Rapid Earthquake Viewer) which provides web-based access to global earthquake data. GEE can be downloaded at http://www.seis.sc.edu/GEE



GEE screenshots of USArray "hot spot" mode (top) and a record section from a M=4.4 earthquake in Central California on 2/5/05 as recorded by select USArray stations.

Persistence of Relief and Erosion on the Eastern Passive Margin

Milan Pavich
U.S. Geological Survey

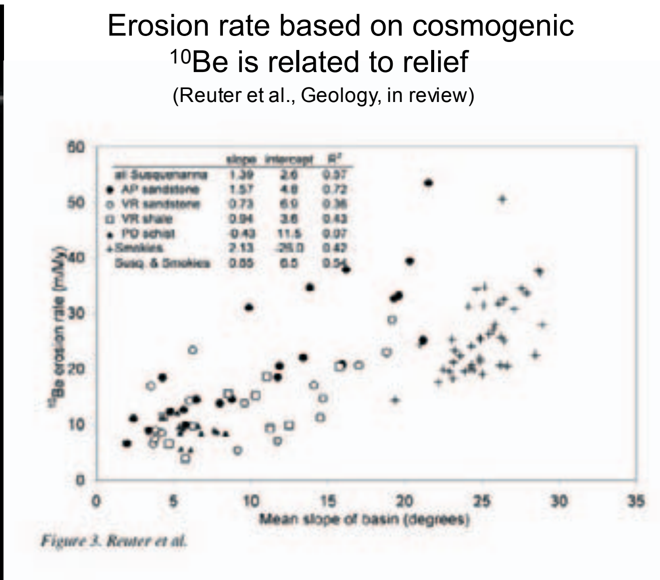
Joanna Reuter
University of Vermont

Paul Bierman
University of Vermont

Despite the absence of thermally-driven uplift, the eastern passive margin is not static. Erosion drives ongoing isostatic compensation (Matmon et al., 2003) and relief has been maintained despite significant erosion over the Cenozoic (Pazzaglia and Gardner, 2000). Neogene uplift may have been significant, as shown by a pulse of Miocene sedimentation on the Atlantic shelf (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996). Relief has apparently increased in some Appalachian river valleys during the Neogene and localized acceleration in bedrock river incision has occurred in the last 40 kyr (Resusser et al., 2004). The most recent Laurentide ice loading and unloading over the past 70 kyr has caused measurable, ongoing deformation of the lithosphere (Pelltier, 1996). These observations suggest that a simple decay model for Cenozoic passive margin evolution (Davis, 1899; Ahnert, 1970) does not provide sufficient explanation of the Cenozoic landscape evolution of this region. Neotectonic landforms (e.g. uplifted plateau and escarpments, incised valleys) sediment stratigraphy (Pazzaglia and Brandon, 1996), faulting (Mixon and Newell, 1977; Prowell, 1988) and seismicity (reviewed in Gardner, 1989) provide evidence for active lithospheric processes in the eastern lithosphere.

Relating geomorphic process studies to dynamic topography can provide information about mantle processes. The dynamic surface topography of North America shows that it stands low relative to a purely isostatic model. In other words, the topography is overcompensated by the crustal root and lithospheric structure. Contemporary increases in mean elevation of the Appalachians may be an isostatic response of ongoing changes in the crustal root compositional and density structure. Thermochronology, particularly He/U-Th of apatites, provides additional long-term data on rates of orogen unroofing. Regional strain is thus measurable over a range of timescales. Deploying a GPS array to measure contemporary strain is a high priority; such an array will have to be maintained for decades to discern a measurable signal. Relating temporal and spatial scales of contemporary deformation to longer-term deformation provides important information about the possible drivers of lithospheric strain.

We now have techniques to study the dynamics of topographic change over the range of annual to million year timescales. Rates of topographic change, particularly changes in mean elevation (surface uplift) and relief (river incision vs. landscape erosion) can be measured over decades using GPS and related geodetic measurements and over millennia using studies of river long profiles, paleo-long profiles (terraces), modern erosion rates, and paleo-erosion rates. Age data for these millennia-scale studies are provided by biostratigraphy, and increasingly, cosmogenic techniques that are particularly effective at determining modern and paelo-rates of erosion. New data from the Appalachians (Reuter et al., in review) show a strong relation of erosion rate based on *in situ* ^{10}Be to mean basin slope. These data provide information at the million-year time scale, and support hypotheses for topographic rejuvenation in the Appalachians in the late Cenozoic. Cosmogenic isotopic measurement of erosion rates should, therefore, be a critical component of quantifying the geomorphic evolution of this passive margin.



Fundamental Principles of Seismic Imaging with the USArray

Gary Pavlis
Indiana University

The primary purpose of this paper is to educate nonspecialists about principles of seismic imaging and to simultaneously outline fundamental principles that I hope can serve as the foundation for meaningful discussions on the potential performance of the USArray. Seismic methods all use seismic waves to probe the interior of the earth. Imaging methods, however, can be classified into two main categories: inversion and direct imaging methods. Inversion approaches have dominated seismology since the early 1970s and are characterized by a litany of terms heard at any scientific meeting today: tomography, waveform inversion, and velocity model estimation. Direct imaging methods, on the other hand, have totally dominated the oil and gas industry since the 1950s and are associated with terms like CDP stacking, deconvolution, and migration. The primary distinction between inversion methods and direct imaging is that inversion method mostly focus on parameteric measurements derived from raw time series data., These parametric data are converted to an Earth model (inverted) by solving some (usually large) set of simultaneous linear or nonlinear equations. Direct imaging methods, in contrast, commonly aim to directly manipulate recorded data to reconstruct an image of the subsurface from the full seismogram. The later approach has demonstrated ability to dramatically improve resolution because it automatically includes all the data instead of parameters derived from the data. On the other hand, I will show that both approaches are actually inversion solutions but the methods are simply cast in different language and utilize vastly different numerical methods. Both of these approaches will undoubtedly be applied to the USArray, but I make this assertion; the community is well prepared to apply numerous inversion approaches to USArray data, but we face large technical barriers before we can produce direct imaging results that we can confidently interpret to constrain Earth structure and associated geologic processes. Numerous technical barriers need to be surmounted if USArray is to yield it's full scientific potential and a key to this I will claim is development of a unified theory for direct imaging of seismic data. Most existing wavefield methods are founded on the Born approximation that requires a separation of the illuminating and scattered wavefields. A fundamental reason why seismic reflection imaging works is that this process is relatively simple. A key problem in passive array imaging is that this is too often fundamentally impossible. Important results have been obtained recently with P to S converted phases because although the separation is not trivial it is feasible. Promising frontiers are being explored by the community to utilize the teleseismic P wave reflection off Earth's free surface as a secondary source; differential methods that simplify reconstruction of a special region by subtraction of common propagation paths; and direct imaging with surface waves.

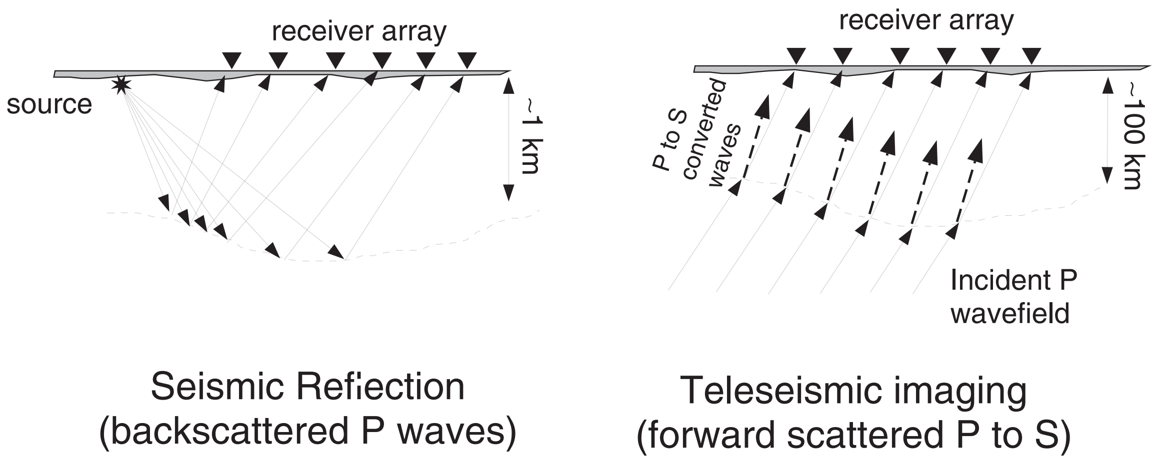


Diagram showing two major geometries of direct imaging. On the left is the backscattered wave geometry that is always used in seismic reflection imaging. On the right is the forward scattering geometry that USArray will need utilize to image P to S converted phases. Note the teleseismic P wave reflected off the free surface can also serve as a secondary source to illuminate the subsurface from both above and below. This figure also illustrates an interesting scaling concept. In reflection seismology the weathered layer causes a number of practical barriers to imaging. At the scale of USArray entire sedimentary basins will probably play a similar role in complicating imaging.

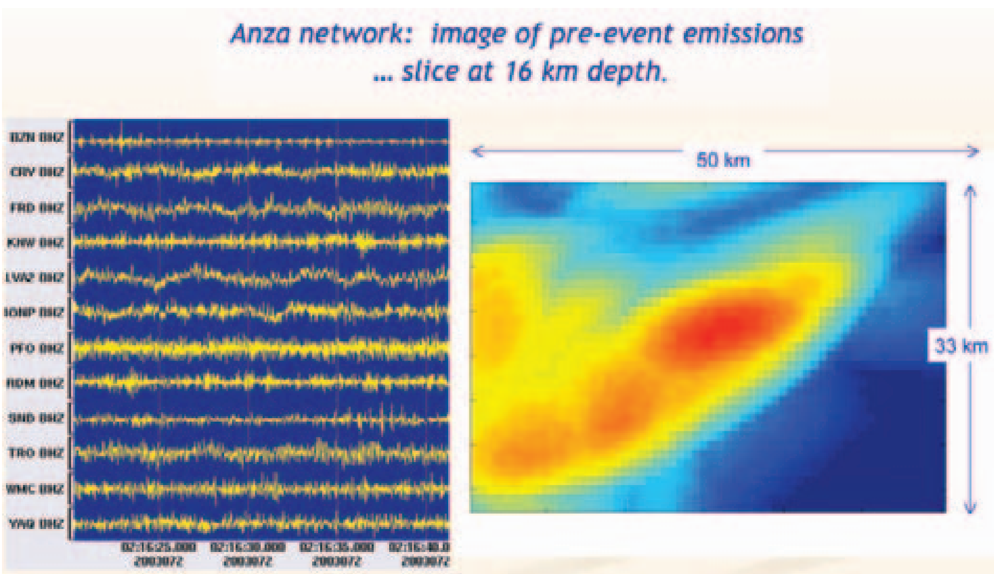
Detection of Energy Emission by Micro-events

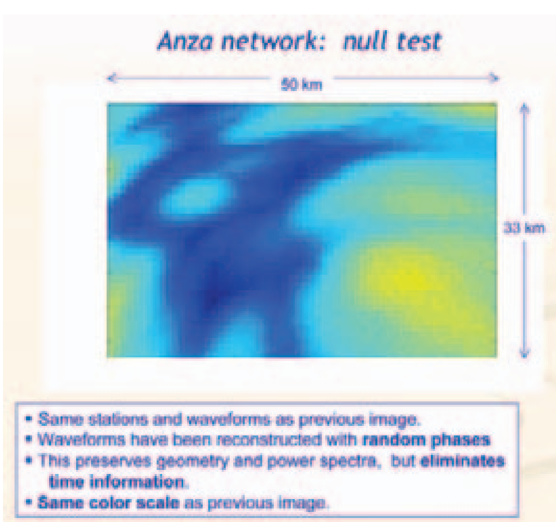
Robert Phinney
Princeton University

Matthew Cromwell
Princeton University

Conventional practice in the detection, location, and characterization of small local events entails the use of single-channel arrival detection, the association of multiple-station detections, and the location and characterization of each event, based on these associated arrivals. At smaller magnitudes, arrivals are lost in the noise, and insufficient detections are obtained to identify and locate an event. Thus each network has a magnitude below which only a small fraction of events are detected and catalogued. Two strategies are available for lowering this network threshold. [1] Single-instrument (1 or 3 channels) data processing to lower the single-instrument detection threshold; [2] All-station processing, to utilize the multichannel time series. We show numerical experiments in which migration-stacking of data flow from the Anza network is used to create subsurface 3-d images of seismic emission. Any experiment involves a specified time window. When the window is a few seconds, the experiment is scanning for individual events... thus looking at events which are just below the usual detection threshold. Windows of minutes to hours can be used, and the stacking generalized to entail stacking over such windows. Thus, detection of the emission of seismic energy by large numbers of micro-events is achieved by this time averaging. A reliable velocity model of the subsurface is required, as with conventional event detection. Implementation involves a variety of discretionary analysis options for noise balancing, bandpass selection, and stacking. It represents a fruitful area for exploratory data analysis.

Following studies by Archambeau, we have detected emission from a pre-event time window, from the location of a well-detected m1.5 event. The seismic energy studied represents a portion of the noise window with partial coherence across the network. We conjecture that this represents in effect a proxy monitor of creep in the tectonically active subsurface.





Left: Emission image of a 15km deep slice under the Anza network, for a noise sample pre-m1.5 event. Right: Null test of the processing.

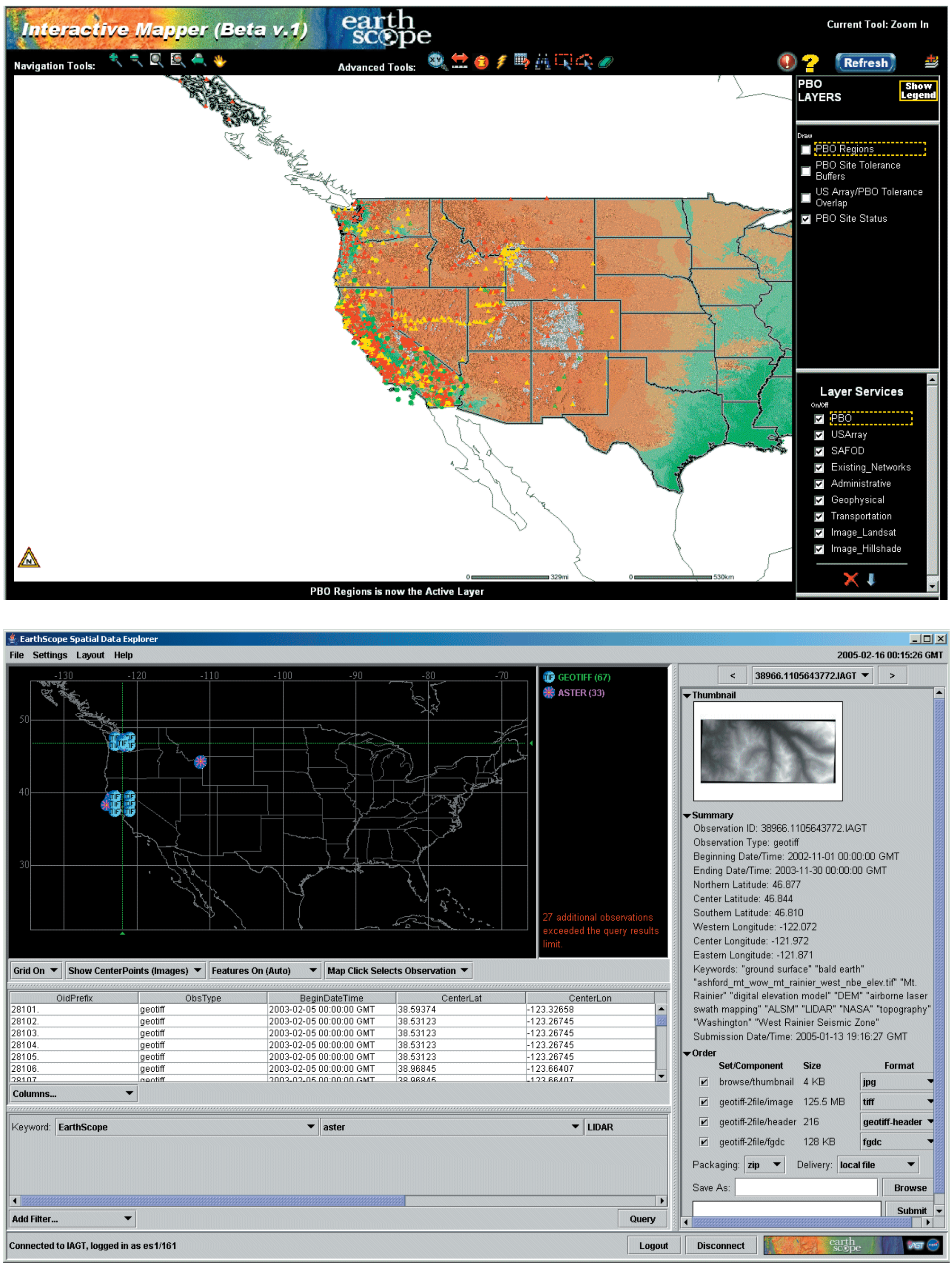
EarthScope Spatial Data Explorer

Fred Pieper

Institute for the Application of Geospatial Technology

The EarthScope Spatial Data Explorer (ES SD-Explorer) is a java application for querying, browsing, and acquiring data from the ES Spatial Data Repository (ES SD-Repository). ES SD-Explorer and ES SD-Repository are two components of the ES Spatial Data Distribution Network (ES SD-DNet) designed to enable distributed access to a shared repository of ancillary spatial data (e.g. LIDAR, SRTM elevation data, Landsat images, etc.) relevant to the EarthScope community beyond the primary EarthScope data products themselves.

The ES SD-Explorer is being developed by the Institute for the Application of Geospatial Technology (IAGT) with support from the National Aeronautics and Space Administration (NASA), a partner in the EarthScope project.



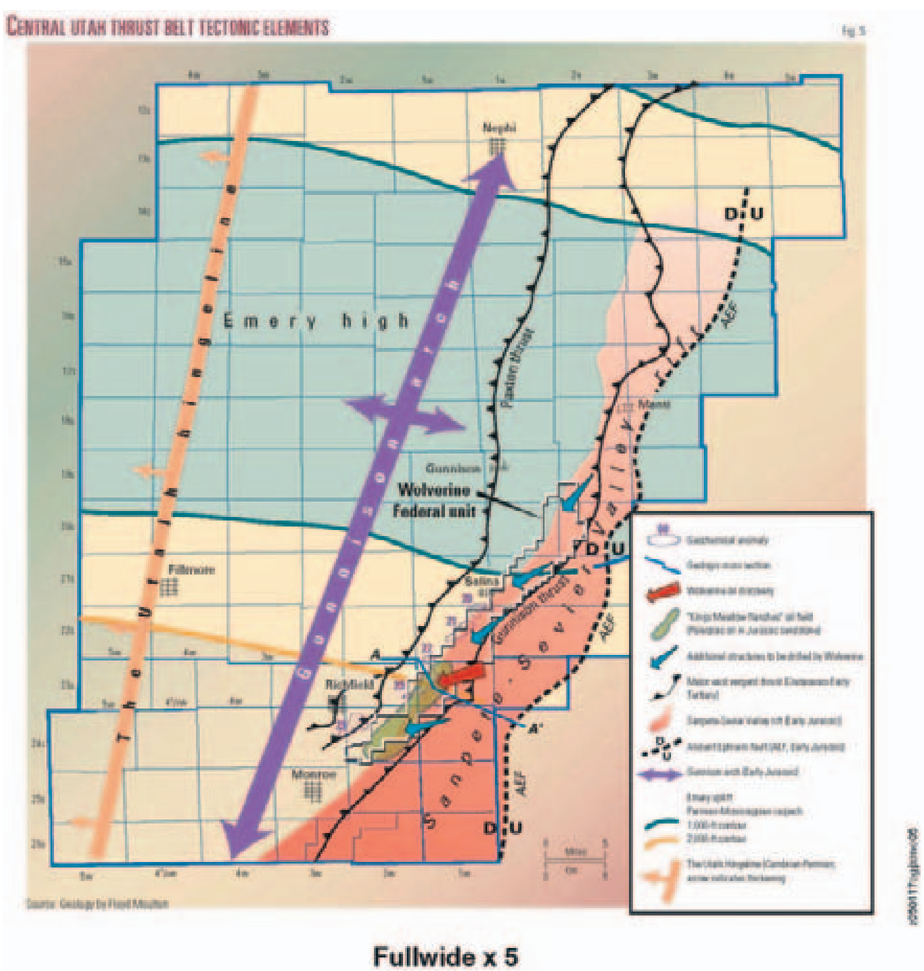
The EarthScope Spatial Data Explorer.

Central Utah's Ancestral Continental Margin Manifests Shallow, Complex Geology Conducive to Previously Unknown World-class Petroleum Reserves Resulting in What May Become the Most Scrutinized Ancient Continental Margin in the World

Michael Pinnell
Pioneer Oil and Gas

Floyd Moulton
Pioneer Oil and Gas

A tremendous oil field with recoverable reserves approaching one billion barrels has been recently discovered in central Utah. The accumulation is so significant that the first two wells, when produced at their maximum capacity, overwhelm the refining capacity of the state of Utah. Fifteen additional wells will exceed the production rate of all oil wells in the entire state. Sixty wells may be required to produce the oil from this behemoth alone. An analysis of the oil defines a surprising Paleozoic source with high API gravity (40) and low sulfur content (0.057%). The 50 by 150 mile area of potentially productive fields may contain five additional accumulations of this magnitude or a large number of smaller fields with equivalent reserves. The area with the greatest potential is directly associated with the ancient continental margin. The Pennsylvanian age westerly trending Emery High morphed into the Jurassic, north-northeasterly tending Gunnison arch. This arch and the Ancient Ephraim Fault to the east accentuated the Sanpete-Sevier Valley Rift with its thick evaporite and mudstone deposits exceeding 6,000 feet. The entire area of older uplifts and pseudo-rifting was then overridden by Sevier thrusting from west to east consisting of four major thrust sequences ranging in age from early-late Cretaceous to earliest Tertiary. The easternmost thrust system, the Ginnison, has been subsequently modified by post-thrusting salt tectonics wherein an 80 mile long "Salt glacier" has cut up section at an approximate 45 degree angle, affectively hiding the oil productive anticline and the possible extent of subsequent, productive structures below this now inactive red massive feature. Subsequent Basin and Range extension has modified but not destroyed these hydrocarbon filled anticlines. The oil and gas industry will acquire thousand of miles of new, super quality seismic data simultaneously with new gravity and magnetic data. And perhaps hundreds of wells will be drilled, some to depths exceeding 20,000 feet. This work will help to better define the nature and economic significance of the ancient, central Utah continental margin-transition zone. This new exploration province of Sevier thrusting superposed on older structural diversity will finance innumerable geophysical and geological research opportunities and may become one of the most scrutinized ancient continental margins in the world when combined with the ongoing data being gathered by EarthScope.



Tectonic elements in central Utah, although diverse, have been active since at least the Cambrian. They are the result of a variety of ongoing tectonic plate interactions and are manifest along a zone or zones of crustal weakness.

A Physical Model of the Western U.S. Strain Rate Field

Fred Pollitz
U.S. Geological Survey

Mathilde Vergnolle
U.S. Geological Survey

Constraints on long-term deformation characteristics of the continents are provided by geologic slip rates on major faults, paleomagnetic rotations, and estimates of instantaneous velocity as measured by Global Positioning System (GPS) or other geodetic measurements over a short time span. Geologic slip rates and paleomagnetic rotations represent the long-term velocity field (i.e., that averaged over a timescale much longer than the earthquake cycle on an individual fault) in the vicinity of the corresponding faults or blocks. On the other hand, instantaneous velocity measurements correspond to a timescale that is much shorter than a typical earthquake cycle on a major fault. In order to satisfactorily explain the instantaneous velocity field, one generally requires estimates of slip of significant historic earthquakes, the mechanics of tectonic loading, and the underlying rheology. We present a relationship between the long-term dislocation rates and instantaneous velocities. The main elements of this relationship are the secularly increasing forces imposed by the bounding Pacific and Juan de Fuca plates on the North American plate and viscoelastic relaxation following selected large earthquakes. In detail, the physical model allows separate treatments of faults with known geometry and slip history, faults with incomplete characterization (i.e., fault geometry but not necessarily slip history is available), creeping faults, and dislocation sources distributed between the faults. For faults with known slip history, the relationship depends on a viscoelastic Earth model and accounts explicity for viscoelastic cycle effects. For discrete faults with unspecified slip history as well as distributed dislocation sources, it is appropriate to use the average interseismic velocity produced by viscoelastic relaxation over an entire cycle.

The contribution of secularly increasing forces to the stress field is balanced in the long term by those contributions from coseismic and postseismic stress changes associated with earthquakes. Horizontal forces arising from lateral gradients in gravitational potential energy likely play a role in driving western US active deformation (e.g., Flesch et al., 2000). However, such forces do not play an explicit role in shaping the active deformation in our framework because a constant force does not contribute to the instantaneous velocity or strain rate fields. Indirectly, these forces generate an absolute stress field which promotes Basin and Range normal faulting and fault-perpendicular shortening around the SAF system. The moment release associated with these dislocation sources contribute to the instantaneous velocity field.

We apply the physical model to the instantaneous strain rate field in the western United States, derived from 746 GPS velocity vectors (Figure 1), in order to test the importance of the relaxation from historic events and characterize the tectonic forces imposed by the bounding Pacific and Juan de Fuca plates. Our modeling of the western US strain rate field shows that relaxation following major earthquakes (M 8.0) strongly shapes the present strain rate field over most of the plate boundary zone. Equally important are lateral shear transmitted across the Pacific - North America plate boundary along about 1000 km of the continental shelf and downdip forces distributed along the Cascadia subduction interface. Post-earthquake relaxation and tectonic forcing constructively interfere near the western margin of the plate boundary zone, producing, locally large strain accumulation along the San Andreas fault (SAF) system. However, they destructively interfere further into the plate interior, resulting in smaller and more variable strain accumulation patterns in the eastern part of the plate boundary zone. Much of the right-lateral strain accumulation along the SAF system is systematically underpredicted by first-order models, which account for relaxation only from known large earthquakes. This discrepancy can be reduced by introducing additional, distributed strike-slip (and normal) faulting centered primarily around the SAF system, but a strong alternative explanation is steady aseismic slip/creep in the deeper elastic lithosphere.

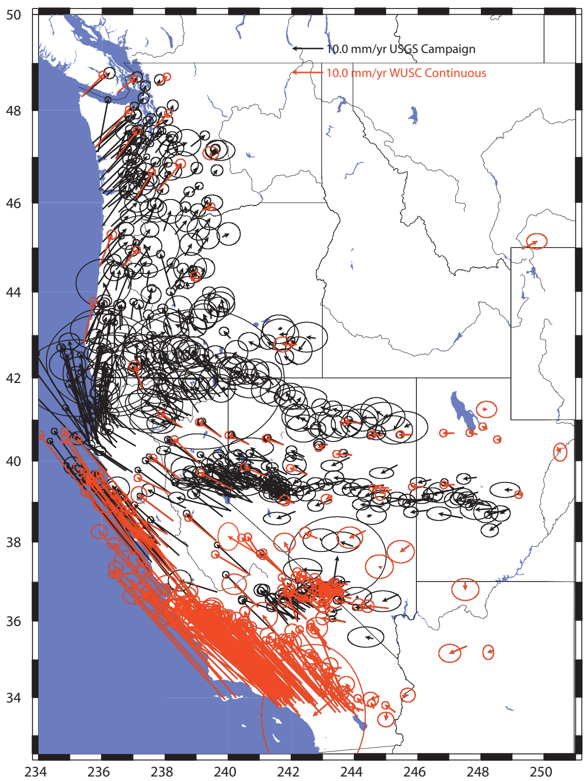
In the future, the Plate Boundary Observatory will provide the data necessary to refine the present image of the western US strain rate field. This will allow better discrimination among the loading, viscoelastic relaxation, and creep processes and allow inferences to be drawn on the roles of rheology (transient versus Maxwell) and lateral variations in material properties.

Figures on Page 215 >

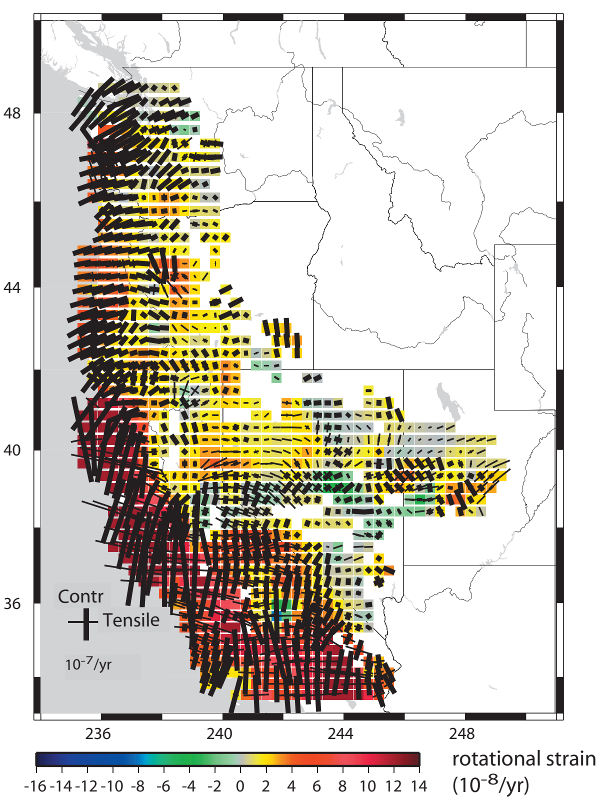
A Physical Model of the Western U.S. Strain Rate Field
Continued

Fred Pollitz
U.S. Geological Survey

Mathilde Vergnolle
U.S. Geological Survey



Representation of wesetern US strain rate field in terms of the andplitudes and directions of the principal strain rate axes (thick and thin line segments denoting a principal contractile or tensile strain rate axis, respectively) and rotational strain rate (indicated by color shading). The strain rate field is derived from the GPS velocity field using the method of Shen et al. (1996).



Composite GPS velocity field from several USGS campaigns conducted in the western US from 1993 to 2003 plus continuous GPS data provided by R. Bennett (version 002 of the WUSC velocity field). There are a total of 486 GPS velocity vectors contributed by the USGS campaign data and 260 velocity vectors contributed by the WUSC velocity field. The two data sources (USGS campaign; WUSC) have 84 common sites, and we determined a rotation between the two associated velocity fields that aligns the two velocity fields to within the measurement errors (generally ~1 mm/yr standard deviation in both East and North components for the USGS campaign measurements; ~0.5 mm/yr for the WUSC continuous measurements).

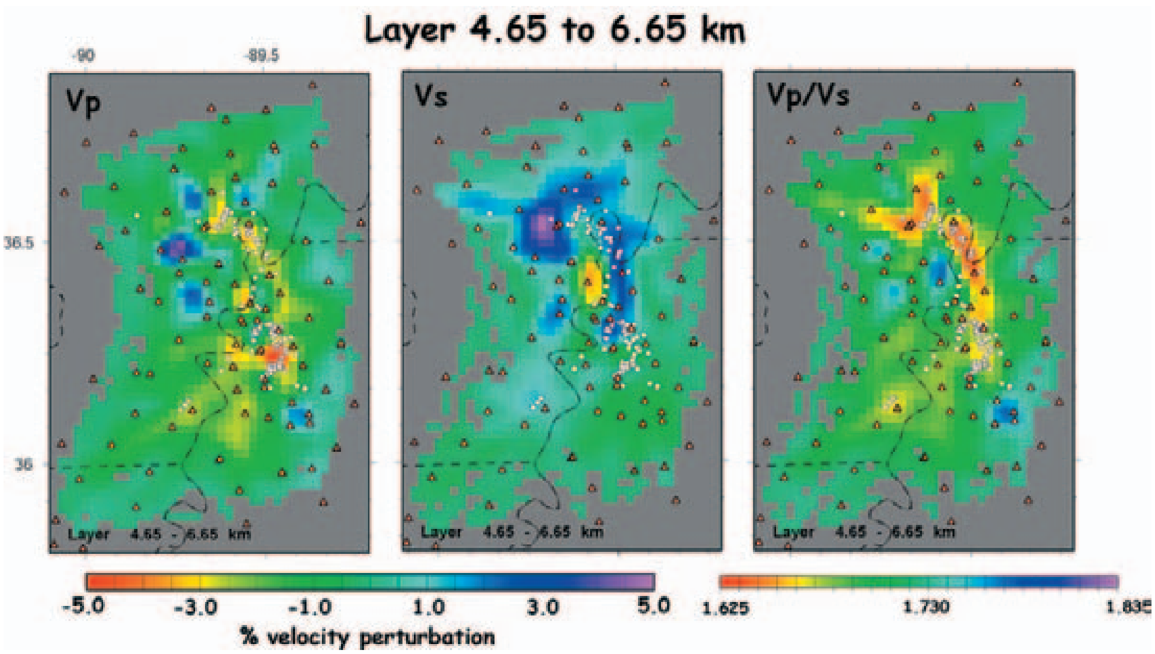
Anomalous V_p/V_s Ratios and Intraplate Seismicity: An Important Target for USArray?

Christine Powell
University of Memphis

Mitch Withers
University of Memphis

Gordana Vlahovic
North Carolina Central University

Detailed P and S wave velocity models and V_p/V_s values have been determined for the New Madrid Seismic Zone (NMSZ) using arrival times recorded by the New Madrid seismic network and by PANDA stations. The combined data set consists of 11,778 P wave arrivals and 8,579 S wave arrivals recorded by 97 stations. We performed a simultaneous inversion for P and S wave velocities and hypocentral locations. Block size was reduced to 2x2x2 km, yielding the most detailed image of the NMSZ ever obtained. Inversion results were tested using chessboard models, spike tests and reconstruction techniques. Intrusions were imaged in great detail. Low P wave velocity and high S wave velocity appear to be correlated with earthquake occurrence; this results in distinct regions of low V_p/V_s values that correspond to the major arms of seismicity. The unusual low V_p/V_s values could be due to lithology variations (e.g. very quartz rich rocks) but may be related to factors such as fracturing, fluid saturation and porosity variations. The striking coincidence of low V_p/V_s values and earthquake occurrence in the NMSZ suggests that detecting low V_p/V_s ratios in intraplate regions may be an important target for USArray. Careful mapping of V_p/V_s may provide insights into why certain portions of intraplate failed rifts are seismically active while other portions are not.



New Madrid seismic zone P and S wave velocity models (percent velocity perturbation) for the depth range 4.65 to 6.65 km. Note the anomalously low V_p/V_s values and that these values coincide with the major arms of seismicity. White dots are earthquakes in this layer. Triangles are stations.

Detecting Magma Reservoirs: What Should We Expect Based on Magmatic Timescales?

Mary Reid
Northern Arizona University

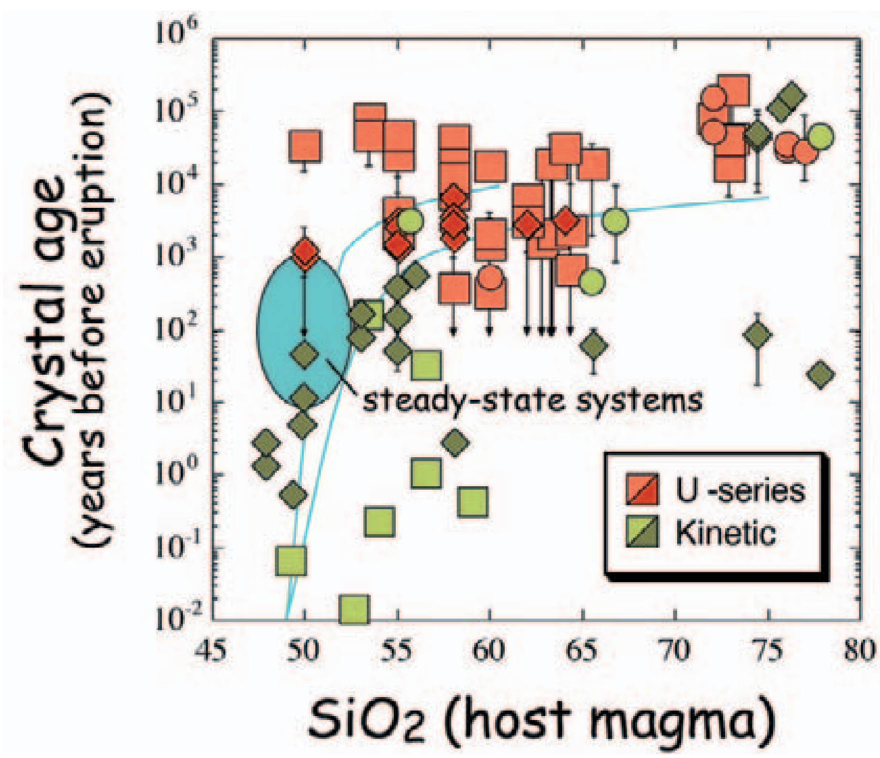
Magma systems can be imaged by a wide variety of geochemical and geophysical approaches for insights into the duration and dynamics of magma residence in the crust. The duration of magma residence should help to predict the probable success of detecting magma reservoirs. Most studies of magma residence have been applied to volcanic rocks and may preferentially image the most-fluid portions of a magma reservoir.

For basaltic magmas, relatively short periods (<<1 k.y.) for magma residence have generally been inferred and could reflect the absence of shallow magma reservoirs or, where present, its small volume and/or high turnover rate. Thus, except where shallow and at quasi-steady-state, it may be difficult to remotely detect the presence of a mafic magma reservoir.

Andesitic to dacitic magmas - at least those associated with arc stratovolcanoes - are complicated by the effects of magma recharge, crustal assimilation, and recycling and ascent-related resorption of crystals. Magmatic residence times appear to be relatively short (<1 ky) and "old" (tens of k.y.) ages obtained on mineral aliquots from these magmas could reflect intrusion into and recycling of earlier (co-genetic and mushy?) intrusive bodies. Multiple magma domains may coevolve in limited geographical areas as, for example, in a subvolcanic plexus of dikes and sills which may diminish the probability of capturing images of magma reservoirs in these systems.

The relative monotony of some silicic magmas at scales of tens to hundreds of km3 would seem to imply the potential for long and well-integrated conditions of magma storage to be established. Moreover, crystallization timescales obtained by mineral dating lend support to magmatic timescales of tens to hundreds of k.y. It is possible, however, that once differentiated, silicic magmas solidify and are stored in the crust, only to be later remobilized by reheating. Or, rather than the commonly held image of shallow magma storage, magma bodies might persist at depths where remote sensing approaches are resolution-limited.

Overall, the several year to few thousand year residence times for the majority of magmas show that individual magma batches are very transient features of the ~0.5 to several m.y. life-spans of many individual volcanic and plutonic systems. Even the timeframes inferred for silicic magmas are short-lived with respect to repose intervals between the more voluminous silicic eruptions and therefore the duration of silicic activity at any particular volcanic system. If the liquid portions of reservoirs responsible for these magma batches are equally ephemeral features, detection of several magma reservoirs by EarthScope will be statistically improbable but not impossible.



Compilation of crystals ages based on radiometric dating ("U-series") and kinetic considerations of crystal growth rates and relaxation of chemical and isotopic gradients within crystals. Also shown are magmatic timescales estimated from steady-state magma reservoir models and from the presence of Ra excesses in lavas (curved lines). Modified after Reid (2003).

Borehole Recordings of Fluid Pressure, Strain, and Microearthquakes at Long Valley Caldera, California, Following the September, 2004, Adobe Hills Earthquake Swarm and the December 26, 2004, M9.0 Sumatra Earthquake

Evelyn Roeloffs
U.S. Geological Survey

J. Andres Chavarria
Duke University

Christopher Farrar
U.S. Geological Survey

Long Valley caldera, California, is a volcanically active area where microearthquakes have been triggered by seismic waves from several earthquakes of magnitude greater than 7 at distances of hundreds of km. Borehole instrumentation at the caldera, which includes fluid-pressure sensors and strainmeters operated by the U.S. Geological Survey, and seismometers operated by Duke University, can directly measure the effects of earthquake-generated seismic waves. Seismic waves are observed to produce both oscillatory and persistent fluid pressure and strain changes, which are of interest for their likely relation to the mechanism of the remotely triggered microseismicity.

Seismic events of extremely different sizes produced fluid pressure and strain changes at Long Valley during 2004: the September 18 mainshocks (M5.5, M5.4) of the Adobe Hills earthquake swarm, and the December 26 M9 Sumatra earthquake.

The Adobe Hills swarm is about 40 km NE of the Long Valley caldera. At an instrumented thermal well in the caldera south moat, each mainshock produced pressure fluctuations reaching 0.1 m of water peak-to-peak, with fluctuations in excess of 1 cm of water lasting less than 5 minutes. The first Adobe Hills mainshock also produced a gradual water-level drop at the LKT well, outside the thermal aquifer. No additional changes were induced by the second mainshock, consistent with the observed responses to previous earthquakes closely spaced in time.

The Sumatra earthquake, whose epicenter was 14199 km from Long Valley along a great circle route, produced pressure fluctuations in excess of 1 cm of water that lasted more than 1.5 hours, with fluctuations of 0.1 m or greater lasting more than 30 minutes. Borehole strainmeters recorded peak-to-peak fluctuations of 0.5 microstrain, with oscillations 0.1 microstrain peak-to-peak persisting for at least 20 minutes. The Sumatra earthquake, however, was not followed by gradual, persistent fluid pressure changes.

The lack of persistent fluid-pressure changes in response to the relatively large and long-duration pressure and strain oscillations imposed by the December 26 Sumatra earthquake imply that the changes caused by the September 18 Adobe Hills earthquakes involve processes that cannot be reactivated until a period of time exceeding 90 days has elapsed. Examples of such processes would be unclogging of fractures by removal of gradually deposited particles, or triggering of a small pulse of dome inflation by release of slowly accumulated stress.

The relationship of the earthquake-induced fluid pressure and strain changes to remote triggering of seismicity is less clear. No marked increase of seismicity occurred during the passage of surface waves from either the Adobe Hills mainshocks or the Sumatra earthquake.

However, a borehole seismometer at a depth of 2349 m in the Long Valley Exploration Well recorded an increased number of microearthquakes during the 4 days following the September 18 Adobe Hills mainshocks. No such increase followed the December 26 Sumatra event. If the increased seismicity following the Adobe Hills mainshocks represented low-level triggering, then the same process was not reactivated by the seismic waves from the Sumatra earthquake.

In the future, Plate Boundary Observatory borehole strainmeters, seismometers, and fluid pressure sensors planned for Long Valley will record these processes in greater detail.

Using USArray to Study the Spatial and Temporal Distribution of Sources of the Earth's Hum

Barbara Romanowicz
University of California Berkeley

Junkee Rhie
University of California Berkeley

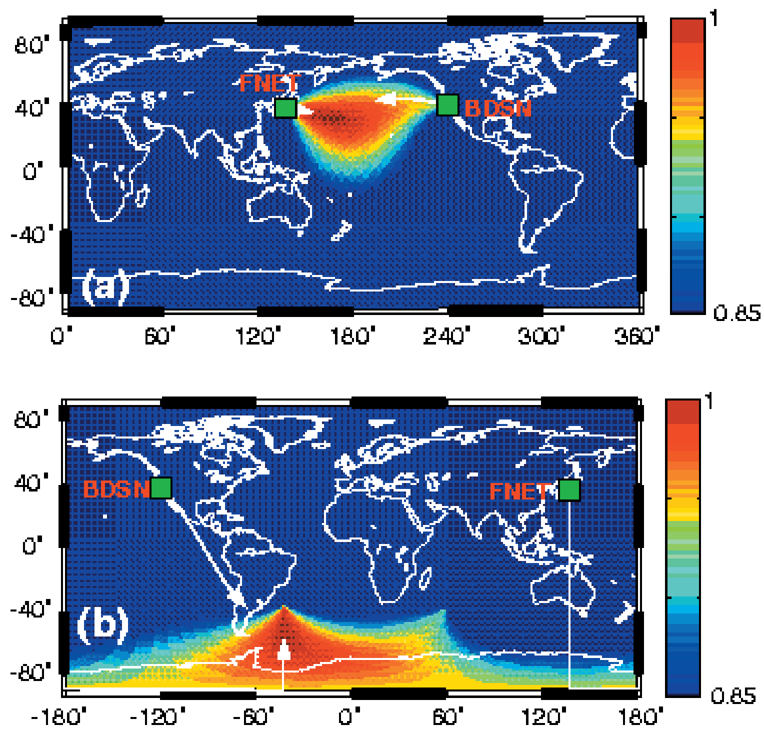
The observation of continuously excited free oscillations of the Earth, in the absence of earthquakes, was first made by Japanese scientists in 1998. Since then, attention has focused on elucidating the physical mechanism responsible for them. The mechanism must be shallow, as fundamental modes appear to be preferentially excited and the observed amplitudes show seasonal variability.

We have developed an array-based method to detect and locate sources of the hum, using a propagating wave approach, the dispersive properties of Rayleigh waves and data from two large aperture arrays of very long period seismometers, in California and in Japan. We have shown that, for each array, there is a well defined preferential direction, which is stable over one season but changes significantly from winter to summer. The fluctuations as a function of time of the maximum stack amplitudes are correlated across the two arrays and point to the northern Pacific ocean in the northern hemisphere winter and the southern Oceans in the summer, correlating with the temporal fluctuations in the distribution of maximum wave height on the global scale (Figure 1). We have inferred that the background oscillations originate primarily in the oceans, and are caused by a non-linear coupling mechanism involving the atmosphere (winds), the oceans (infragravity waves) and the seafloor (Rhie and Romanowicz, 2004).

Further analysis of several particularly large North Pacific storms indicates that a given ocean storm can produce a series of relatively weak seismic sources, and that the coupling occurs most likely when the ocean waves reach the continental shelf, by interaction with the complex ocean floor topography. We show in particular that the Rayleigh waves produced can be followed deep inside the north American continent. To elucidate this mechanim further, we need to determine the location of the ocean/seafloor coupling more accurately. We discuss that how the "Backbone" and BigFoot USArray data will contribute to form a powerful antenna to better resolve the temporal and spatial distribution of the sources of the "hum".

Reference:

J. Rhie and B. Romanowicz (2004) Excitation of earth's incessant free oscillations by Atmosphere-Ocean-Seafloor coupling, *Nature*, 431, 552-556.



Seasonal variations in the distribution of hum-related noise in the year 2000. Data are narrow-band filtered with a center period of 240 sec. Stacks are computed for each array (Berkeley Digital Seismic Network in California) and F-NET in Japan, accounting for Rayleigh wave dispersion, as a function of possible back-azimuth of arrival. The stack amplitudes are averaged over the summer months (April- September) and winter months (October-March). For each point on the globe, we compute the sum of the corresponding stack amplitudes. Directions corresponding to mean amplitudes over the that are larger than 85% of the maximum are shown for the winter (a) and for the summer (b). Arrows indicate the back-azimuths of the seasonal maximum for each array (Rhie and Romanowicz, 2004).

Assembling Virtual California

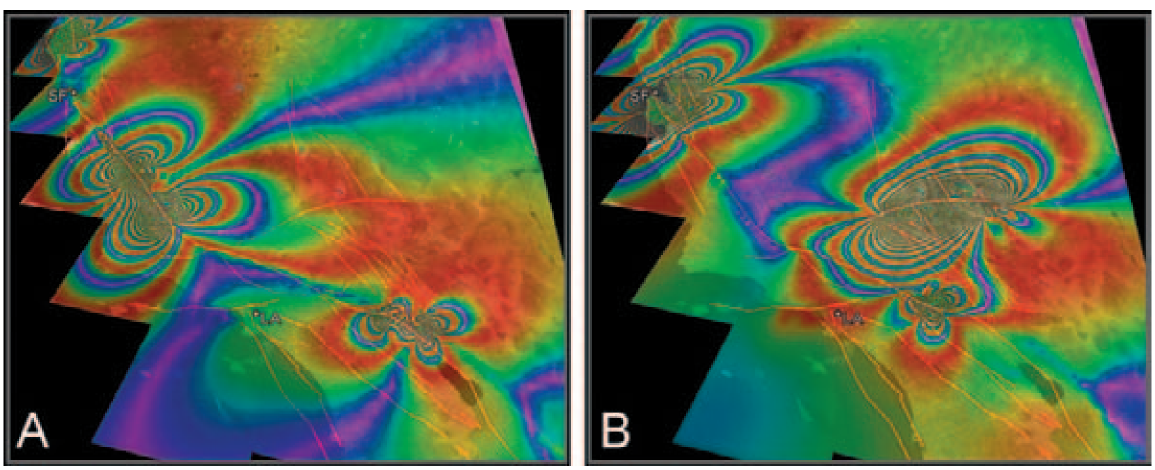
John Rundle
University of California Davis

Paul Rundle
Harvey Mudd

Morein Gleb
University of California Davis

Andrea Donnellan
Jet Propulsion Laboratory

Observations associated with the InSAR component of EarthScope will provide a very large, but unique window into the complex nonlinear dynamics of the earth's crust. To understand and illuminate these observations, we have developed a earthquake fault system-level simulation capabilit, Virtual California. Using these topologically and dynamically realistic simulations, it will be possible to develop ensemble forecasting methods similar to that used in weather and climate research. To effectively carry out such a program, one needs 1) a topologically realistic model to simulate the fault system; 2) data sets to constrain the model parameters through a systematic program of data assimilation; 3) a computational technology making use of modern paradigms of high performance and parallel computing systems; and 4) software to visualize and analyze the results. In particular, we focus attention of a new version of our code Virtual California (version 2001) in which we model all of the major strike slip faults extending throughout California, from the Mexico-California border to the Mendocino Triple Junction. We use the historic data set of earthquakes larger than magnitude M > 6 to define the frictional properties of all 650 fault segments (degrees of freedom) in the model. By analyzing the statistical physics of the simulations, we can show that that the frictional failure physics, which includes a simple representation of a dynamic stress intensity factor, leads to self-organization of the statistical dynamics, and produces empirical statistical distributions (probability density functions: PDFs) that characterize the activity. An example is the Gutenberg-Richter magnitude frequency distribution obtained from simulations, which is seen to be similar to the corresponding distribution in nature (although modified by the restricted range of spatial scales in the simulations). Another type of distribution that can be constructed from empirical measurements of simulation data are PDFs for recurrence intervals on selected faults. Inputs to simulation dynamics are therefore based on the use of time-averaged event-frequency data, and outputs include PDFs representing measurements of dynamical variability arising from fault interactions and space-time correlations. As a first step for productively using model-based methods for earthquake forecasting, we propose that simulations be used to generate the PDFs for recurrence intervals instead of the usual practice of basing the PDFs on standard forms (Gaussian, Log Normal, Pareto, and so forth). Subsequent development of simulation-based methods should include model enhancement, data assimilation and data mining methods, and analysis techniques based on statistical physics. Examples of InSAR patterns produced by Virtual California are shown in the figures here.



Simulated InSAR fringes from large earthquakes in Virtual California.

Scattered Wave Imaging of the Lithosphere and the Asthenosphere Beneath Eastern North America

Catherine Rychert
Brown University

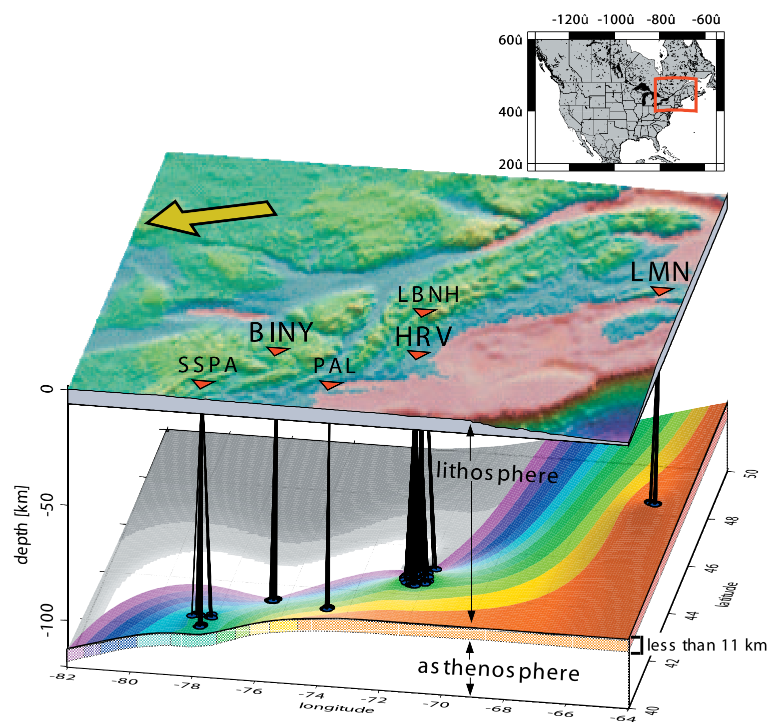
Karen Fischer
Brown University

Stephane Rondenay
Massachusetts Institute of Technology

To better understand the properties that define the lithosphere and the asthenosphere beneath continents, we have analyzed P-to-S phases produced by scattering beneath permanent broadband seismic stations HRV, PAL, LMN, LBNH, BINY, and SSPA in eastern North America. We image a negative velocity discontinuity (velocity decrease with depth) at 90-110 km depth, increasing in depth toward the west. The depth of this discontinuity is consistent with the westward dipping lithosphere-asthenosphere boundary imaged by surface-wave tomography. The existence and depth of the discontinuity are independently confirmed by S-to-P scattered phases at HRV.

Although the scattered and surface waves see a lithosphere-asthenosphere boundary at similar depths, the higher frequency energy in the P-to-S scattered phases provides much sharper resolution of the associated velocity gradient. After modeling shallower discontinuities, we use the shape of the converted phase to invert for the depth, magnitude, and depth range over which the discontinuity occurs. The period of the incident P-wave is independently constrained by the auto-deconvolved component of P-wave motion. Inversions of data at LMN and HRV require that this velocity gradient be strong, a 3-11% drop in shear-wave velocity, and sharp, occurring over less than 11 km in depth. Experimental studies suggest that a temperature increase on the order of 100°C could easily account for the observed velocity contrast. However, based on typical thermal models of lithospheric cooling and mantle convection boundary layers, concentrating such a gradient over depths of less than 11 km is implausible. Therefore, the lithosphere-asthenosphere boundary in this region is not defined by temperature alone, and requires another mechanism such as dehydration, depletion, or melt. Although, taken separately, depletion or dehydration may be too small to explain the upper limits of the observed contrast, the combination of a depleted lithosphere with a hydrated asthenosphere can explain most of the observed velocity gradient. Alternatively, a small amount of partial melt in the asthenosphere can easily explain the observed strong, sharp velocity contrast.

To investigate the properties of the asthenosphere at greater depths, we are now investigating later scattered arrivals at these stations. A strong phase in the ~240-270 km depth range is observed at station HRV on both the SH and the SV migrated waveforms. Analysis of these particle motions demonstrates that the phase has undergone shear-wave splitting, and that anisotropy is required above the discontinuity.



Three-dimensional view of the lithosphere-asthenosphere boundary and surface topography. Red box in the inset map highlights the location of the study region within North America. Shading on the top plate indicates topography. Yellow arrow points in the direction of absolute plate motion; plate velocity is 2.5 cm/yr. Red triangles denote station locations. The larger text corresponds to the stations (HRV, LMN, BINY) where this phase is most clearly observed. The lower surface represents the location of the base of the lithosphere interpolated from migrated Ps waveform images at the 6 labelled stations. The surface ranges from 90 km (orange) to 110 km (pink). Each color band covers 2 km in depth. Blue circles on the discontinuity surface indicate the conversion points of the Ps phases. Black lines connect piercing points to the station at which the conversion is observed.

Structure of the San Andreas Fault Zone in the Vicinity of SAFOD — Evidence from Surface Geologic Mapping and Seismic Profiling

Michael Rymer
U.S. Geological Survey

Rufus Catchings
U.S. Geological Survey

In the vicinity of the San Andreas Fault Observatory at Depth (SAFOD) and at the southeast end of Middle Mountain, near Parkfield, California, new geologic mapping, combined with high-resolution seismic reflection and refraction profiling, indicate a wide and structurally complex San Andreas fault zone. The geologic and geophysical investigations both indicate the location and orientation of previously unmapped faults. The San Andreas fault zone near the SAFOD site is at least 5 km wide and is dominated by faults oriented subparallel to the surface trace of the San Andreas fault. Subsurface orientation of faults indicate that the San Andreas fault zone is composed of at least two flower structures in the upper 3 km, with the main trace approximately centered on the more easterly of these structures. The SAFOD drill site is located near the center of the other flower structure. A third flower structure may lie farther to the southwest of our studies. The flower structures likely merge at depth, but at least in the upper 3 to 4 km (the target depth of the SAFOD main hole), they are distinct features. Based on inferred ages of rock types juxtaposed across faults and geomorphic evidence along faults, it appears that the plate boundary (San Andreas fault zone) near the SAFOD site has jumped eastward during the past approximately 20 million years, forming new flower structures during the jumps.

The San Andreas fault zone near the southeast end of Middle Mountain likewise is structurally complex. There, multiple subparallel active fault strands, along with short faults that transfer strain between subparallel strands, form a zone that is 1 to 2 km wide; these active faults, which moved in the 2004 Parkfield earthquake, are set between older, currently inactive strands that, in total, form a fault zone that is 4 to 5 km wide. Slip on faults within the San Andreas fault zone has juxtaposed different rock types that result in both fault-parallel and fault-normal variations in rock velocities.

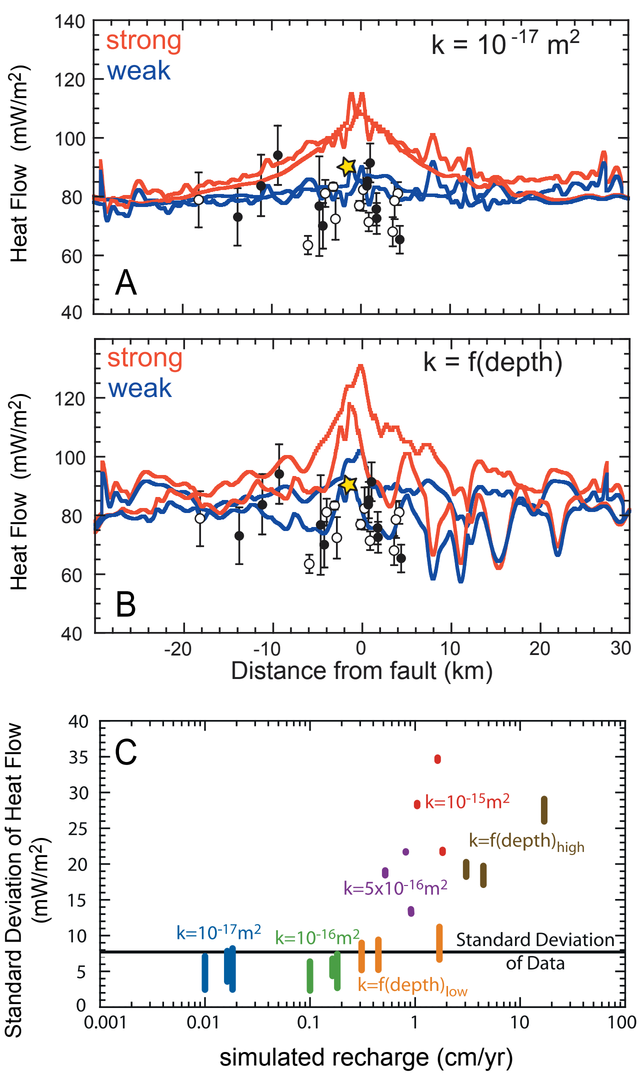
Heat Flow Data as an Indicator of Fault Strength: Insights from a Hydrologic Perspective

Demian Saffer
Pennsylvania State University

Patrick Fulton
Pennsylvania State University

Barbara Bekins
U.S. Geological Survey

Evidence for a weak San Andreas Fault (SAF) includes (1) borehole heat flow measurements that show no evidence for a frictionally generated heat flow anomaly, and (2) the inferred orientation of sigma 1 nearly perpendicular to the fault trace. Interpretations of the stress data remain controversial, at least in close proximity to the fault, leading some researchers to hypothesize that the SAF is, in fact, strong, and that its thermal signature may be obscured by topographically driven groundwater flow. To evaluate this scenario, we use a steady state, 2-D model of coupled heat and fluid flow within cross sections oriented perpendicular to the fault and to the primary regional topography in the Parkfield and Mojave (Palmdale) areas. Our results show that for a wide range of groundwater flow scenarios, models that include frictional heat generation along a strong fault are inconsistent with heat flow data when corrected for 3-D topographic refraction effects, suggesting that the SAF does not generate appreciable frictional heat. For constant permeabilities less than ~10-16 m^2 or permeabilities that decrease exponentially with depth following Manning and Ingebritsen [1999], topographically-driven groundwater flow does not significantly impact patterns of heat flow. For these scenarios, frictional heat generation along the SAF results in a clear fault-centered heat flow anomaly, which is not observed. For higher permeabilities, the near-field thermal anomaly is obscured. However, such high permeabilities result in distinct patterns of heat flow and elevation that are not observed, and also lead to considerably greater variability in heat flow than is observed. More complex permeability structures that include a fault conduit, fault barrier, or combined fault barrier-conduit also yield heat flow patterns that are incompatible with existing data. The robust results demonstrate that topographically driven groundwater flow, at least in two dimensions, is inadequate to obscure the frictionally generated heat flow anomaly from a strong fault. This result suggests that (1) the SAF is indeed anomalously weak, or (2) frictional heating along a strong SAF constitutes a considerably smaller fraction of the energy budget than estimated by previous authors.



Comparison of heat flow data and simulated heat flow for plausible groundwater flow conditions from three model transects at Parkfield, projected along-strike and registered to the fault at x = 0, for k = 10-17 m^2 (Panel A), and k = f(depth) (Panel B). Colored lines show simulated heat flow for heating along a strong (red) and weak (blue) SAF; the two lines for each scenario indicate the maximum and minimum simulated heat flow for the three transects. We differentiate between boreholes that have thermal conductivity measurements (open) and those that use formation averages (solid). The star (yellow) represents the heat flow value for the SAFOD pilot hole. Panel C shows the variability in observed heat flow (black line) compared with that predicted by each groundwater flow scenario (colored bars) as a function of the mean recharge flux required. Models that require recharge rates > ~1 cm/yr predict a large degree of variability which is not observed.

Strain Accumulation Across the Central San Andreas Fault: Impact of Laterally Varying Crustal Properties

Gina Schmalzle
University of Miami

Timothy Dixon
University of Miami

Rocco Malservisi
University of Miami

Rob Govers
University of Utrecht

Major strike slip fault systems, such as the San Andreas Fault, have one common characteristic: lateral juxtaposition of geologically dissimilar terrains. Terrains on opposite sides of the fault may vary in both geometry of the elastic upper crustal layer and in their material properties. The Carrizo segment of the San Andreas Fault is a prime area to study the effects of asymmetry imposed by strike slip faulting because it is a straight segment and exhibits relatively simple seismic behavior. We present new GPS data on the Carrizo segment to quantify the asymmetry, as well as a series of numerical models designed to investigate various classes of asymmetry. Our models are implemented with the finite element technique, and investigate differences in elastic layer thickness and variable material properties of the upper crust. We find that available data are well fit by a simple model whereby a relatively weak zone (approximating the upper and middle crust) 10-20 km wide exists on the northeast side of the fault.

The Role of Supplementary Data Sets in EarthScope Science

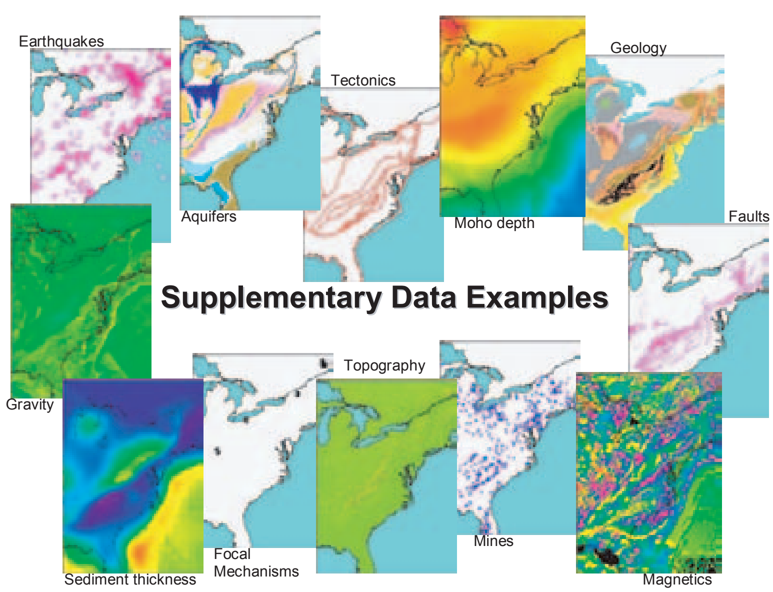
Dogan Seber
University of California San Diego

Krishna Sinha
Virginia Tech

Over the next 10 years and beyond, the EarthScope project will generate large amounts of new data sets across the continental U.S and Alaska. The primary EarthScope (ES) data sets (USArray, PBO, and SAFOD) will be maintained and disseminated through well-established major data centers such as IRIS and UNAVCO. However, in order to conduct the integrative science needed to make the ES project a major success will require non-EarthScope data sets to be organized and disseminated as well. Most of the scientific questions addressed by the EarthScope science plan such as 4-D evolution of continents, as well as a more quantitative understanding of hazards, require utilization of supplementary data sets covering the entire spectrum of the Earth sciences. For example, the ES science document states that ES seeks answers to questions such as "How is continental lithosphere formed? How are continental structure and deformation related?" This requires the community to move from discipline specific thinking to a broader comprehensive problem solving environment. Such an environment requires access to comprehensive data resources and integration tools.

To be successful an EarthScope supplementary data system will have to include rich and comprehensive data sets, provide tools to analyze and integrate such data, and serve multiple purposes from the design of ES stations to final science integration issues. However, to build such a system brings about significant challenges that need to be addressed. Some of the challenges to be faced are: developing a requirements document identifying the information technology needs in such a system, identification of data sets and their sources/locations, acquiring identified data sets (formatting/digitization), developing comprehensive metadata, developing search/access mechanisms, developing tools to quickly browse, map collected data sets, and develop the required semantic framework for data integration and interpretation. Although many research activities are underway, to meet some of these challenges, significant research needs remain. Without such a comprehensive and collaborative effort led by the community, ES efforts will fall short of their maximum potential profitability.

To build such a system we consider three models. The first and the least effective one is a model where individuals maintain their data and share them at their will with their colleagues. The second model would involve building a centralized ES supplementary data warehouse where community members submit their data sets and resources to be maintained and disseminated. This model would require that all earth scientists agree to follow standards for data formats, archiving and distribution. This activity would require a permanent staff and new hardware to manage the data. We, however, suggest that the most beneficial option would be to build a system based on a distributed and shared network model. In this model, data sets are maintained, coordinated, and integrated via web-based collaborative efforts. We suggest that EarthScope science goals can be readily met by the development of a cyberinfrastructure where scientists would discover data, tools, and models via portals using advanced semantic-based search engines and query tools. We envision this to be a web-based interpretive environment for EarthScope science. However, in order to get community acceptance of shared data resources, we believe there is the need to rapidly develop a community recognized system that provides proper citation and credit for sharing data and tools. Although the development and operation of such a system will require significant resources, the costs could be reduced significantly by taking advantage of existing cyberinfrastructure efforts in the earth science community.



Sample regional-scale supplementary data sets that will be helpful in EarthScope science activities.

Direct Constraints on Glacial Isostatic Adjustment (GIA) Motion North American Using GPS and Implications for Plate Rigidity

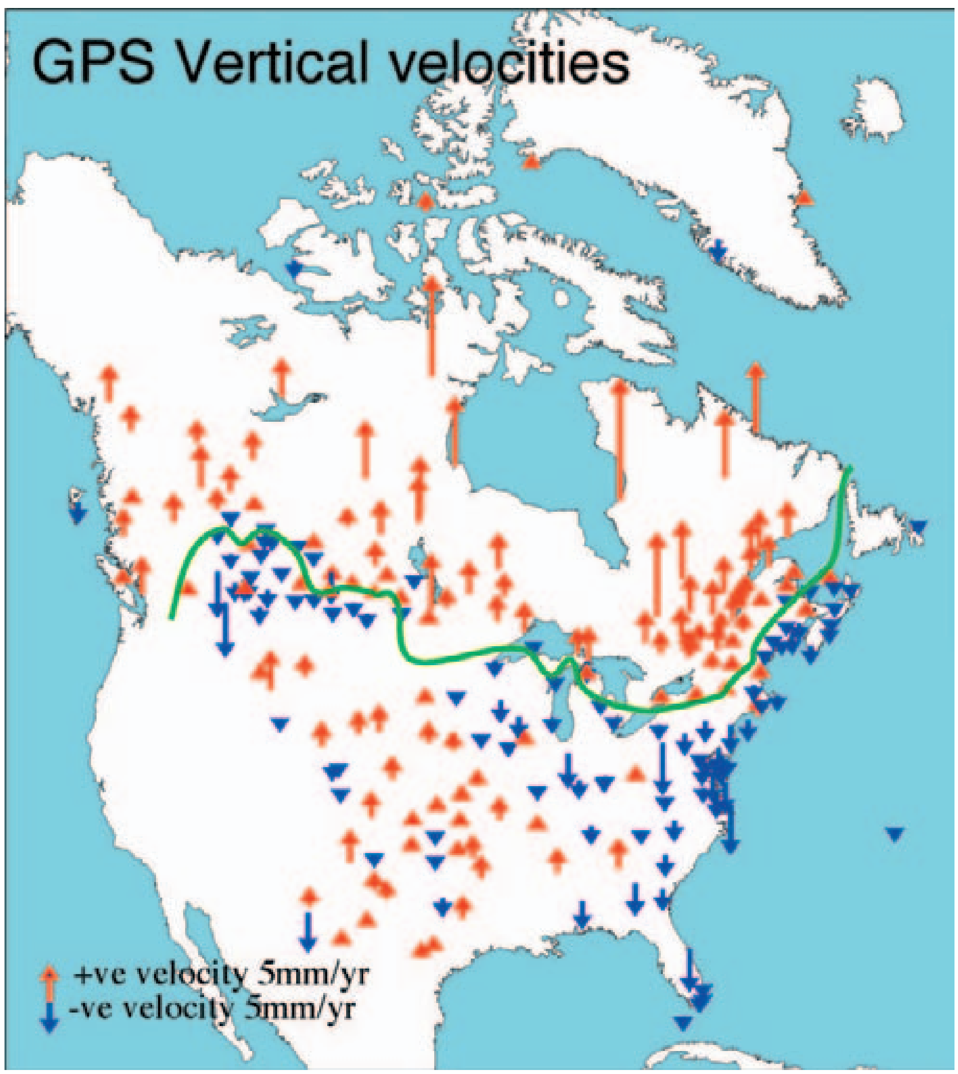
Giovanni Sella
National Geodetic Survey

Seth Stein
Northwestern University

Shimon Wdowinski
University of Miami

Timothy Dixon
University of Miami

Quantifying the motion due to glacial isostatic adjustment (GIA) due to glacial unloading in eastern North America is important since it has been proposed as a mechanism for the seismicity that occurs in stable North American (the area east of the Rocky Mountains). Estimates of the amount of motion associated with glacial isostatic adjustment (GIA) has been limited due to the small number of long term tide-gauge stations available along the northern coastlines of North America. Space geodesy, and GPS data in particular, offer an excellent method to observe this motion. At present it is challenging to quantify GIA motion in North American due to the limited number of continuous GPS sites (CGPS) in and around Hudson Bay, the area of maximum glacial loading. Episodic GPS (EGPS) sites provide a low cost and higher density alternative, but often have large errors, especially in the vertical. However, the large vertical signal due to GIA (>10mm/yr) in the area of maximum uplift permits this motion to be resolved, even with EGPS data. We present data from 130 CGPS sites throughout North America and almost 100 EGPS sites of the Canadian Base Network (CBN). The CBN sites are located across central and southern Canada and have been occupied periodically between 1994 and 2002. We detect a coherent pattern of vertical motions around the area of maximum glacial loading, Hudson Bay. The observed velocities are initially large and upward, and decrease southward from Hudson Bay to zero, delineating the hinge line near the Great Lakes. The position of the hinge line is in agreement with some numerical GIA predictions. As the number of CGPS sites on stable North America and the lengths of data have increased we have seen a steady improvement in the root mean square misfit of the horizontal site velocities to less than 1 mm/yr compared to that expected for a perfectly rigid plate.



Vertical velocities observed by GPS with respect to IGS-2000.

Engaging Native American Stakeholders in EarthScope

Steven Semken
Arizona State University

Matthew Fouch
Arizona State University

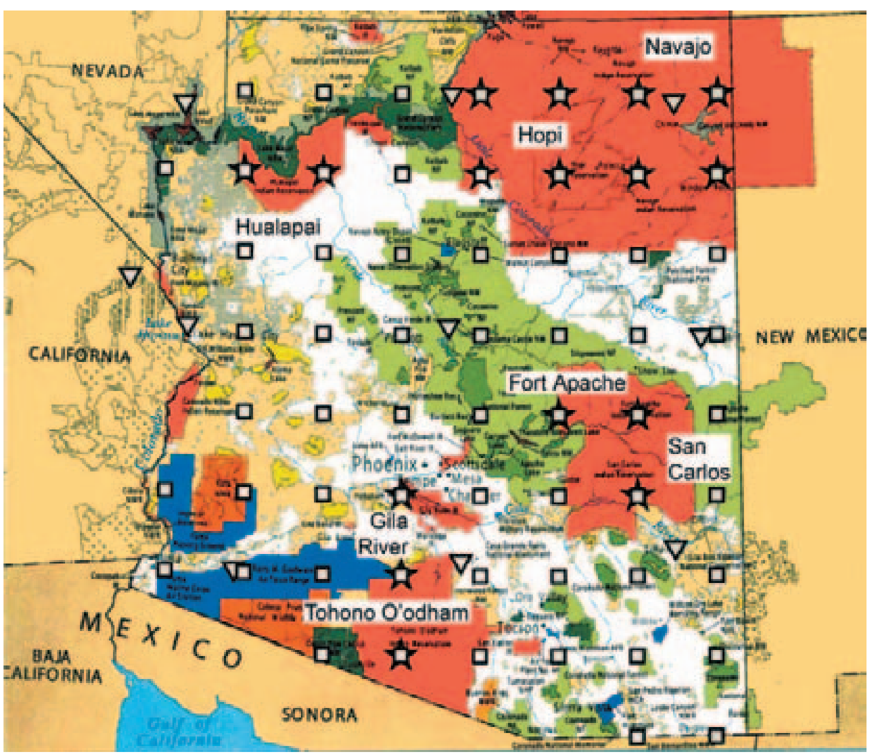
Edward Garnero
Arizona State University

A grid of USArray and PBO geophysical stations is scheduled for deployment in the southwestern United States within the next four years. In this region, a significant number of these stations would be sited on Native American homelands; in Arizona, for example, seven different Native nations would be affected (see figure). Other EarthScope projects involving short-term deployment of instruments to specific areas may also require access to Native lands. Obtaining permits for these stations could prove to be unusually laborious and slow, owing to factors that include unfamiliarity of Tribal agencies with EarthScope, unfamiliarity of researchers with indigenous cultures and culturally-based regulations, and the likelihood that some Native landholders will question the value of the research or suspect hidden motives such as oil and gas exploration.

In addition to timely permitting and access, education and outreach (E&O) activities suited to local needs and interests are crucial to a fully-effective EarthScope program on Native homelands. The EarthScope Education and Outreach Program Plan calls for direct affiliations with Native schools and communities, but lines of communication needed to build such alliances remain limited.

Early and full participation by Native American stakeholders in EarthScope research and E&O will facilitate cross-cultural awareness for researchers and crews; enable community members, teachers, and students to contribute to all phases of the work from siting to decommissioning; enhance Earth science classes (particularly in grades 8-12 and Tribal Colleges) with access to real-time geophysical data obtained locally; link remote reservation schools with the national EarthScope effort; and enrich place-based courses and workshops for pre- and in-service teachers with abundant new knowledge of regional structure and tectonic evolution.

Drawing on our experiences working with Native American communities and on Native lands, we will present a preliminary outline of potential issues and opportunities related to making contact with Tribal governments and agencies, siting and permitting of geophysical stations, working with local K-14 education systems, and sharing EarthScope discoveries with all of these stakeholders. This will be a prelude to a fall 2005 workshop at Arizona State University that will bring researchers together with a group of representative experts in cultural resources, land management, and education from the seven Arizona Native nations that will soon be affected by EarthScope. The results of this workshop will be disseminated widely to facilitate collaboration between the EarthScope community and the many other Native American nations situated farther downstream in the project.



The grid of proposed EarthScope stations in Arizona superimposed on the Federal Lands map of the state, from USGS, 2004, National Atlas of the United States. Native American lands are depicted in red, and the seven that would be asked to host EarthScope stations are identified.

Fault Zone Guided Waves Observations in the SAFOD Drill Hole

Eylon Shalev
Duke University

Peter Malin
Duke University

In this presentation we describe new microearthquake observations we have made in the SAFOD Main Hole and their potential relationship to the structure of the San Andreas Fault at this site. The data come from a seismometer and accelerometer sonde we have placed near the end of the 2004 SAFOD drill hole. The position of the sonde is approximately 1 km northeast of the drill site and at a depth of 2.5 km. It is also approximately 0.5 km southwest of the surface trace of the SAF. The instrument's position is on the western edge of a feature that we have imaged using Kirchhoff migration of local microearthquake waves. It is also near a lithological contact seen in the drill core recovered from the end of the 2004 drilling. Several MH sonde seismograms of microearthquakes, originating as far as 12 km to the southeast of the SAFOD site, appear to have strong fault zone guided waves on them. (See the seismograms in the Figure below.) If this interpretation can be substantiated with more observations and modeling, then it implies that the feature in the migration image and drill core is a significant fault, connected in some way to the active trace of the SAF. This has implications not only for interpretation of the geology of the SAFOD site, but for the mechanics of the fault zone and the continued drilling of the SAFOD hole through the SAF.

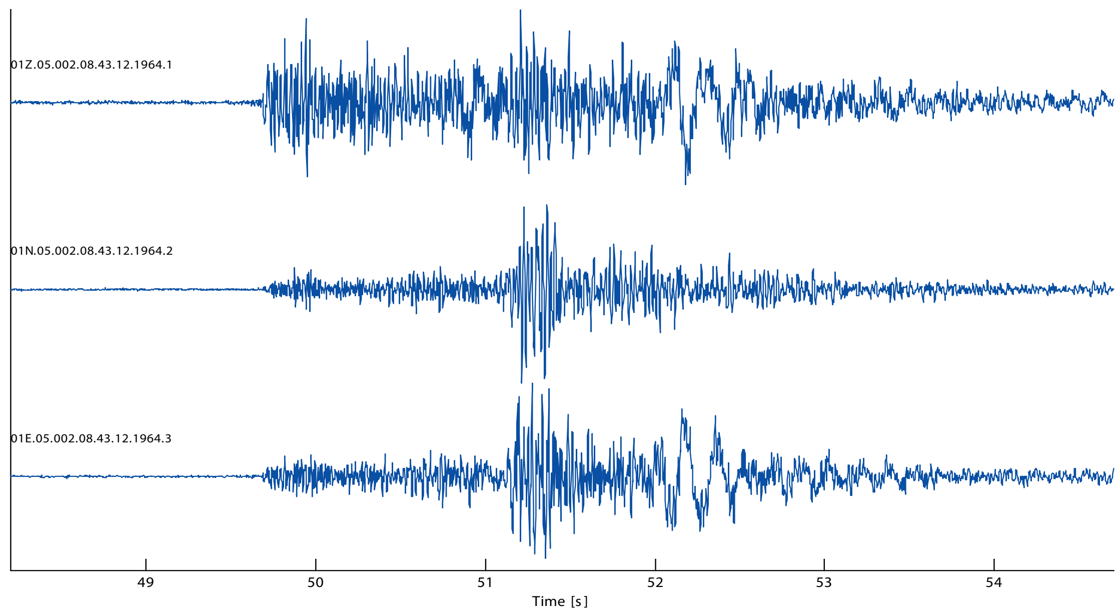


Figure 1. Fault zone guided waves as seen on the three components seismograph in the SAFOD main hole. The distance to the recorded event is about 12 km and the fault zone guided waves arrive 0.9 second after the S-waves.

Measuring Finite-frequency Amplitudes and Travel Times of Teleseismic Body Waves

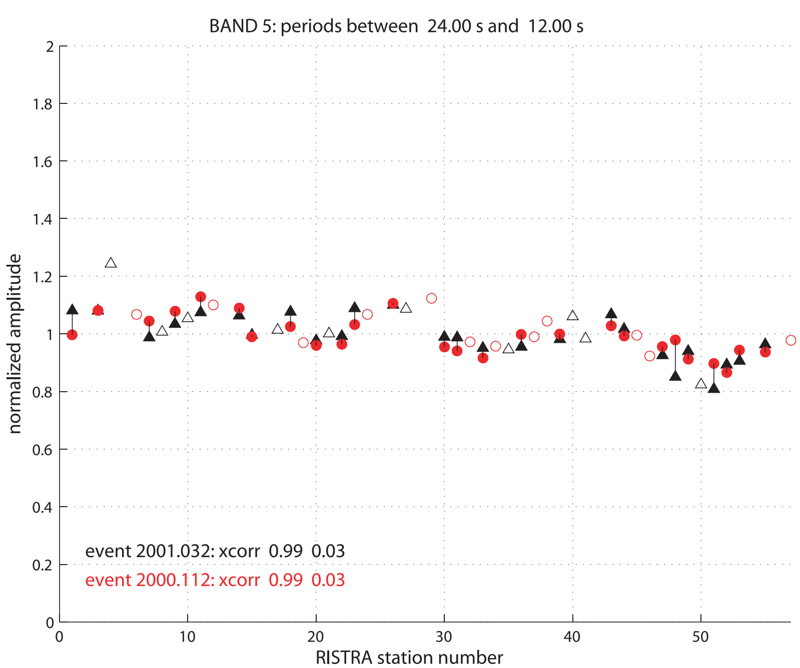
Karin Sigloch
Princeton University

Guust Nolet
Princeton University

We present a method to measure amplitude and travel time anomalies of P waves in finite-frequency bands. We use a matched filtering approach that models the first 20-30 seconds of a seismogram after a teleseismic P arrival. The relatively high modeling effort for waveform fitting is necessitated by the complexities of shallow earthquake data: since the depth phases pP and sP arrive only a few seconds after the P pulse, recorded waveforms change as a function of distance and azimuth. Processing this data is very worthwhile since only shallow events are abundant enough to assemble tomography-sized data sets. We will be using USARRAY data to measure finite-frequency amplitude and travel time anomalies across the Western U.S.

Given a set of broadband seismograms from a teleseismic event, we compute synthetic Green functions using published moment tensor solutions. We deconvolve the first 20-30 seconds of each seismogram with its Green function to obtain the broadband source time function. Subsequent convolution of Green functions with the source time function yields the predicted seismograms, or matched filters. Amplitude anomalies are defined as the multiplicative factors that minimize the RMS misfit between predicted and observed waveforms. The above procedure is implemented in an iterative fashion, which allows for joint inversion of source time function, amplitudes, and a correction to the moment tensor. We run this inversion for many different assumed source depths to determine the most likely depth, as indicated by the quality of waveform fits, and by the shape of the source time function. In order to account for directivity effects in the source time function (especially in global data sets), the data is divided into clusters of similar seismograms, and travel times and source time functions are computed separately for each cluster. To obtain finite-frequency amplitudes and travel times, the observed broadband waveforms and their matched filters are bandpass-filtered to the desired frequency bands. Each seismogram then gets amplitude-adjusted and time-aligned with its bandpassed matched filter.

This method has been tested on digital broadband seismograms from the temporary PASSCAL line array LA RISTRA. We find that robust and reproducible amplitude measurements can be obtained in different passbands. Signal-to-noise ratios are adequate for fitting waveforms of shallow earthquakes with magnitude between 5.9 and 6.9. Matched filter fits to seismograms routinely achieve cross-correlation coefficients of 90% to 98%. Amplitude anomalies of the broadband data are on the order of 20%, with outliers being as large as 60%. Fits in the passbands are good to excellent except in the microseismic noise band. Along the 1000-km-long RISTRA array we find several smoothly oscillating amplitude patterns on the scale of hundreds of kilometers. Focusing/defocusing by refraction in the mantle would be expected to generate this kind of pattern. We also present the results of extensive synthetic tests that assess the accuracy and robustness of our method for global-scale data sets. These tests mimic scenarios of actual teleseimic events as recorded on the GSN network under typical noise conditions.



P wave amplitude variations along the RISTRA array, for the frequency band of 12-24 sec. Station indices of the 1000-km-long array run from Texas (#1) to Utah (#54). The figure compares amplitude anomalies obtained from two shallow, magnitude 6 events in the Aleutians, which had epicenters less than 50 km apart. Stations that measured both events are highlighted by solid symbols and connecting lines. A measure of the goodness waveform fit is given as median and std of the cross-correlation coefficients (xcorr). A reproducible, smoothly oscillating pattern along the array is clearly seen in this band.

Developing a Methodology for Measuring Stress Transients at Seismogenic Depth

Paul Silver
Carnegie Institution of Washington

Fenglin Niu
Rice University

Tom Daley
Lawrence Berkeley National Laboratory

Ernest Majer
Lawrence Berkeley National Laboratory

The dependence of crack properties on stress means that crustal seismic velocity exhibits stress dependence. This dependence constitutes, in principle, a powerful means of studying transient changes in stress at seismogenic depth through the repeat measurement of travel time from a controlled source. While the scientific potential of this stress dependence has been known for decades, time-dependent seismic imaging has yet to become a reliable means of measuring subsurface stress changes in fault-zone environments. This is due to 1) insufficient delay-time precision necessary to detect small changes in stress, and 2) the difficulty in establishing a reliable in-situ calibration between stress and seismic velocity. These two problems are coupled because the best sources of calibration, solid-earth tides and barometric pressure, produce weak stress perturbations of order 10^2 - 10^3 Pa that require precision in the measurement of the fractional velocity change *dlnv* of order 10^{-6}, based on laboratory experiments. We have thus focused on developing a methodology that is capable of providing this high level of precision. For example, we have shown that precision in *dlnv* is maximized when there are Q/π wavelengths in the source-receiver path. This relationship provides a means of selecting an optimal geometry and/or source characteristic frequency in the planning of experiments. We have initiated a series of experiments to demonstrate the detectability of these stress-calibration signals in progressively more tectonically relevant settings. Initial tests have been completed on the smallest scale, with two boreholes 17 m deep and 3 meters apart. We have used a piezoelectric source (0.1ms source pulse repeated every 100ms) and a string of 24 hydrophones to record P waves with a dominant frequency of 10KHz. Recording was conducted for 160 hours. The massive stacking of ~36,000 high-SNR traces/hr leads to delay-time precision of 6ns (hour sampling) corresponding to *dlnv* precision of 3×10^{-6}. We find that barometric pressure fluctuations are easily observed in the delay time data with a SNR of 1000. Also, while lower in amplitude, diurnal and semidiurnal solid-earth-tidal components are also observed. We have also conducted preliminary tests at the Richmond Field Facility permits cross-borehole recordings at a distance of 30 m, and depths to 70 m, using the same equipment. The dominant frequency in this case was 1KHz. While only very short time segments have thus far been analyzed, the preliminary data show that we are able to attain the same high precision (*dlnv* of order 10^{-6}) as in the first experiment. The third and most tectonically relevant experiment is being conducted at the Parkfield site of EarthScope's SAFOD drill hole, performing a cross-hole experiment at approximately 2km depth using both the SAFOD pilot hole as the source hole, and a geophone string in the main hole. The cross-hole distance is approximately 400m. Making use of a specially designed 750Hz 18-element piezoelectric source, we expect to obtain stress-induced temporal changes in *dlnv* along this path, which if confirmed, would demonstrate the ability to measure KPa-level stress variations at near-seismogenic depth.

Surface Latent Heat Flux Associated with Coastal Earthquakes

Ramesh Singh
George Mason University

Guido Cervone
George Mason University

Menas Kafatos
George Mason University

The analysis of surface latent heat flux (SLHF) from 300 earthquakes has shown association of anomalous peaks prior to these earthquakes. The anomalous peaks are generally observed with the occurrence of earthquakes, hurricanes and due to atmospheric perturbation. The atmospheric perturbations and hurricanes are associated with the local SLHF peaks whereas the anomalous SLHF peaks associated with the earthquakes show space and time continuity along the fault lines. In the present paper, details of SLHF and its association with coastal and inland earthquakes will be discussed in developing an early warning system based on atmospheric parameters. The association of SLHF prior to earthquakes confirms a strong coupling between land-ocean-atmosphere and ionosphere.

A Community Vision of EarthScope Science Frontiers in Eastern North America

Krishna Sinha
Virginia Tech

Robert Hatcher
University of Tennessee Knoxville

Karen Fischer
Brown University

Alessandro Forte
Université du Québec à Montréal

John Ebel
Boston College

Milan Pavich
U.S. Geological Survey

Dogan Seber
University of California San Diego

William Thomas
University of Kentucky

Larry Brown
Cornell University

Arthur Goldstein
Colgate University

Linda Gundersen
U.S. Geological Survey

Fred Read
Virginia Tech

EarthScope is the largest earth science initiative to date, designed to make new and fundamental contributions to our understanding of the 4-D evolution of continents, as well as develop new insights into the origins of hazards, such as earthquakes and volcanoes. Towards this vision, at a workshop in Ballston, Virginia, earth scientists were able to formulate questions that would be not only uniquely solved by studying the geologic and geophysical record of eastern North America including the Appalachian orogen, but provide the impetus for securing significant scientific benefits for the entire EarthScope initiative. The participants organized themselves into many breakout groups, and this summary reflects their bold scientific vision.

Eastern North America provides a geologic and geophysical template to explore fundamental hypotheses which address the core EarthScope scientific goals of understanding the 4- D evolution of North American lithosphere, and the response of the lithosphere to modern mantle dynamics. Of the many hypotheses discussed by the community, the two overarching concepts are:

I. What processes contributed to the formation of eastern NA lithosphere?
II. How is eastern NA lithosphere responding to modern mantle dynamics?

The following hypotheses require the integration of data and knowledge from both the available record, and those to be acquired in the future.

Hypothesis I - Tectonics and magmatism during assembly of a late Middle Proterozoic supercontinent controlled timing, geometry and nature of the following subsequent cycles of supercontinent breakup and reassembly in eastern North America. Along- strike variations in particular reflect this long term tectonic heredity. Along strike segmentation of the belt is a reflection of early rift transforms coupled with later strike slip cutoffs of terranes, evidence of which persists at all levels of the crust and upper mantle

Hypothesis II - Lateral transitions in the structure and composition of mantle lithosphere from craton to margin (Archean craton through Mesozoic rifted margin) reflect fundamental changes in the geochemical and geophysical evolution of the earth.

Hypothesis III - Deep subcontinental flow under the eastern US, driven by the descending Farallon plate, influences modern tectonics in the eastern US.

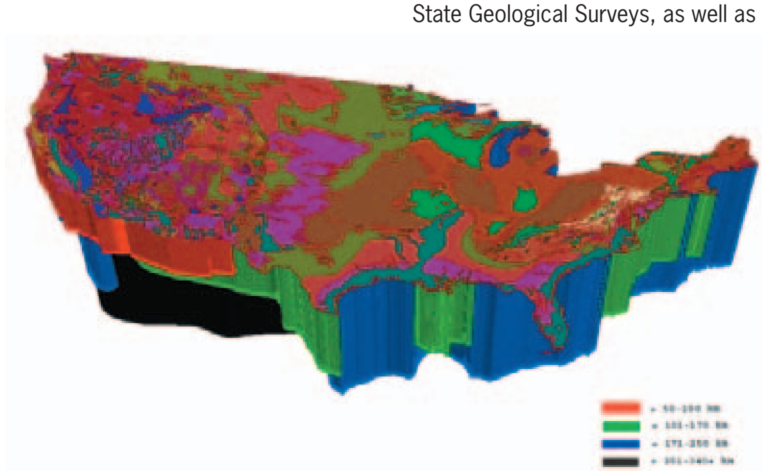
Hypothesis IV - Spatial variations in lithospheric thickness and structure and temperature distribution influence the occurrences, spatial distributions, and stress directions of modern earthquakes, and neotectonic deformations in the intraplate eastern North America.

Hypotheses V - Landscape evolution of eastern North America is driven by processes with a wavelength larger than the Appalachian orogen, such as time-dependent changes in composition, plate-scale reorientation of the regional stress field, or interaction of vertically-stacked lithospheric plates, as well as climate.

Synoptic databases: data and knowledge from the existing record

Database research activities to facilitate hypothesis /model evaluation as listed above. Without this activity the models and hypotheses are only partially testable .This activity will provide information on what databases and tools are needed to facilitate hypothesis evaluation

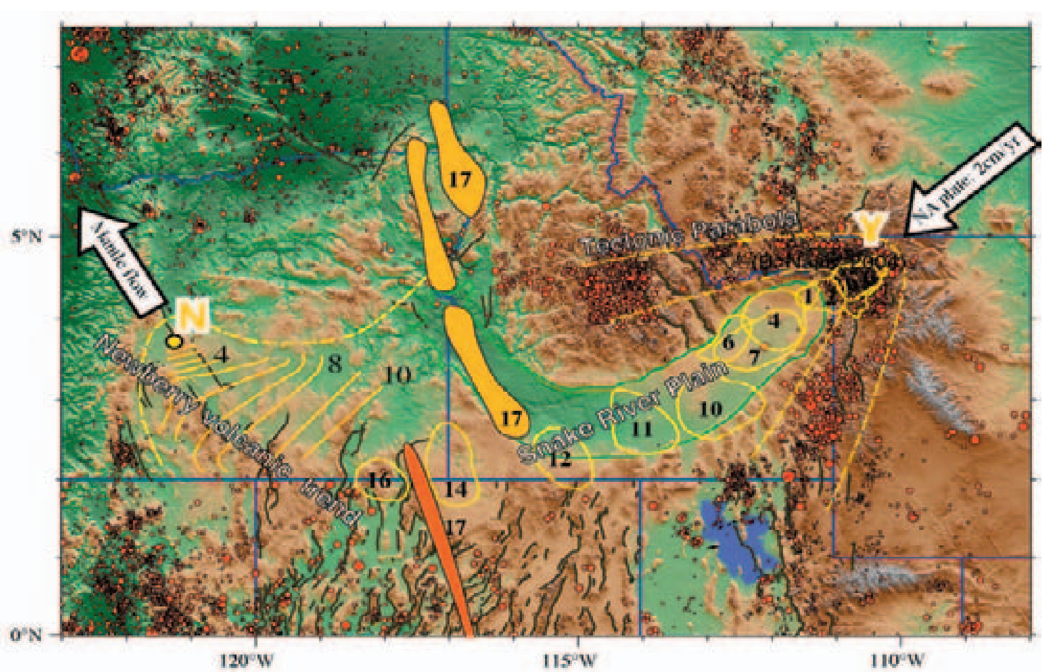
The hypotheses presented here are capable of yielding significant new insights towards resolving centuries old geologic questions. Understanding the fate of lithospheres through episodes of assembly and breakup of supercontinents, recognizing the impact of tectonic heredity on both past and present deformation, and elucidating the interaction of modern mantle flow regimes, extinct subducted slabs at great depths, and surface dynamics and plate interior seismicity will provide some of the new paradigms in earth science for this century. To facilitate new discoveries in regions of the United States where the EarthScope facilities are currently deployed, it is critical that pre-facility deployment EarthScope science be supported in the eastern United States. The entire EarthScope science community would also benefit from creation of strong working groups including researchers at the U.S.Geological Survey, State Geological Surveys, as well as those in Canada.



Yellowstone Hotspot: Integrative Research and Complimentary Goals of EarthScope

Robert Smith
University of Utah

The western U.S. provides the best place for EarthScope to begin as no other place on Earth offers such a rich set of active and accessible plate tectonic elements for study: plate convergence, transform faulting, and intraplate extension. Moreover, the western U.S. contains the world's largest, active continental hotspot: Yellowstone. While Earth's most violent forces have produced the renowned scenery of America's first national park, and the world's largest display of geysers, the energy responsible for these features is the Yellowstone hotspot, a coupled crust-mantle magmatic system. Furthermore, the hotspot has had a profound influence on the tectonics and magmatic evolution of a much larger area of the western U.S., the Yellowstone-Snake River Plain-Newberry volcanic field (YSRPN). The Yellowstone volcanic system, the largest volcanic field of North America, and its track across the continent, the 800 km-long, 16 million year old track of the Cenozoic time-progressive volcanism of the Snake River Pain, and a complimentary NW trend of magmatism across the High Lava Plains to the Newberry caldera, is the focus of my presentation. Unique to Yellowstone is a topographic swell of plate-proportions followed by plate subsidence in the wake of the hotspot, extraordinary high heat flow, and a parabolic rim of active faulting with earthquakes as large as M7.5. Yellowstone's origin has been variously ascribed to plume-plate interaction, lithosphere extension, return mantle flow, decompression melting, etc. that are key processes in intraplate magmatism and tectonics. Combined analyses and various aspects of volcanic and tectonic history with geophysical and geodetic information provide a better understanding of the evolution and processes of this and other intra-continental hotspot systems. The Yellowstone system thus offers a natural geologic laboratory on continent-hotspot interaction and is an example of a key problem in continental dynamics, namely the origin and interaction of magmatic and tectonic processes in intraplate regimes. Historically the Yellowstone region has been the focus of field projects for several years. For example, an international seismic experiment of the YSRP in 1978-80 began to acquire seismic data on the structure of the YSRP. Based on this project, Purdue and the University of Utah proposed to NSF to acquire an array of portable seismographs for shared university studies. NSF recognized the concept of pooled equipment that lead into the successful IRIS-PASSCAL facility. Also, during this period, field studies were done by various USGS and university scientists that began to resolve the systematic tectonic and volcanic history of the region. Recognition of the unusually good correlation of the volcanic field with systematic variations in crustal structure and crustal deformation, fostered multidisciplinary research. In the late 1990's a collaborative project of the Universities of Oregon, Utah and Wyoming, and UCLA similar to the intent of EarthScope projects, acquired extensive seismic and geodetic data to assess the kinematics and dynamics of the Yellowstone hotspot. This was paralleled by studies focused on volcanic history, geochemistry, and modernization of the Yellowstone geophysical monitoring system. I will describe the integrative results of the above research and hypothesize the origin of the Yellowstone hotspot in the perspective of its role in plate tectonics and as a plate boundary laboratory. Also, I point out the role that EarthScope data can provide in earthquake and volcano hazard assessments.



Yellowstone-Snake River Plain-Newberry volcanic system (YSRPN) showing Quaternary faults, earthquakes, volcanic centers and topography. Silicic eruptive centers along the track of the hotspot are noted with yellow circles and ages in Ma. Figure after Smith and Siegal [2000].

Some Topics in Lithospheric Evolution

Scott Smithson
University of Wyoming

Topics presented include Proterozoic sutures in the Southern Rockies, Archean crust, eclogites and delamination, and lower crust. Lower crust is analyzed with respect to metasedimentary rocks, xenoliths, and velocity anisotropy and composition. The CD-ROM, 250-km-long seismic reflection profile was acquired over The Cheyenne belt suture (CB) and a possible cryptic suture, the Farwell-Mtn Lester-Mtn zone in southern Wyoming and northern Colorado. A wide-angle reflection / refraction line was also recorded in the same area, and we interpret both profiles together. The CB appears as a complex interwedging of Archean passive margin and Proterozoic island arc. The wide-angle interpretation shows a high-velocity lower crust in Colorado, a low velocity zone associated with the Colorado Mineral Belt batholith and a Moho bulge north of the CB. The CB suture is formed by a complex interwedging of Archean and Proterozoic crust caused by pre-existing mechanical heterogeneities and continued convergence. A cartoon (Fig. 1) illustrates our preferred interpretation of stages of lithospheric development along this profile. An early Proterozoic, thinned passive margin of an Archean microcontinent receives a thick sequence of sediments and a thick underplate of basalt. As the microcontinent approaches and collides with an island arc along a south-dipping subduction zone similar to Australia and Indonesia today, the arc indents the microcontinent inducing thrusting in the crust and overlying sedimentary pile. The arc develops a medial rift, and with continued extension; the arc splits and a back-arc basin forms. South-dipping subduction transfers to the second arc, and continued convergence results in re-docking of the two arc halves and further interleaving of the original continent-arc suture. Continued docking of arc terranes to the south causes further contraction in the suture zone steepening the structures formed. At a late stage, the basalt underplate is eclogitized, starts to delaminate, and is frozen in.

Most seismic reflection profiles show subhorizontal lower crustal reflections. Thus, the lower crust is layered at seismic scales and probably at all scales, and this layering is subhorizontal. Thus it probably exhibits anisotropy caused by both small-scale fabric (LPO) and layering. Anisotropy may range from 2 to 16%, and the fast direction is horizontal, which will be sensed by refraction measurements, suggesting that anisotropy must be considered when interpreting composition from seismic velocity. Anisotropy could cause velocity-base compositional estimates to be two mafic. The Archean, called the greatest crust-forming episode, shows a wide range of crustal thicknesses (25-54 km) and velocity structures with a range of average crustal velocities and both low and high velocity lower crust. Crustal velocity structure of the Archean should be related to the mode of formation, but this goal is complicated by the overprinting of events such a delamination. In general, delamination triggered by eclogite formation should leave behind “pockets” and “chimneys” of eclogite in the remaining lower crust.

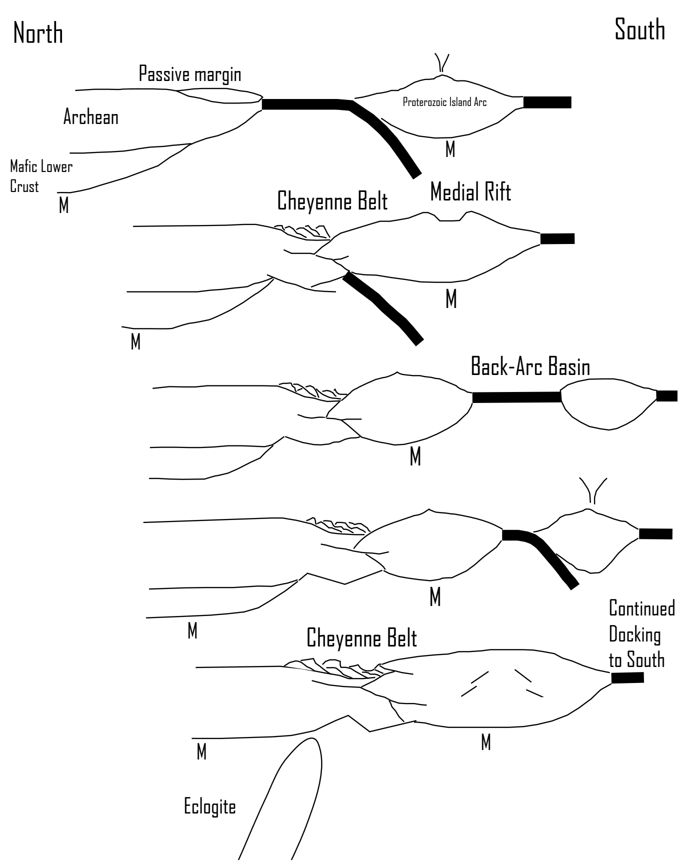


Figure 1. Cartoon illustrating stages in the formation of the CB and FM-LM sutures. An Archean micro-continent approaches and docks with a Proterozoic island arc, the island arc splits along its medial rift and a back-arc basin forms, subduction shifts to the southern arc fragment closing the back-arc basin and suturing the arc halves along the FM-LM cryptic suture. Docking of island-arc terranes continues to south steepening structures. Mafic lower crust under the Archean turns to eclogite and starts to delaminate but is frozen in. Uplift in Moho just north of CB forms during collision along zones of weakness from passive margin stage.

Relating Tide Gauge Records of Sea Level Change to Local Vertical Motions

Richard Snay
National Geodetic Survey

Michael Cline
National Geodetic Survey

William Dillinger
National Geodetic Survey

Tomas Soler
National Geodetic Survey

We relate local rates of relative sea level change to ITRF2000 vertical velocities via a simple function involving a regional rate of sea level change G and the components Vx, Vy, and Vz of a constant 3-D velocity vector referred to the X-, Y-, and Z-axis, respectively, of ITRF2000. Using rates from 36 tide gauges spanning the U.S. coast (Atlantic, Gulf, and Pacific as well as the coast along southern Alaska, Hawaii, Kwajelein, Guam, and Bermuda) together with ITRF2000 vertical velocities for 38 continuously operating GPS reference stations (CORS), each of which is located within a few tens of kilometers of one of these 36 tide gauges, we estimate that G = 1.8 +/- 1.1 mm/yr, Vx = 2.3 +/- 0.9 mm/yr, Vy = -0.2 +/- 1.1 mm/yr, and Vz = -6.0 +/- 1.4 mm/yr, where uncertainties represent standard errors. The misfit between these local sea level rates and the corresponding ITRF2000 vertical velocities at their associated CORS has a WRMS value of 1.6 mm/yr. This misfit is due primarily to uncertainties in the CORS-derived vertical velocities because of the relatively short history of these sites (2 - 9 years). Our results imply that a few years of GPS data from a CORS located along the U.S. coast may be used to predict the rate of local sea level change with a standard error of 1.6 mm/yr. Conversely, a few decades of tide gauge data may be used to predict local ITRF2000 velocities with this same level of accuracy. Moreover, rates of relative sea level change can also be related to vertical velocities expressed in any other spatial reference frame whose velocities are related to ITRF2000 velocities by a transformation as is the case with the realization of the North American Datum of 1983 that is known as NAD 83 (CORS96).

Imaging the Las Vegas Basin: Integration of Basin Scale and Crustal Scale Data

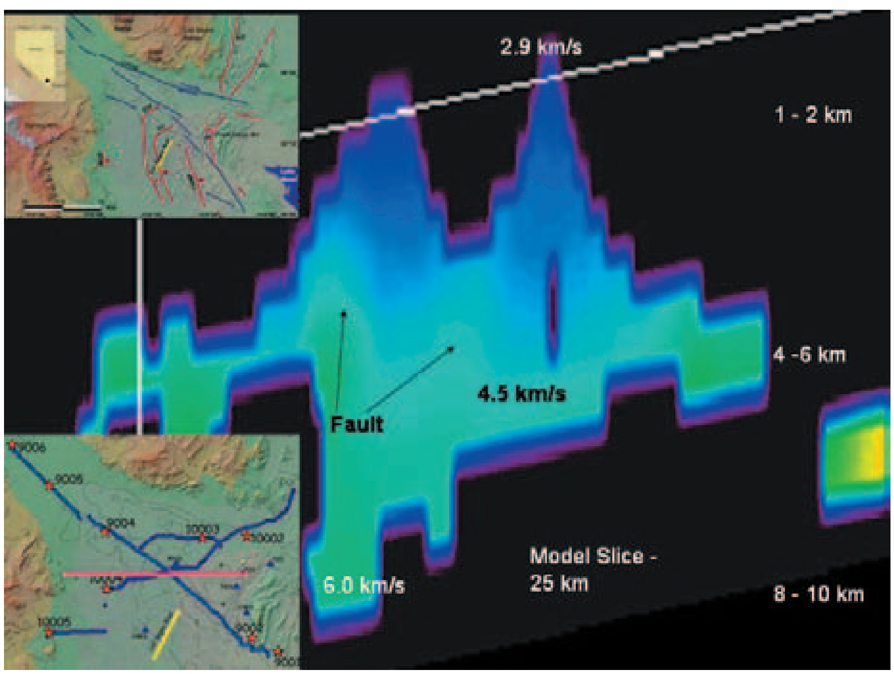
Catherine Snelson
University of Nevada Las Vegas

Darlene McEwan
University of Nevada Las Vegas

Aaron Hirsch
University of Nevada Las Vegas

Shelley Zaragoza
University of Nevada Las Vegas

The Las Vegas Valley sits atop a deep basin that has been shown to amplify energy from strong ground motions. As a result, a series of seismic refraction experiments have been conducted in order to better characterize the Las Vegas basin for seismic hazards and test site readiness. The basin is located within the central Basin and Range, and is characterized by local strike-slip fault zones (inactive) and a series of normal faults (active). Several of these normal faults within the Valley have been identified as potential sources of future seismic activity with the potential are capable of producing M 6 to 7 earthquakes within the highly populated Valley. In addition, within a 150-km radius of the Valley are several regional strike-slip fault zones, including the Furnace Creek fault zone, that have the potential for generating large magnitude earthquakes that could pose a significant seismic threat to the Valley. Three seismic refraction experiments have taken place over the last two years to image the geometry of the basin to better understand potential focusing effects as well as determine the depth and lithology of the basin. These projects are part of a larger collaborative study called the Las Vegas Valley Seismic Response Project (LVVSRP), which is presented in more detail by Rodgers et al. and Louie et al. (this meeting). In May 2002, the Quarry blast experiment used 434 vertical component seismic instruments to record three quarry blasts. These data were of limited use, because of the amount of cultural noise within the city. In September 2002, the Watusi experiment used 400 vertical component seismic instruments to record a chemical blast at the Nevada Test Site along the corridor of the Las Vegas Valley Shear zone (LVVSZ). The LVVSZ is a local structure that has been suspected to focus energy into the basin. These data have illuminated more detail of the deeper crustal structure than has been imaged in the past. In August 2003, the SILVVER (Seismic Investigations of the Las Vegas Valley: Evaluating Risks) experiment commenced using 800 vertical and 25 three-component seismic instruments to record 9 chemical blasts within the Las Vegas Valley. This project was designed to obtain a 3D image of the basin as well as obtain the depth of the basin. The 3D velocity shows a larger sub-basin within the main basin, indicating a change from the unconsolidated sediments to more consolidated materials. The velocities range from 2.5 to 4.5 km/s within the basin. The 4.5 km/s contour indicates the base of the basin where velocities increase to 6 km/s to the base of the model (9 km depth). Several zones of high velocity correlate to faults that have been mapped at the surface. The model shows that the deepest portion of the Valley is located to the northeast as previously estimated. Integration with the geologic and geotechnical results indicates that not only does the basin thickness effect amplification, but also the shallow sub-surface where there is a significant amount of clay deposits. The incorporation of the deeper crustal velocity model with the geologic and other geophysical data provide a base for a 3D community model that can be used to simulate strong ground motions.



Slice from the Las Vegas Basin 3D velocity model. Color ranges from magenta (2.9 km/s) to red (6.0 km/s). The basin/bedrock contact is identified by the 4.5 km/s contour. The velocity pull-ups are associated with mapped faults across the Valley. The top inset is the generalized fault map for Las Vegas. The bottom inset is the location of the slice across the recorded array. These data are currently being incorporated with other exisiting datasets to develop the full 3D geologic/geophysical model.

Extracting Information on Fault Properties from the Mineral Assemblages of SAFOD

John Solum
U.S. Geological Survey

Stephen Hickman
U.S. Geological Survey

Diane Moore
U.S. Geological Survey

David Lockner
U.S. Geological Survey

Clay mineral assemblages vary systematically in many exhumed (San Gabriel, Punchbowl) and active fault zones (Nojima, Chelungpu). Studies of fault-related minerals provide a means to constrain fault properties if the signature of faulting contained within fault zone mineral assemblages can be distinguished from non-fault-related sources. We plan to study bulk cuttings and clay separates using X-ray diffraction (XRD).

The bulk mineralogy of washed cuttings from SAFOD Phase 1 rotary drilling is being determined using powder XRD at 100 ft (30.5 m) intervals from 110 to 10025 ft (33.5 to 3055.6 m) measured depth (MD), and at 10 ft (3 m) intervals across alteration and shear zones. Grain mounts (thin sections) were made from the same washed cuttings used for XRD. Point counts conducted on these thin sections will allow detection of phases that are present in concentrations too low to be detected using XRD, which is approximately a few weight percent. The point counts also provide a sound basis for comparison with point counts from the SAFOD Pilot Hole, drilled at the same site as SAFOD in the summer of 2002.

Clay separates will be extracted from samples of shear zones, which will be used to quantify clay mineral assemblages using XRD. Separates will be produced using an environmental chamber, which uses repeated freeze/thaw cycles to disaggregate a rock. This approach minimizes grain size reduction of non-clay phases, which results in cleaner clay separates than are provided by other crushing methods.

To ascertain the degree to which formation clays were removed during the cuttings washing process (along with the drilling mud) unwashed cuttings were collected every 10 ft during drilling of SAFOD. Unwashed cuttings from selected intervals of the SAFOD borehole, particularly sedimentary/metasedimentary sections and alteration/shear zones, will be analyzed using XRD from the kickoff point (1450 m) to the bottom of the hole. XRD studies of washed cuttings from the SAFOD Pilot Hole have shown that the clays in the drilling mud (dominantly montmorillonite) can be distinguished from formation clays on samples solvated with ethylene glycol, and this technique will also be used in analyzing the SAFOD Main Hole samples.

Cuttings collected during coring are also being analyzed. Analyses of thin sections from the core indicate that the shallower interval (1462.4-1470.4 m MD) is composed of hornblende-biotite granodiorite, while the deeper interval (3055.6-3067.2 m) is composed of a combination of granitic rocks and meta-arkose. Our XRD and optical observations on cuttings from these cored intervals will help us to “calibrate” our interpretation of cuttings from the rotary-drilled intervals of the hole and will allow the few spot cores that were obtained in Phase 1 to be placed into a broader lithological context.

These analyses will be continued as we drill (and conduct spot coring) across the San Andreas Fault Zone in the summer of 2005, providing a critical tool for recognizing fault- and non-fault-related phyllosilicates and determining how clays and other alteration products might influence the mechanical behavior of faults like the San Andreas.

Mineral Assemblages of SAFOD: Implications for Fault Properties

John Solum
U.S. Geological Survey

Ben van der Pluijm
University of Michigan

As phyllosilicate mineralization is common in fault zones, studies of fault zone mineral assemblages provide the means to constrain fault properties. A reference phyllosilicate data set for the SAFOD Main Hole was established from the SAFOD Pilot Hole and study of exhumed an exhumed segment of the SAF system, the Punchbowl Fault. The chlorite assemblages in cuttings from two intervals of the SAFOD Pilot Hole are separated into two populations based on X-ray diffraction (XRD) characteristics. The first population is found in granite in both the deeper and shallower interval, whereas the second population occurs only in clastic sedimentary rocks in the shallower interval. The characteristics of the first population match those for crystalline and clastic sedimentary protolith and cataclasite of the exhumed Punchbowl Fault, whereas samples from two intensely deformed zones of ultracataclasite are most similar to the second. This supports previous findings based on XRD and scanning and transmission electron microscopy that the mineral assemblages in the ultracataclasite formed after the cessation of motion along the fault, above a depth of ~2km, and that mineral assemblages in these exhumed fault rocks have been overprinted by post-faulting alteration.

The ability to quantify fault and non-fault mineral assemblages provides the means to infer fault properties such as fluid sources and abundance and possibly timing. ICP-MS will be used to measure the elemental composition of samples at 10' intervals from alteration/shear zones encountered during Phase I drilling of the SAFOD Main Hole. Identification of these zones will be provided by wireline logs and quantitative XRD of washed and unwashed cuttings. These studies can be used to infer the elemental signature of processes associated with faulting.

As fault rocks are composed of a physically inseparable mixture of protolithic and neoformed phases, the ability to quantify the concentrations of those populations is a critical component of SAFOD. Such quantifications provide the means to use stable isotope analysis (D) to infer fluid sources and perhaps to directly date fault rocks through $^{40}Ar/^{39}Ar$ dating of clay size fractions, assuming K-bearing clays such as illite are present in cuttings. These approaches will provide powerful means to study the role of clays in fault properties.

Possible Source of the Walker Lane Anomaly

Teh-Ru Song
California Institute of Technology

Don Helmberger
California Institute of Technology

Long period Pn tomography, and waveform complexity indicates that a prominent low-velocity-zone (LVZn, V_p = 7.6 km/s) exists beneath Walker Lane (Savage and Helmberger, 2003). The structure extends downward to about 100 km with a complex fast bottom (V_p=8.2 km/s). The source of this massive slow material appears to be related to the still deeper LVZ just above the 410 km discontinuity to the north beneath the westernmost Basin-and-Range, (Song et al, 2004). The evidence for deep LVZ structure near the 410 comes from a combination of receivers function analysis and upper-mantle triplication data. The low-velocity zone (5% low) near the 410 has a thickness that varies from 20 to 90 km with rapid lateral variations. Its spatial extent coincides with both an anomalous composition of overlying volcanism (HAOT) and seismic 'receiver-function' observations observed above the region. We interpret the low-velocity zone as a compositional anomaly, possibly due to a dense partial-melt layer, which may be linked to prior subduction of the Farallon plate and back-arc extension. Here we present modeling of TriNet triplication data sampling the western boundary of this LVZ.

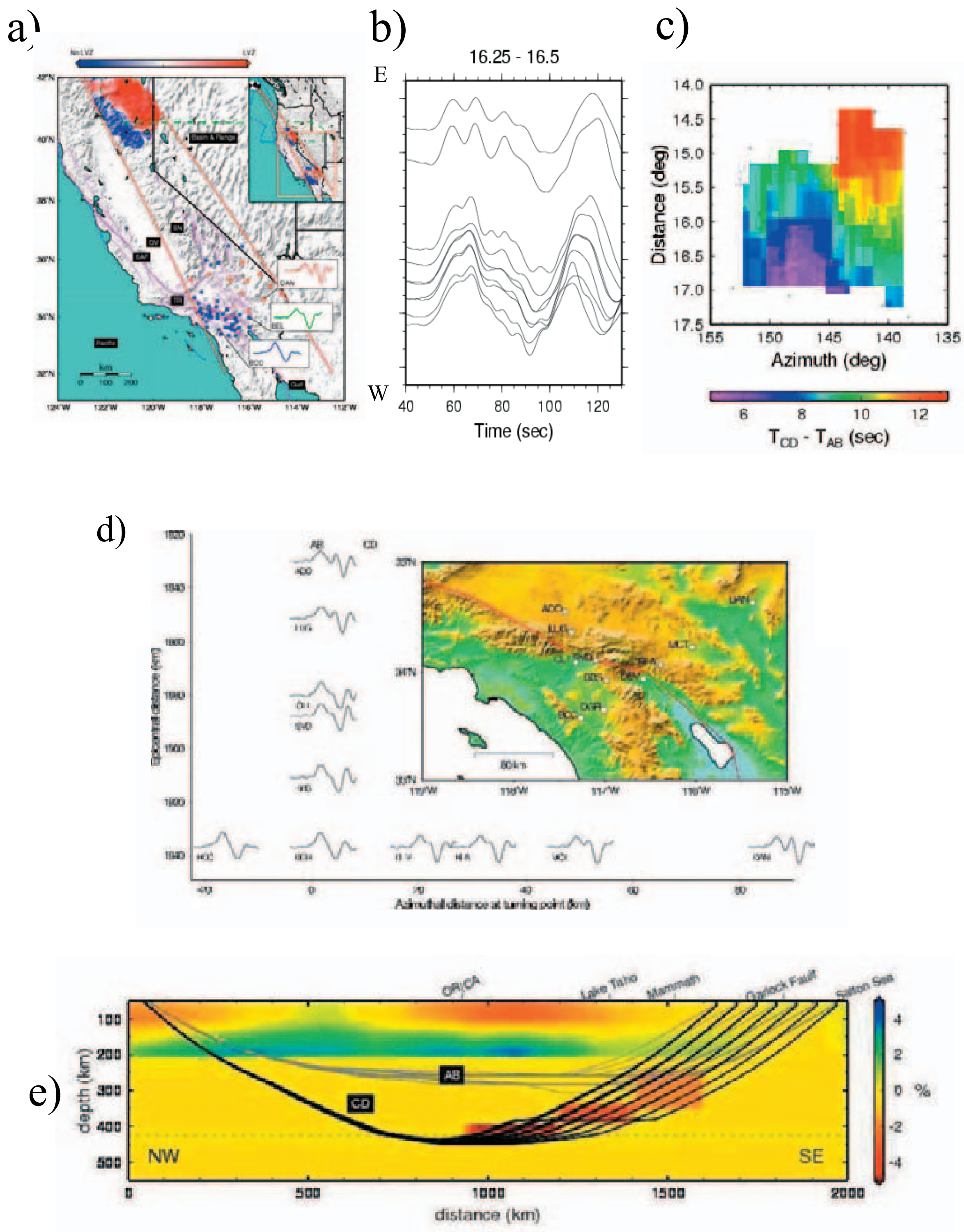
We adopt regional tomographic model (Godey et al., 2004) to constrain the shallow upper mantle. 2-D finite difference method interfacing Kirchhoff diffraction operator (DiFD) is implemented to account for the response off the great circle path. Strong azimuthal variations in the interferences of S wave triplication are clearly observed over less than 100 km. To reconcile such rapid change in waveform interferences, we model this array data with DiFD and find a low velocity zone with a sharp western edge atop the 410 can explain the whole dataset quite well. The structure seems dipping upward towards Owens Valley although it's eastern edge is not presently well established.

Next Page: a) The low velocity structure directly above the 410 seismic discontinuity beneath the edge of western Basin and Range. The mapped spatial extent of the LVZ is projected to the surface. Red region indicates the existence of LVZ while blue region shows no LVZ. The structure changes very fast across the swath. Three stations DAN, BEL and BCC are shown as examples. b) Tangential, displacement waveform at epicentral distances of 16.25-16 degrees. Note the Love wave (around 110 secs) arrives much earlier along the path to the west. In addition, the CD branches is, however, slower along the path to the east. This indicated the velocity structures is complicated at both shallow and deep upper mantle. c) Measure differential time of branch CD and branch AB. Note the large separation toward the eastern path. Besides, the change in differential time is very fast. d) A subset of TriNet data is shown in a way that both distant and azimuthal variations in S waves triplications can be clearly seen. Records in blue are along a a distance section (1840-1940 km). The CD branch is well seperated at 1840 km (ex. ADO) and quickly merge with the AB branch (ex. DGR). Amazingly, we also observe equally rapid changes in an azimuthal section (shown in red). At epicentral distance of 1940 km, the separations of AB and CD branches rapidly diminish from the east to the west. Note record DAN and ADO are almost alike and so are LUG and MCT; BLA and SVD. The azimuthal distance is calculated at the turning point. Station DGR are used for both distance and azimuth sections. Each records is 40 secs long. e) S wave tomographic model by Godey et al (2004) is implemented in the numerical DiFD calculation. Raypaths of AB and CD are shown to illustrate the geometry. Note the sensitivity of AB and CD branches are not limited to the raypath.

Figures on Page 240 >

Teh-Ru Song
California Institute of Technology

Don Helmberger
California Institute of Technology



GeoSystems: Probing Earth's Deep-time Climate and Linked Systems

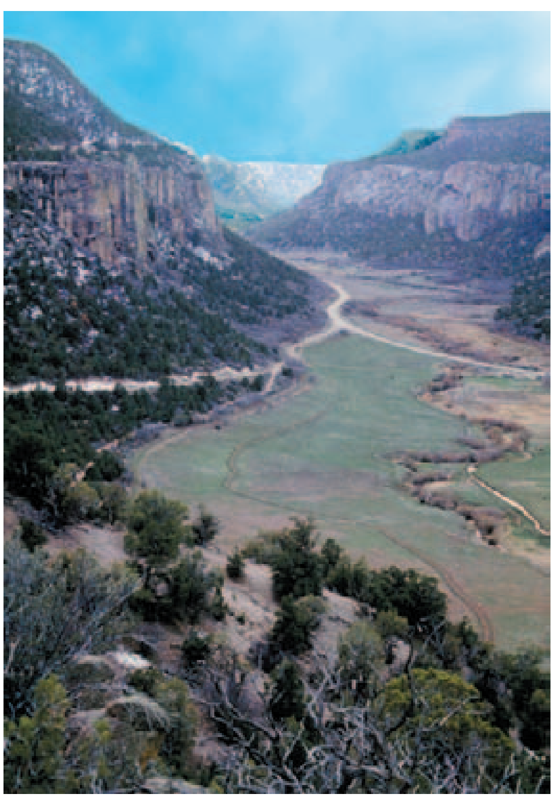
Gerilyn Soreghan
University of Oklahoma

Climate research in "deep" (pre-Quaternary) time has experienced a decade of intense discovery aided by a revolution in analytical techniques. An emerging theme is that Earth has experienced numerous episodes of extreme climatic states, ranging from near-global freezing, to extreme "hothouse" conditions. These events had profound effects on life and the global carbon cycle. GeoSystems is an interdisciplinary, community-based initiative stemming from the growing recognition that a full understanding of Earth's climate system –and our climate future– lies in examining this wealth of "alternative-Earth" climatic extremes.

A multitude of powerful new models and proxies and sharp increases in the precision and resolution of chronology have energized deep-time climate research. Combined, these advances enable extensive reconstruction of Earth's paleoenvironments, with accurate estimates of rates and magnitudes of past global change. The geologic record is an archive of the full magnitude of extreme climate events—from onset through peak and recovery. Our modern climate state – that of a relatively stable interglacial phase of an icehouse with glaciation at both poles – is representative of only 80,000 yrs, or 0.015%, of the Phanerozoic Eon (last 540,000,000 yrs). Earth's climate changes perpetually, far beyond the limits known from the modern and near-modern world. Only through knowledge of Earth's full range of climatic possibilities can we fully grasp the cause-and-effect relationships between climate and civilization and, thereby, prediction of future climate states.

A large community of geoscientists who hail from a variety of subdisciplines has assembled around the GeoSystems initiative. This community recognizes and embraces the importance of the deep-time perspective for understanding the complexities of Earth's atmosphere, hydrosphere, biosphere, and surficial lithosphere using climate as the nexus. Our collective vision in GeoSystems is to create synergy among earth-, ocean-, and atmospheric geoscientists in pursuing research that spans diverse analytical, numerical and field-based approaches in striving to achieve a holistic understanding of Earth's climate and linked systems. This initiative has garnered widespread support, resulting in a cohesive set of needs that cross the artificial boundaries that have historically limited climate research. Among other needs, research in GeoSystems will require an ambitious continental drilling program to acquire pristine records in key successions; related to this is the need for appropriate geophysical imaging of potential target sites.

The focus on climate in deep time demands participation from a very broad cross-section of the geoscience community; notably, this cross-section includes those structural geologists, tectonicists, and geophysicists focused on lithospheric processes and interactions relevant to Earth's climate system. (e.g., elevation-erosion feedbacks, etc.) New opportunities for study of such climatic-tectonic links are emerging as we recognize feedbacks between these processes. We are at the forefront of recognizing such links, and these represent key opportunities with which to integrate the efforts of GeoSystems with relevant objectives of EarthScope.



A Glacial Landscape in Equatorial Pangea: Sedimentologic and geochemical studies of strata within and at the mouth of Unaweep Canyon (Colorado) suggest a remarkable hypothesis: that Unaweep Canyon dates from 300 My ago, and that it was carved by ice– at what was then the equator. If confirmed, its genesis and preservation raise fundamental tectonic and climatic questions that will require detailed- and reconnaissance-level geophysical investigations for resolution.

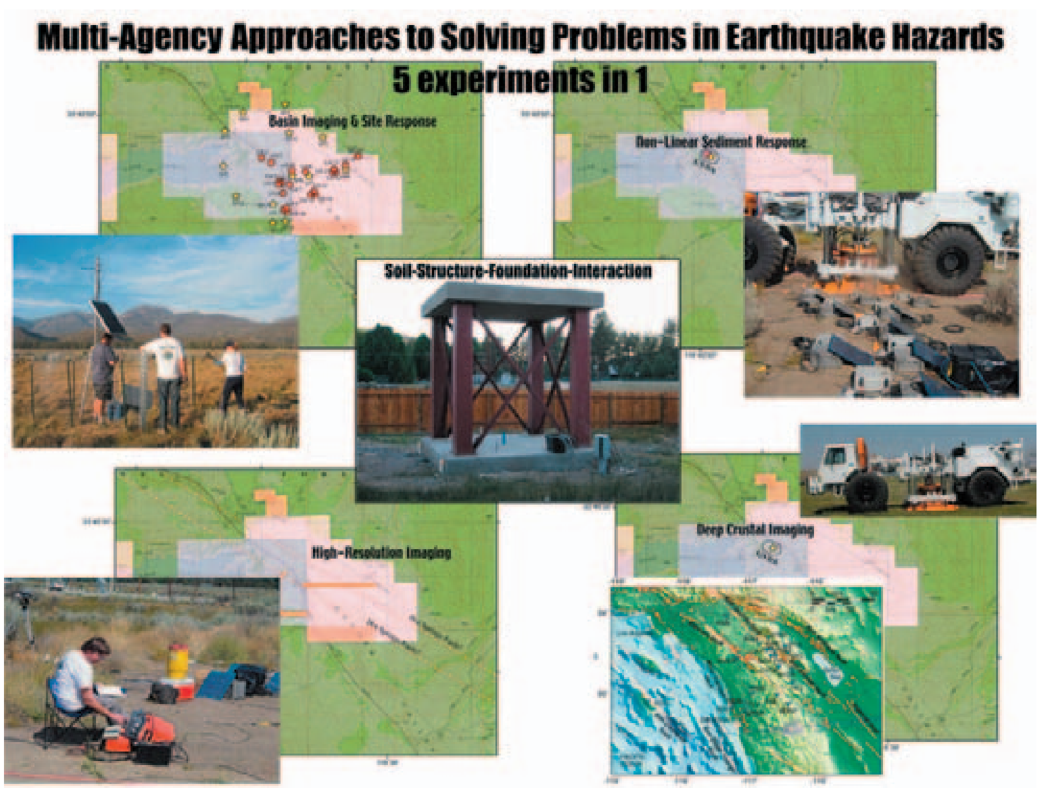
Multi-facility Approaches to Solving Problems in Earthquake Hazards

Jamison Steidl
University of California Santa Barbara

In August and September of 2004 a pilot field experiment was conducted in Garner Valley, CA to examine the potential for collaboration between a number of different agencies involved in solving problems in earthquake hazards and earth sciences in general. The primary objective of this project was to assess the potential to solve challenging problems related to earthquake hazards and engineering by marshalling the combined facilities of the NSF-funded Network for Earthquake Engineering Simulation (NEES) consortium, the Incorporated Research Institutes for Seismology (IRIS) consortium, and the United States Geological Survey (USGS) National Earthquake Hazards Reduction Program. As word of the project hit the community, the number of agencies and collaborating investigators grew. Other contributing agencies included the Southern California Earthquake Center (SCEC), the Mid-America Earthquake Center (MAEC), the High Performance Wireless Research and Education Network (HPWREN), the Los Alamos National Laboratory (LANL), and the Center for Embedded Network Sensing (CENS).

The field experiments that were conducted over a 7-week period included basin response imaging, high-resolution seismic imaging of subsurface structure and faults, studies of nonlinear sediment response, soil-foundation-structure interaction experiments, and imaging of regional crustal structure. The project grew from a planned NEES grand opening demonstration project at the Garner Valley, CA NEES facility. At the Garner Valley site the University of California at Santa Barbara (UCSB) maintains a permanent array facility for monitoring ground response, liquefaction, and soil-foundation-structure interaction (SFSI). Two other NEES equipment sites participated, the University of Texas at Austin (UTA) and the University of California at Los Angeles (UCLA). The opportunity of having these three NEES facilities in the same location was the catalyst for the much larger multi-facility project that eventually took place. The UTA and UCLA NEES facilities both have the ability to bring mobile shakers out to the field and shake the ground (UTA) or structures (UCLA) and at the same time deploy a network of sensors and data acquisition systems. The potential for collaboration between structural engineers, geotechnical engineers, engineering seismologists and earth scientists was quickly realized by the more than 45 participants who took advantage of this opportunity.

As the data from the 2004 experiment begin to get analyzed in detail and the scientific results start to come out it has become clear that this multi-agency, multi-facility, multi-disciplinary experiment was a great success. Plans are already in the making for potential follow on experiments in the future pending funding of one or more proposals to support the effort. The experiment also serves as an example of the potential for this kind of cross-disciplinary effort at solving problems in earthquake hazards and earth sciences.



Multi-agency collaboration in August 2004: Field experimentation at Garner Valley, CA.

Slow Slip in the December 2004 Sumatra Earthquake and EarthScope Implications

Seth Stein
Northwestern University

Emile Okal
Northwestern University

A significant fraction of EarthScope activity is directed to understanding the subduction process in Cascadia and Alaska, for both scientific and hazard mitigation purposes. What we are learning about the recent December 26, 2004 Sumatra earthquake has important implications for this goal. Analysis of long period normal mode data shows that the earthquake was even bigger than first appeared. The earth's longest period normal mode, 0S2, shows a seismic moment of 1.3e30 dyn-cm, or moment magnitude M_w = 9.3, approximately three times larger than previously reported, making the earthquake the second largest ever instrumentally recorded. The larger magnitude likely reflects slow slip along the entire rupture zone suggested by aftershocks, a much larger area than previously inferred, which is comparable to rupture of much of the Cascadia subduction zone. These observations have various important implications. It is the first time we have observed seismic moment systematically increasing with period at such long periods. Hence methods normally used to assess earthquake size dramatically underestimate it. This has not been previously observed, raising important issues about the physics of faulting, notably at what period the moment stabilizes.

Although this issue will be difficult to resolve for Sumatra, it illustrates the need to integrate seismology with GPS. Another surprising implication for tsunami physics is that the tsunami observations are in accord with our model in which the entire fault rupture contributed to the tsunami, raising the question of how slow slip could do so. Finally, the larger area indicates that strain on the entire rupture zone has been released, leaving no immediate danger of a comparable tsunami being generated on this part of the plate boundary. This rupture zone is larger than observed in earlier earthquakes along this boundary segment, indicating the variable mode of subduction zone rupture. In addition, this great earthquake presents a "teachable moment" for EarthScope E&O in that it has drawn great interest and illustrates the dual nature of plate tectonics - posing hazards that society seeks to mitigate but also being necessary for the survival of life.

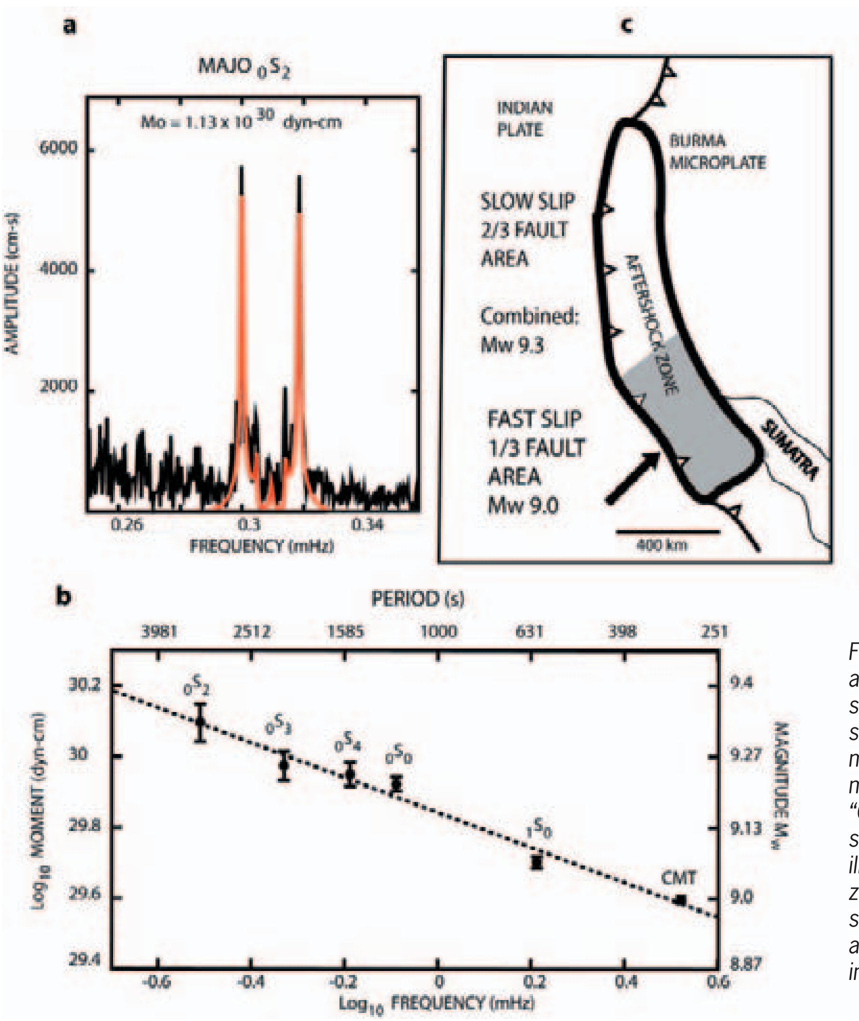


Figure 1: a, Observed (black) and predicted (red) amplitude spectrum for a 0S2 multiplet, showing best-fitting seismic moment. b, Variation in seismic moment and Mw with period. "CMT" denotes result from 300-s surface waves. c. Schematic illustration comparing aftershock zone to minimum area of fast slip estimated from body waves and possible area of slow slip inferred from normal modes.

EarthScope Project Management

Blaise Stephanus
UNAVCO

Rob Woolley
IRIS

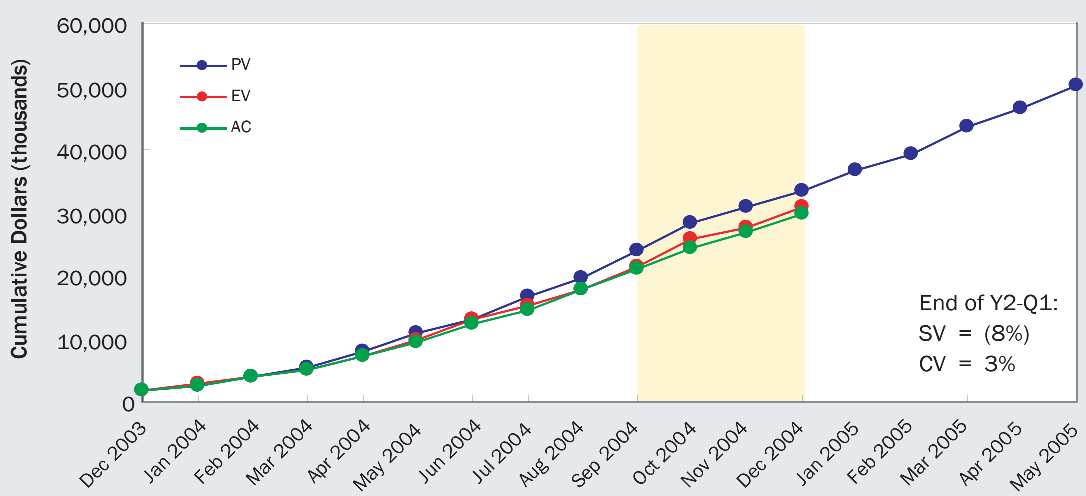
EarthScope is a new NSF-funded activity of unprecedented scope and scientific ambition. Over the next two decades, EarthScope will be taking a multi-disciplinary approach to studying the structure and evolution of the North American continent at all scales – from the active nucleation zone of earthquakes, to individual faults and volcanoes, to the deformation along the plate boundary, and to the structure of the continent. To achieve this goal EarthScope will install an array of almost 4,000 instruments spanning the content.

The construction and maintenance of this non-linear, geographically-distributed project present a unique project management challenge. EarthScope's project management system will assess progress of a project that is managed by three independent entities (IRIS, UNAVCO, and Stanford), and a collaboration of geologists, scientists, engineers, and the National Science Foundation over 15 years.

A successful project management system has to mesh with EarthScope's scientific culture and be comprehensible by and credible to key project personnel. It has to also fit within the administrative constraints of a lean EarthScope management organization but at the same time provide timely and accurate performance and forecasts for the $200 million dollar EarthScope Project.

We will show how EarthScope uses modern project management tools including work breakdown structures, earned value management and change control to assess project performance.

1 EarthScope **(Level 0)**



Spatial and Temporal Sampling Issues for Characteristic Earthquake and Seismic Hazard Studies: Illustrations for the Wasatch, New Madrid, and Other Seismic Zones

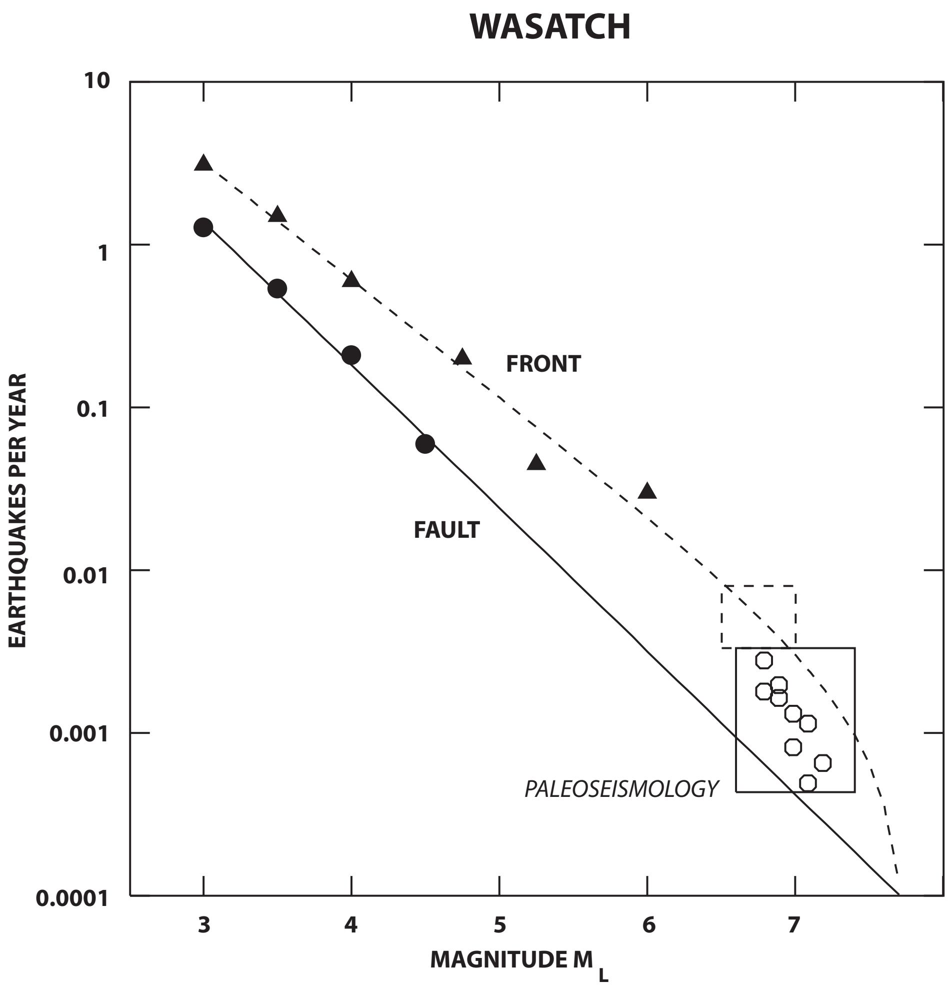
Laura Swafford
George Mason University

Seth Stein
Northwestern University

Anke Friedrich
University of Hanover Germany

Andrew Newman
Los Alamos National Laboratory

Attempts to study earthquake recurrence in space and time are limited in simple but frustrating ways by the short history of instrumental seismology compared to the long and variable recurrence time of large earthquakes. As a result, apparent differences in seismic hazard within a seismic zone inferred from the earthquake history are likely to simply reflect the short earthquake record. Similarly, large earthquakes are likely to appear "characteristic", more frequent than would be inferred from the rates of smaller ones, for two reasons. First, a short history is likely to underestimate the rate of large earthquakes because fractions of earthquakes cannot be observed. Second, because the rates of small earthquakes are typically determined from the seismological record whereas the rates of large earthquakes are inferred from paleoseismology, biases in estimating paleomagnitudes can produce apparent characteristic earthquakes, as appears to have occurred for New Madrid. A further complexity is illustrated by results for the Wasatch seismic zone, where some studies find characteristic earthquake behavior whereas others do not. The discrepancy arises primarily because some studies consider the entire Wasatch front area whereas others focus on the Wasatch fault, on which only some of the smaller earthquakes but many more of the large paleoearthquakes occur. Similar situations may arise in other seismic zones containing a major fault and a number of smaller ones. In such cases, different spatial selections within a seismic zone can give different answers, and it is not clear there is a right or wrong way to do this.



Whether characteristic earthquakes occur in the Wasatch region depends on whether the entire Wasatch front or only the Wasatch fault area are considered. Triangles are earthquakes on the Wasatch front, the dashed line is the best-fit line, and the dashed box is the estimated range from paleoearthquakes (Pechmann and Arabasz, 1995). Closed circles are instrumentally recorded earthquakes on the Wasatch fault (Chang and Smith, 2002 and pers. comm.), and the solid line is the best-fit line. Open circles are the paleoseismic earthquakes on the Wasatch fault with the solid box showing the range. The Wasatch front events predict rates similar to the paleoseismic earthquake rates. However, the Wasatch fault events predict a lower rate of earthquakes per year than the paleoseismic events and make the paleoseismic earthquakes appear characteristic events.

Detection of a Fault-zone Heterogeneous Structure of the San Andreas Fault, CA, Using a Multimode Imaging of Seismic Coda Waves

Taka'aki Taira
Carnegie Institution of Washington

Paul Silver
Carnegie Institution of Washington

Fenglin Niu
Rice University

Robert Nadeau
University of California Berkeley

Fault zone (FZ) heterogeneous structures in seismogenic zone play an important role in generating earthquakes within a FZ. We attempted to reveal a FZ heterogeneous structure of the San Andreas Fault (SAF) at Parkfield, CA, as multimode scattering coefficients (P-P, P-S, S-P, and S-S). We first established a source array by selecting 10 aftershocks of the October 20, 1992, M=4.7 Parkfield earthquake. These aftershocks have almost the same source radiation pattern estimated by a grid search method (Reasenberg and Oppenheimer, 1995). Locations of aftershocks were determined precisely by the double-difference earthquake relocation algorithm introduced by Waldhauser and Ellsworth (2000). We analyzed three-component borehole seismograms recorded by nine seismometers of the High Resolution Seismic Network (HRSN) (Karageorgi et al., 1992) in a frequency range of 2 to 4 Hz. As a first stage of our analysis, we corrected the effects of seismic-source radiation and surface geology, based on the coda-normalization method (Aki, 1980). Attenuation effects (including intrinsic attenuation and geometrical spreading) were corrected with a statistical amplitude recovery technique, using by the Akaike Information Criteria (Taira, 2004). By incorporating a frequency-wavenumber (f-k) and polarization analysis, coherent scattered arrivals in both the P and S codas were identified. In this study, these arrivals were defined using the following two criteria: (1) high coherency (f-k power spectra > 1000) and (2) high linearity (particle motion ellipticity < 0.3). We found that P-S scattering is much more dominant than S-P scattering. This property is consistent with the expected response from structural heterogeneity, based on both theoretical and numerical analyses of the properties of scatterers (Aki, 1992; Zeng, 1993). In addition, we revealed that S-S scattering is much stronger than P-P scattering, a result that is most consistent with scatterers associated with fluid-filled cracks or fractures (Kuster and Toksoz, 1974; O'Connell and Budiansky, 1974). Using a 1-D wavespeed structure appropriate for the region (Michelin and McEvilly, 1991), we located these scattering coefficients based on the travel time and slowness vector of each of the detected scattered phases, under the assumption of a single isotropic scattering model (Sato, 1977). As a result, P-S and S-S scatterers appear to be primarily located just beneath and to the south of the epicenter of the 1966 M=6 Parkfield earthquake. Assuming S-wave speed to be 3.45 km/sec, the size of the S-S scatterers is to be of the order of 300 m.

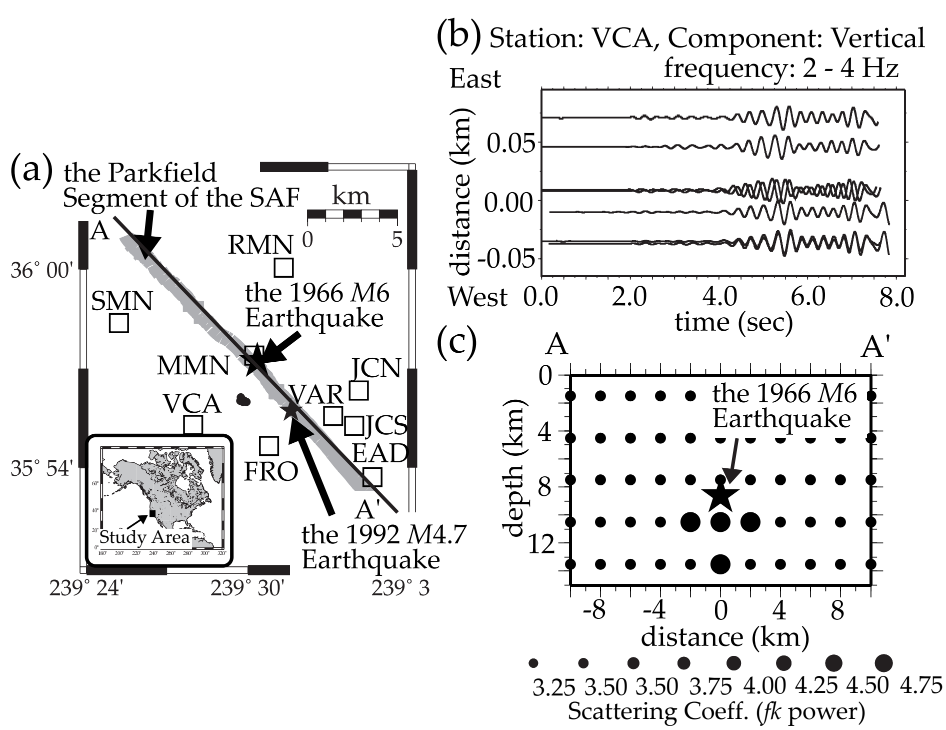


Figure 1. (a) Distribution of borehole seismic stations of HRSN and the location of the earthquakes source array used in this study. Black dots denote selected 10 aftershocks of October 20, 1992, M=4.7 Parkfield earthquake. Open rectangles indicate borehole seismic stations. The large and small stars are the epicenters of the 1996 M=6 and the 1992 M=4.7, respectively. Inserted figure shows our study area of the SAF. (b) Seismograms after corrections of seismic-source radiation, surface geology, and attenuation effects at VCA station in the vertical component with a frequency range of 2 to 4 Hz. Traces are aligned on origin times from relocations and are arranged by distance from the center aftershocks of the source array. (c) Vertical distribution of S-S scattering coefficients along the profile of A-A' in Figure 1a.

Insights into the Mechanism of Intraplate Earthquakes and Studies Proposed to Test Them

Pradeep Talwani
University of South Carolina

Abhijit Gangopadhyay
University of South Carolina

Inmaculada Dura-Gomez
University of South Carolina

Robert Trenkamp
University of South Carolina

Analyses of seismicity, geological, geophysical, and GPS data suggest that the current intraplate seismicity near Charleston, South Carolina is occurring on the NE trending Woodstock fault (WF) and on the NW trending Sawmill Branch fault which cuts and offsets WF near Charleston, South Carolina. The intersecting fault geometry is similar to that observed at other locations of intraplate earthquakes where the seismicity is concentrated in the upper crust. Two-dimensional modeling suggests that an optimum geometry for the intersecting fault requires that the main fault (in our case WF) is oriented at an angle (Alpha) 45 +/- 15 degrees to SHmax and that the intersecting fault lies at 80 degrees when Alpha > 45 degrees and ~160 degrees when Alpha < 45 degrees. In either case maximum stress and strain accumulation occurs near the intersecting faults. Direct measurement of strain rates using GPS is consistent with the model results. Delaunay triangles encompassing the 20 km x 30 km seismicity area were associated with strain rates of 2.1 x 10**-7 +/- 1.0 x 10**-7 rad/year, two orders greater than the average background value for the North American plate and an order magnitude greater than the surrounding 60 km x 100 km rectangular area.

These results suggest that targeted monitoring under the EarthScope program can be used to identify potential locations of intraplate earthquakes in eastern North America. This can be done by a determination of the fault geometry to identify potentially seismogenic faults, and the seismicity potential of these faults can be assessed by measuring strain rates using GPS, in the immediately surrounding areas, over periods of a few decades.

Preliminary Images of Subsurface Structure at SAFOD Using the Drill Bit Seismic Method

Stewart Taylor
Duke University

Jakob Haldorsen
Schlumberger, Inc

Christian Stolte
Schlumberger, Inc

Richard Coates
Schlumberger, Inc

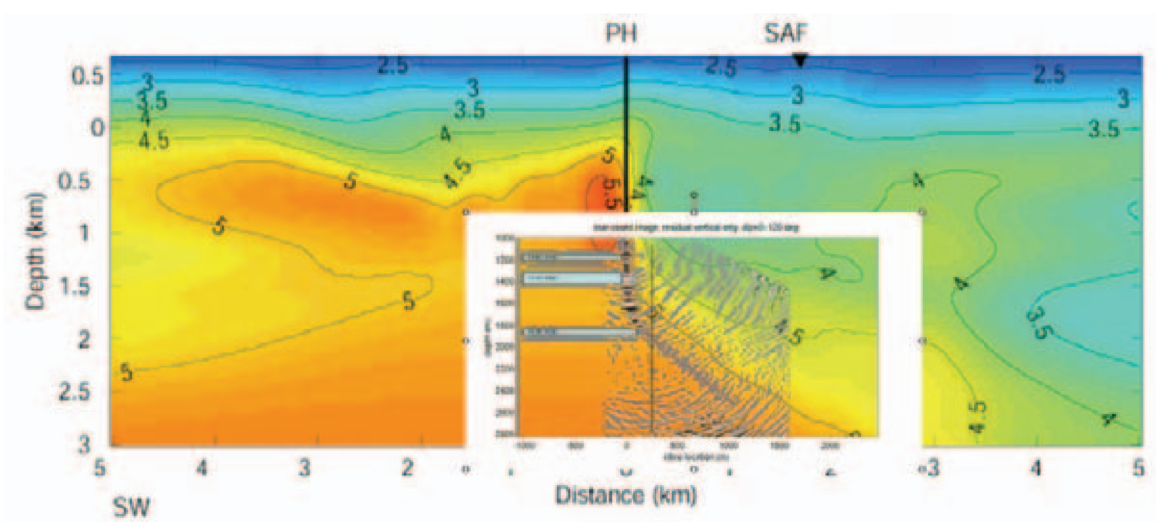
The goal of the drill bit seismic experiment at SAFOD is to make use of the borehole drilling operation itself as a source of seismic energy for imaging the complex subsurface geologic structure of the San Andreas Fault. During drilling of a well, the drill bit itself acts as a downhole seismic source capable of illuminating its surrounding. The energy generated by the drill bit can be recorded by geophone arrays to produce an inverse vertical seismic profile which may then be used for subsurface imaging.

During our experiment at SAFOD, the drill bit energy was simultaneously recorded by three geophone arrays installed at the site as well as accelerometers mounted on the top drive of the drill rig. In this paper, we present an overview of the acquisition system deployed at the site and the drill bit seismic data processing architecture. In addition, we present initial one way-time wavefields derived from records of the 46-channel (vertical component) surface geophone array that was deployed over the planned trajectory of the SAFOD well.

The initial one way-time wavefields we present were developed in three stages with processing continuing at this time. One was developed at the site, and two subsequent to the field acquisition activities. From these wavefields, we have developed preliminary subsurface images of the SAFOD site. These images are presented in a sequence that illustrates a progression from on-site processing to laboratory seismic data processing capabilities.

We present preliminary subsurface images that are interpreted in light of borehole geological data acquired during drilling of the SAFOD pilot hole and main borehole as well surface seismic data profiles acquired by the USGS. Our preliminary images include both non-migrated and migrated profiles. Shear zones in the SAFOD pilot hole described by Boness and Zoback (1984) occur at depths of 1150, 1300, and 1850 meters. An initial migrated image using drill bit seismic from the 46-channel surface array exhibits good correlation of low impedance reflectivity to these shear zones. Furthermore, our initial migration, though not optimal, shows linear, low-impedance reflections that have the correct orientation to be possible images of the Buzzard Canyon and associated faults. These faults have been described by Rymer et al. (2003), Catchings et al. (2003), and Chavarria et al. (2003).

We are continuing processing at this time so that we can improve the subsurface images because we have determined that our initial processing parameters included the usage of harsh beamforming filters that limit dips available for later imaging. In addition, our initial choice of offset ranges output from processing of the one way-time wavefield was probably too restrictive in terms of the aperture we utilized. We expect that usage of more optimal processing parameters will not only improve future subsurface images that we develop using the 46-channel surface array but will also increase the imaging capability of data from the three component surface array that we are currently processing.



A tomographic inversion computed using data recorded by the vertical array in the SAFOD pilot hole (PH) is shown with an inset of a preliminary drill bit seismic profile. The input data to the tomographic profile consisted of p-wave travel times from 47 shots of the 2003 VPI/GFZ crustal profiling effort. The resulting image is divided by the PH since no rays cross this point. Orange colors indicate areas of highest velocity that are interpreted to be the locations of Salinian granite. Blue and green colors indicate areas of lowest velocity that are interpreted to be the locations of Franciscan sediments or younger Tertiary age sediments. The well penetrated sediments at the approximate location of solid vertical line within the inset. The gray boxes to the left of the pilot hole (PH) indicate shear zones interpreted by Boness and Zoback from well log data acquired in the pilot hole. The red line within the inset indicates the path of the well bore. Possible fault locations are indicated by linear features proximal to the borehole.

The Cordilleran Orogen: An Andean-type Eocene Continental Plateau?

Christian Teyssier
University of Minnesota

Andreas Mulch
University of Minnesota

Seth Kruckenberg
University of Minnesota

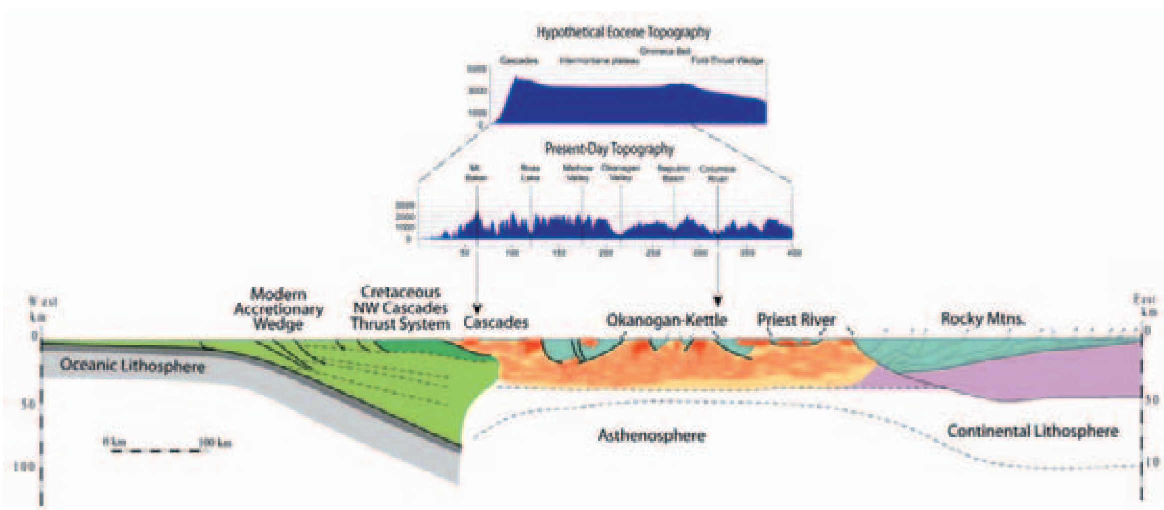
Robert Miller
San Jose State University

Collaborators
Donna Whitney
Page Chamberlain
Annia Fayon
Olivier Vanderhaeghe

At the approximate latitude of the U.S.-Canada border the Cordilleran orogen consists, from west to east, of the Northwest Cascades thrust system, the North Cascades metamorphic core, the Intermontane terrane and associated Mesozoic basins, the metamorphic core complexes of the Omineca belt, and the foreland fold-thrust belt (see figure). This 400 km geotraverse widens northward into British Columbia where the Cascades core merges with the Coast Plutonic Complex. Seismic profiles in the U.S. (COCORP) and Canada (Lithoprobe) show that the Moho is deepest beneath the Rockies (~50 km) and is essentially flat and shallow (30-35 km) across the metamorphic core complexes and the Intermontane terrane, irrespective of surface geology. The Cascades/Coast Plutonic Complex and the metamorphic core complexes of the Omineca belt display very similar ages of crystallization, cooling, and exhumation of high-grade metamorphic rocks, migmatites, and crustal-derived plutons (around 50 Ma). Geologic observations of the metamorphic core complexes indicate that migmatites commonly compose the footwall of detachment zones and display fabric and kinematic continuity with detachment mylonites. Dominant E-W extension of upper crust and flow of partially molten lower crust were temporally and kinematically linked. During this Eocene event, the Cascades/Coast Plutonic Complex underwent a component of wrench motion and experienced a significant component of orogen-parallel flow.

A possible interpretation of such a rapid and ubiquitous extension and crustal flow involves the demise of a continental plateau that was built during Mesozoic crustal shortening and thickening. There is ample evidence that at least some of the present-day Cascade topography developed during/after Miocene time but little is known about the pre-Miocene topography of this part of the Cordillera. Pre-Miocene high elevations of the Intermontane terrane have previously been suggested from paleobotany studies of Eocene floras. Our initial results of stable isotope-based paleoelevation reconstructions in Eocene detachment mylonites from the Kettle MCC indicate that a significant amount of topography has been removed since the onset of Eocene extension. The temporal and spatial data pattern is consistent with mean elevations of 3500-4000 m immediately preceding the demise of a high-elevation plateau. A drop of elevation may have resulted from crustal extension and coeval flow of crust from underneath the Intermontane paleo-plateau toward the east (Omenica belt) and the west (Cascades/Coast Plutonic Complex), such that the present Moho is flat and relatively shallow.

The cross-disciplinary nature of the EarthScope initiative has enormous potential for understanding the interplay between tectonic processes active in the upper crust, lower crust, and mantle. In particular this geotraverse of the North American Cordillera poses some key questions: What structures in the crust and the mantle accommodated extension and flow, and can we recognize older structures that can serve as markers of deformation history? Did the lithospheric mantle thin by flow, or did it thin by delamination? Since each of these processes predicts a characteristic topographic response, can EarthScope decipher the structures critical to discriminate these mechanisms and reconcile seismic data with paleoelevation proxies, low-temperature thermochronology, and erosion records?



Schematic geotraverse of the North American Cordillera at 48.5° North.

Present Day Continental Block Tectonics: New Results from Tibet and the Aegean to the Western United States

Wayne Thatcher
U.S. Geological Survey

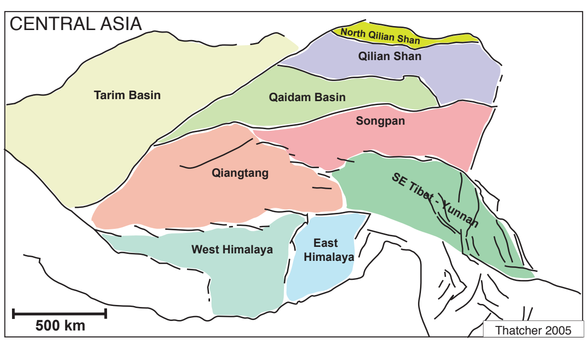
How continents deform has been hotly debated without definitive resolution since the earliest days of the development of the plate tectonic model. The evident wide distribution of seismicity, active faulting, and tectonically generated topography have suggested that active continental deformation takes place over broad regions and differs fundamentally from the narrowly focused straining occurring between plates of oceanic lithosphere. End-member models have postulated this deformation is either quasi-continuous or due to the relative motions of a small number of rigid blocks ('microplates'). The two models merge as the number of faults increase and the blocks required to describe their motions become more numerous and decrease in size.

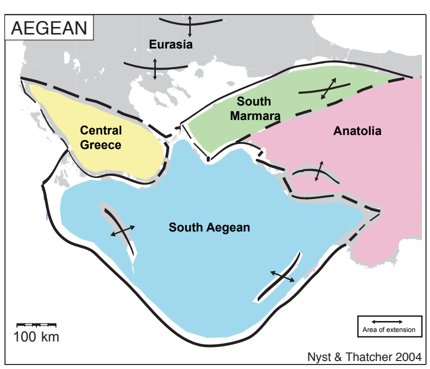
The absence of precise quantitative measures of regional continental deformation has been the chief obstacle in determining which, if either, description is correct. However, Global Position System (GPS) methods have the singular capability of providing the necessary quantification, permitting accurate mapping of site velocities across deforming zones in a common reference frame.

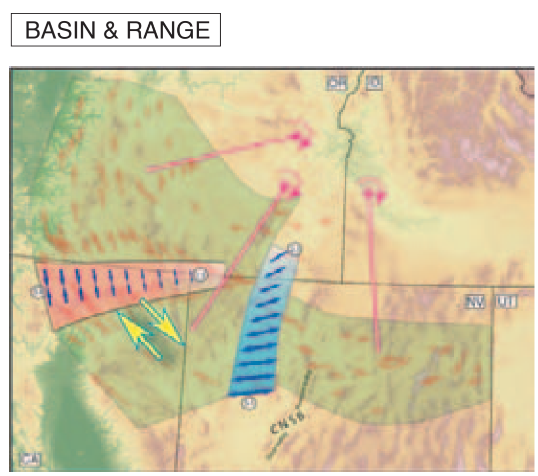
Emerging evidence from survey-mode GPS (SGPS) measurements in Tibet, the Aegean and the western U. S. suggests that present-day active continental deformation occurs largely due to the relative motions of quasi-rigid blocks. Tibet and its surroundings are composed of a mosaic of blocks, including 5 large ones ~1000 km in extent and several smaller ones several 100s of km wide on the periphery of the plateau (Thatcher, 2005). Current deformation of the Aegean region can be understood as the relative motions of 4 microplates ~300-1000 km in extent (McClusky et al., 2000; Nyst and Thatcher, 2004). New survey results provide evidence for low rate internal straining (~ 10 ns/yr or less) and/or substructure to the Anatolian block at levels of 2-5 mm/yr. The western U. S. is composed of a series of fault-bounded slivers related to strike-slip faulting across the San Andreas system and larger blocks in the Basin and Range and Pacific northwest (Thatcher et al., 1999; Bennett et al., 2003; Hammond and Thatcher, 2004; McCaffrey, 2005; Meade and Hager, 2005).

Despite this emerging evidence, it is not universally agreed whether the continental microplate description of the GPS data is superior to models that include more continuously distributed deformation, and controversy continues. SGPS measurements spanning 5-10 year intervals are accurate to 1-2 mm/yr and we have argued that block rigidity in the western U. S., the Aegean, and Central Asia is established within uncertainties of 2-4 mm/yr over length scales of 100s of km or more.

Continuous GPS networks like the Plate Boundary Observatory (PBO) have the potential to test and refine these kinematic models. Steady state velocities accurate to ~0.5 mm/yr or better will provide stringent constraints on block rigidity at levels of a few ns/yr, determine block rotations with comparable precision, and detect slip rates as low as ~0.3 mm/yr on geologically active intraplate faults.







Hammond & Thatcher 2005

Schematic illustration of quasi-rigid blocks derived from analysis of GPS data in Central Asia (top), The Aegean region (middle) and the Oregon-Nevada region of the Basin and range province (right).

EarthScope Resolution of Two Complete Cycles of Supercontinent Assembly and Breakup

William Thomas
University of Kentucky

Randy Keller
University of Texas El Paso

Robert Hatcher
University of Tennessee Knoxville

Krishna Sinha
Virginia Tech

From the southern Appalachians westward beyond the Marathon uplift, and from the Midcontinent southward into the Gulf of Mexico, the continental lithosphere of North America is a mosaic of tectonic elements, representing a succession of crust-generating and crust-modifying events in two complete cycles of supercontinent assembly and breakup. We know from outcrops, deep wells, and geophysical data that products of four successive mega-events are preserved uniquely here, and EarthScope can resolve the three-dimensional geometry of:

(1) the tectonic boundary between the Grenville (and Llano) province (~1.1 Ga) and older Laurentian cratonic crust. Grenville rocks record assembly of supercontinent Rodinia, providing a unique opportunity for EarthScope to characterize and map the three-dimensional geometry of a continental suture within an ancient supercontinent.

(2) an orthogonally zigzag margin of eastern Laurentia, which reflects continental rifting, breakup of Rodinia (565-530 Ma), and opening of the Iapetus Ocean. The rift system includes rift segments offset by transform faults, outlining promontories and gulf-like embayments. EarthScope can define contrasts in structural styles of rifts and transforms from the shallow crust to the upper mantle. During continental rifting, extensional and strike-slip faults propagated into the continental interior, where weak crust localizes modern intraplate seismicity (e.g., New Madrid). Further resolution is required to determine if rift and transform faults, as well as intracratonic faults, accommodated to textures of Grenville and older compressional structures, initiating a pattern of tectonic inheritance.

(3) compressional mountain belts, which, during assembly of supercontinent Pangea (by ~270 Ma), were driven onto the Iapetan rifted margin by collisions with arcs, exotic terranes, and other continents. Sinuous curves of the Appalachian-Ouachita orogen mimic the shape of the Iapetan rifted margin and subsequent passive-margin shelf edge. The orogenic belt includes two significantly different tectonic styles: (1) in the southern Appalachian thrust belt, imbrication of Laurentian carbonate-shelf strata was driven by terrane accretion and collision with African continental crust (Suwannee terrane); and (2) in the Ouachita thrust belt, imbricated continental-slope facies (in an accretionary prism at the leading edge of an arc complex) were thrust onto the continental shelf. PASSCAL wide-angle reflection/refraction data show a thick mass of Ouachita sedimentary rocks above transitional or oceanic crust outboard of the rifted margin of Precambrian crust. The contrasting Appalachian and Ouachita thrust belts converge along the Iapetan transform margin of the Ouachita embayment, providing EarthScope potential to resolve the geometry and kinematics of interactions between the two tectonic styles in the context of deeper lithospheric structure along a single continental margin.

(4) the present Atlantic and Gulf margins, formed by continental rifting and breakup of supercontinent Pangea (~205 Ma). EarthScope can evaluate possible tectonic inheritance along a large Gulf (Triassic) transform that apparently coincides geographically with an Iapetan Cambrian transform. Along the Gulf margin, anomalously great magnitudes of post-rift subsidence and sediment accumulation in the Mississippi delta are within a Cambrian continental embayment, a late Paleozoic thrust-belt curve, and a Triassic continental embayment—the present Gulf of Mexico. Complete resolution will require offshore deployment of seismometers.

Successive events suggest the probable importance of tectonic inheritance in the large-scale structures of the continental lithosphere, and here, where the records of several mega-events are preserved, EarthScope has the opportunity to resolve the geometric forms and compositional variations that drive tectonic inheritance at a continental scale. Both extensional and compressional stresses evidently have reactivated basement faults far into the continent. Deep sedimentary basins in various tectonic settings reflect large-magnitude crustal subsidence. Resolution of these structures can lead to applications ranging from assessment of large petroleum reserves in deep sedimentary basins to better understanding of intraplate seismicity.

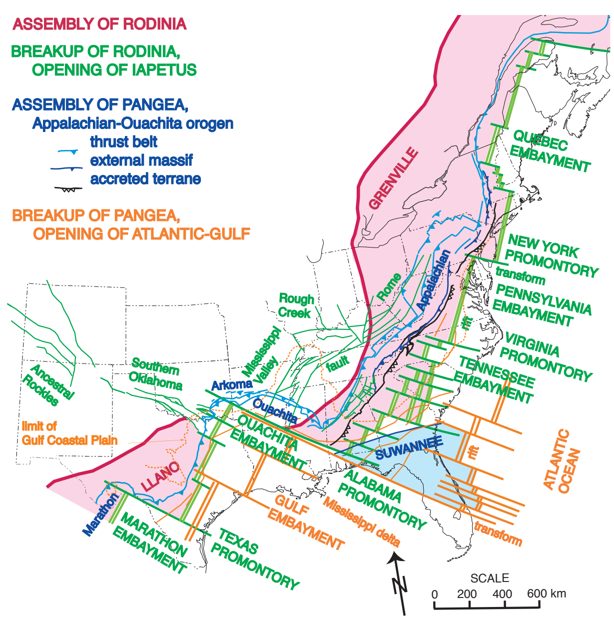


Figure 1. Map of eastern and southern United States showing structural boundaries that define four mega-events: (1) assembly of Rodinia (~1.1 Ga); (2) breakup of Rodinia and opening of Iapetus Ocean (565-530 Ma); (3) assembly of Pangea (by ~270 Ma); and (4) breakup of Pangea and opening of the Atlantic Ocean and Gulf of Mexico (~205 Ma).

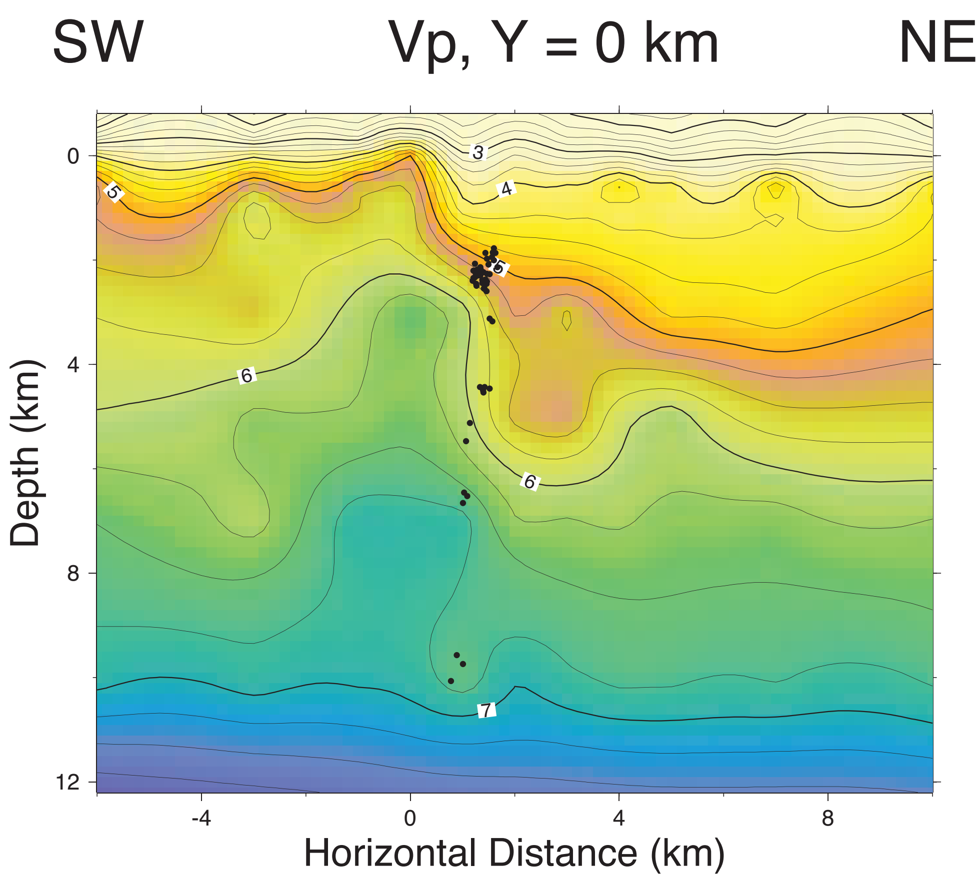
Evolution of an Experiment: The PASO Array and SAFOD

Cliff Thurber
University of Wisconsin Madison

Steve Roecker
Rensselaer Polytechnic Institute

In 1998, momentum for fault zone drilling into the San Andreas Fault (SAF) at Parkfield was gaining strength, but the drilling planners faced a dilemma. Two existing seismic tomography studies that simultaneously determined earthquake locations along with 3D wavespeed models yielded dramatically different answers for the position of the SAF seismicity at depth near SAFOD. One placed the earthquakes directly beneath the surface trace on a vertical fault and the other placed them on a southwest-dipping fault with the shallowest activity nearly a kilometer off the fault trace. We designed a dense seismic array experiment to address this discrepancy, using a combination of array design optimization and model discrimination analysis. We review the history of the Parkfield Area Seismic Observatory (PASO), focusing on how PASO was influenced by the creation of EarthScope and the evolution of the SAFOD drilling plans, as well improving array technology and interplay with other Parkfield projects, including the SAFOD Pilot Hole, the 2003 Hole/Ryberg reflection-refraction line, fault-zone guided wave studies, and the September 2004 earthquake response.

Results from PASO have been critical to the SAFOD drilling plans, but the greatest challenge lies ahead. SAFOD's multi-lateral coring capability offers an incredible opportunity to gain insight into fault mechanics. Quoting the EarthScope MREFC proposal, "The prospects of sampling both seismogenic patches and stably sliding sections of the San Andreas Fault, as well as sub-parallel faults that are no longer active, are especially exciting." Obtaining samples of the fault zone from places where it is, in one case, undergoing brittle failure in magnitude 2 earthquakes and, in the other, undergoing creep, could provide critical evidence about the physics of earthquake nucleation and rupture as well as processes controlling the stability of sliding. Accomplishing this goal, however, requires a level of absolute location accuracy (tens of meters) common in the oil industry but unheard of in earthquake seismology. We describe the concept of "virtual earthquakes" (receiver gathers of surface shot arrivals on borehole geophones) and show how they provide the critical evidence regarding our ability to derive accurate and precise locations for earthquakes in the drilling target zone.



Cross-section through a three-dimensional P-wave tomography model (contours 0.25 km/s) passing through the SAFOD site (horizontal distance = 0 km). The trace of the San Andreas fault is at +1.8 km horizontal distance. Note the sharp seismic wavespeed contrast between the northeast and southwest sides of the fault, and the clustering of earthquakes (filled circles) along the velocity discontinuity beneath the fault trace.

Calibration of Small-to-intermediate Aperture Seismic Arrays: Challenges, Solutions, and Possibilities for Fine Earth Structure Investigations

Ileana Tibuleac
Weston Geophysical Corporation

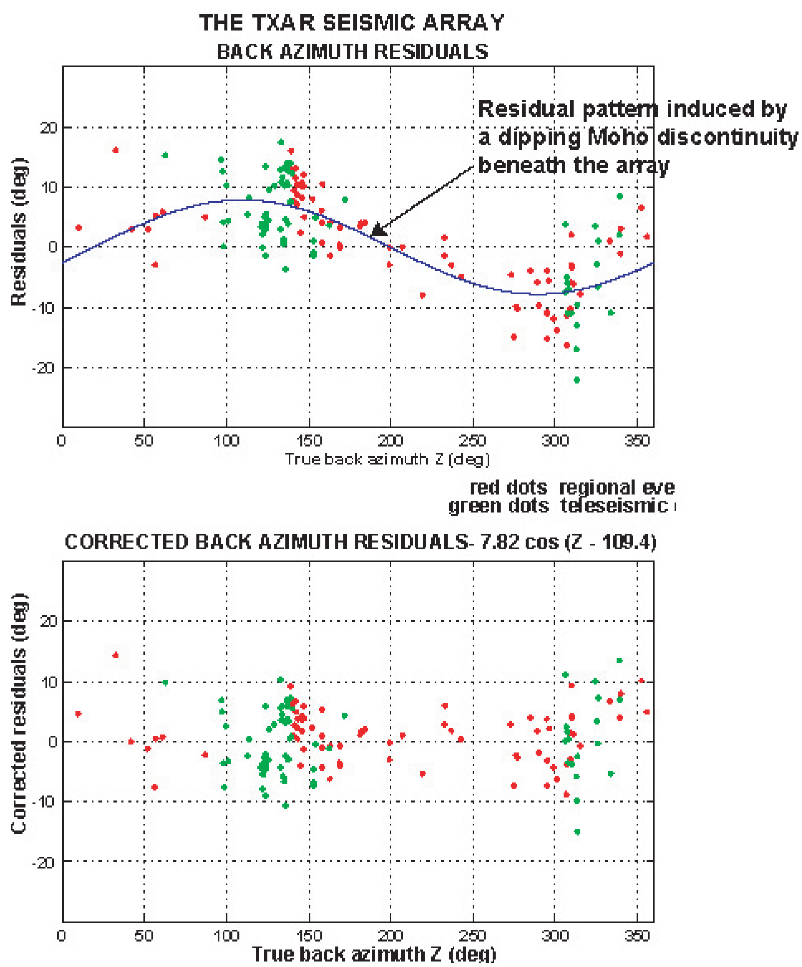
Kent Lindquist
Lindquist Consulting

Roger Hansen
University of Alaska Fairbanks

Investigations using small-to-intermediate aperture (< 25 km) seismic arrays, similar to suggested deployments within the USarray's flexible component, have been effective in estimating high resolution Earth structure images. We present time domain digital data processing algorithms and methodology designed to resolve crustal structure as well as mantle heterogeneity in order to calibrate nine or nineteen element short-period seismic arrays, designed for nuclear explosion monitoring.

Currently, most of the techniques for processing array data are based on frequency-wavenumber (f-k) processing. We present results of an array processing methodology based on crosscorrelation in time domain, developed by Tibuleac and Herrin (1997) and applied to regional-to-teleseismic events recorded at three North American arrays: TXAR (Lajitas, Texas), NVAR (Mina, Nevada), and ILAR (Eilson, Alaska). We show that obtaining accurate array slowness and back-azimuth estimates, i.e, accurate phase time delays between array elements, depends on properly correcting for 1) crustal structure beneath the array, 2) differences in elevation of the instruments, and 3) complicated geology at the site. Patterns in the estimated horizontal velocity and back-azimuth offer information on the tectonic setting of the region, such as the first order attitude of the Moho discontinuity. After correcting for crustal effects, effects due to mantle structures can be more precisely quantified.

We have also adapted the crosscorrelation method to automatically process thousands of events, with fast and efficient review of the results using a package of robust and semi-automatic array processing software called the Automatic Routine Package for Array Calibration (ARPAC1.0). ARPAC1.0 uses Antelope integrated with Matlab for data processing.



Subplot 1: The back-azimuth residuals (estimiated TXAR back-azimuth - USGS back-azimuth) versus the USGS back-azimuth in degrees and a best L1 fit curve. Red dots represent regional events, green dots represent teleseismic events. Subplot 2: The back-azimuth residuals corrected for the dipping Moho: mean = 0.4 degrees, sample standard deviation = 5.2 degrees.

The New Mexico Bureau of Geology and Mineral Resources' STATEMAP Program: Detailed Geologic Mapping in New Mexico

J. Michael Timmons

New Mexico Bureau of Geology & Mineral Resources

Mark Mansell

New Mexico Bureau of Geology & Mineral Resources

The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) geologic mapping program (STATEMAP) is partly funded by the National Cooperative Geologic Mapping Program, a federal program administered through the USGS. We are in the 12th year of a project designed to rapidly produce and distribute state-of-the-art, detailed geologic quadrangle maps of select areas of the state. By June2004, we will have mapped 100 quadrangles (approximately 6000 sq. miles), mostly along the Rio Grande watershed from Taos to Socorro, but also including areas of critical concern in the Pecos River watershed, the Great Plains watershed, and the Colorado River watershed (Figure 1).

In New Mexico, new, digital geological quadrangle maps by the NMBGMR are being developed to support a variety of environmental and hydrologic work by state agencies, local governments, consultants, and researchers. A few recent projects include: a hydrogeologic investigation of the Albuquerque Basin aquifer (in cooperation with the USGS); a hydrogeologic assessment for Sandoval County in the Placitas development area; a hydrogeologic study of the Taos Valley; subsidence and aquifer consolidation modeling in the Albuquerque area; the availability of ground water in the Carlsbad area; and the hydrogeology of the Espanola basin.

Recent mapping also supports ongoing research into basement metamorphic rocks in New Mexico and provides essential primary data to better understand the dynamic interplay between mid-crustal deformation, metamorphism, and plutonism. These larger studies also provide some understanding of mid-crustal processes and their relationship to the crustal tectonic history and geologic architecture of New Mexico.

An example of a derivative map that utilizes and improves upon the original STATEMAP product is the East Mountain compilation, a nine-quadrangle ArcGIS map that includes the Sandia Mountains and adjacent quadrangles to the east. This map was compiled from original maps by NMBGMR and contract mappers. The 1:24,000 compilation shows detailed mapping and includes cross sections that illustrate the entire stratigraphic column of the area, from Paleoproterozoic supracrustal rocks to Quaternary surficial deposits. By combining individual quadrangles into a larger regional compilation, researchers can evaluate and refine current geologic understanding in central New Mexico. The compilation was partially funded by the NM Office of the State Engineer for an East Mountain area hydrologic study conducted by the USGS. It is currently a work in progress, but will be released as an open-file map report in 2005.

Detailed STATEMAP geologic quadrangle maps provide geologists and the public with modern, practical, digital, base-line geologic data. The ArcGIS regional compilations support syntheses of regional geologic models and a variety of derivative uses. The NMBGMR anticipates producing more compilations of detailed mapping for areas of interest to a broad audience and we encourage researchers to exploit these products to augment their research. Many of our maps are available as free Web downloads and digital files are updated as maps are completed. More information can be found at: http://geoinfo.nmt.edu/publications/maps/ofgm/home.html

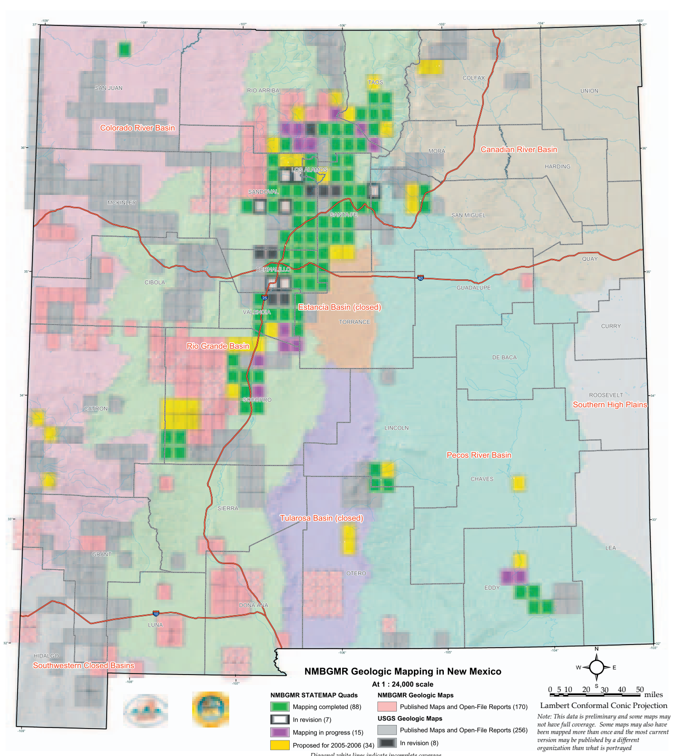


Figure 1: Map of New Mexico showing existing 1:24,000 geologic mapping including NMBGMR and USGS studies. Proposed 7.5 min quadrangles for the 2005-2006 mapping season are shown in yellow.

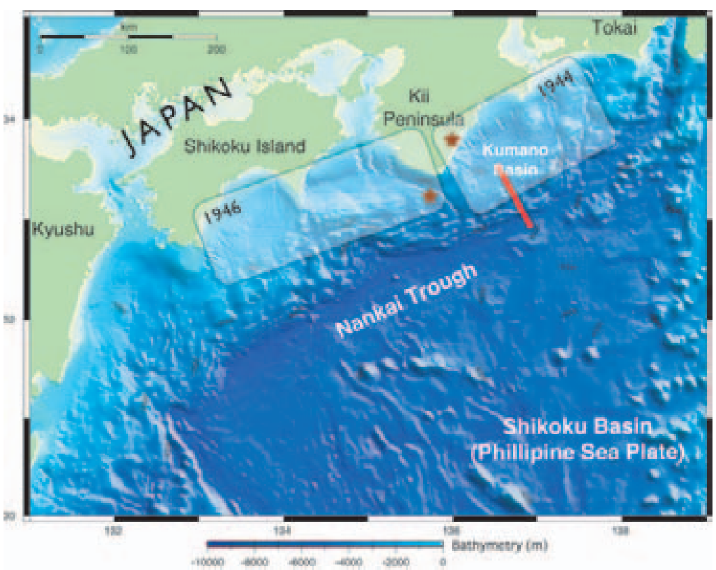
Drilling a Subduction Zone Megathrust: The IODP NanTroSEIZE Drilling Project

Harold Tobin
New Mexico Institute of Mining and Technology

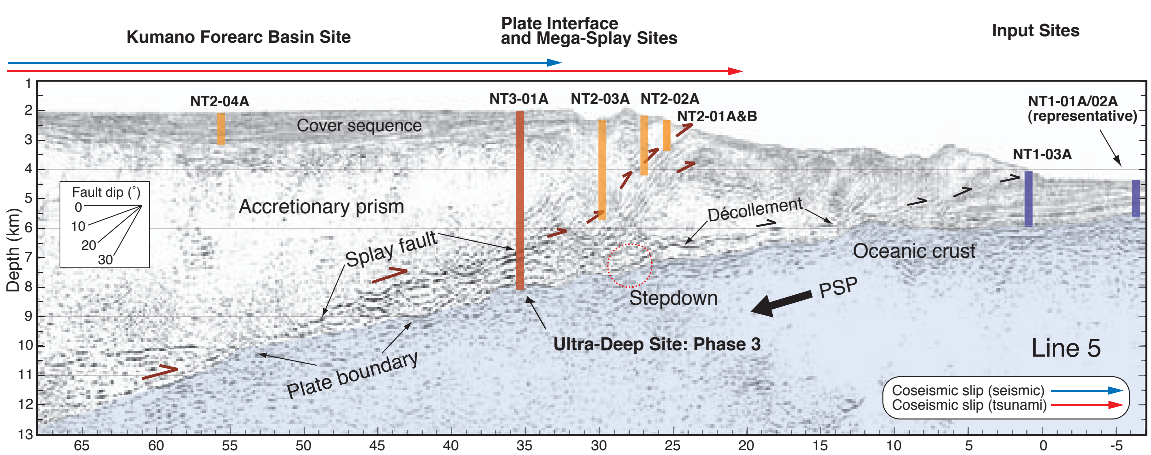
Masa Kinoshita
JAMSTEC, Japan

Subduction plate margins produce the Earth's greatest magnitude earthquakes and most destructive tsunami, yet the fundamental processes that govern their frequency, size, duration, and effects remain poorly understood. Our understanding of the mechanics and dynamics of plate boundary faulting is limited by a lack of information on properties and ambient conditions within active faults at depth. The Integrated Ocean Drilling Program (IODP) has recently accepted the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) as a multi-year drilling and observatory installation project of unprecedented scope in scientific drilling. NanTroSEIZE is an integrated program of geophysical studies coupled to drilling and installation of monitoring instruments using the new IODP drilling vessel Chikyu. It is designed to investigate the aseismic to seismic transition of the megathrust system and the processes of earthquake propagation and tsunami generation at the Nankai Trough subduction zone. NanTroSEIZE shares several objectives with SAFOD and can be viewed as a complementary program in a different plate boundary setting.

Our fundamental goal is the creation of a distributed observatory spanning the up-dip limit of seismogenic and tsunamigenic behavior in the region of rupture and tsunami source in the 1944 Tonankai M8.0 great earthquake. The primary objective is to access and instrument the Nankai plate interface to advance our knowledge of fundamental aseismic and seismic faulting processes and controls on the transition between them. NanTroSEIZE will test models for the frictional behavior of fault rocks across the aseismic – seismogenic transition, the composition of faults and fluids and associated pore pressure and state of stress, partitioning of strain spatially between basal interface and splays, temporally between coseismic and interseismic periods, and between infraseismic and aseismic events vs. seismic events. Long-term borehole observations potentially will ultimately test whether interseismic variations or detectable precursory phenomena exist prior to great subduction earthquakes. Opportunities exist for many new researchers to become involved in the NanTroSEIZE effort.



The Nankai Trough subduction zone (left) has been the site of numerous tsunamigenic megathrust great (M8+) earthquakes, most recently in 1944 and 1946. The red line shows the location of a deep-penetrating seismic reflection line (below) imaging the plate boundary fault system. Tsunami and earthquake inversion show that co-seismic slip propagated to shallow depth on the basal detachment and/or mega-splay fault system in 1944. In NanTroSEIZE, we plan for a series of boreholes accessing this interface at locations spanning the up-dip aseismic to seismic slip transition. Sampling, downhole experiments, and long-term monitoring are planned.



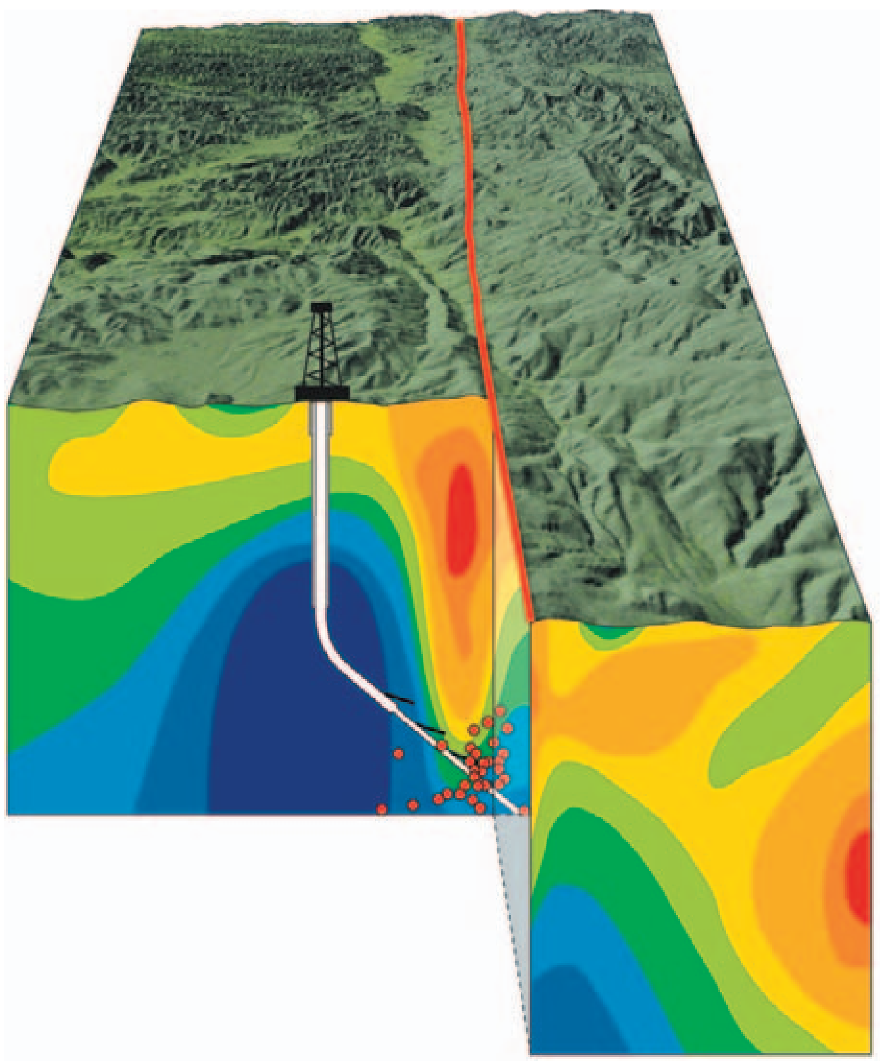
Magnetotelluric Imaging of Fault Zone Structure at the SAFOD Site

Martyn Unsworth
University of Alberta

Magnetotelluric (MT) exploration has played an important role in characterizing subsurface structure at the SAFOD site prior to drilling. The initial MT survey in 1994 revealed a fault zone conductor (FZC) that extended to a depth of 2-3 km. A more detailed MT survey in 1997 showed that this feature was typical of the Parkfield segment of the San Andreas Fault. Other MT surveys have also shown that similar zones of low resistivity are often present worldwide on other major strike faults. These features are generally attributed to a zone of enhanced fracturing, and elevated fluid contents, although clay mineralization can also decrease the resistivity. Some segments of major strike slip faults also exhibit zones of low resistivity in the mid-crust and this may be directly related to crustal flow processes.

Since the MT data collection at Parkfield in 1994-7 additional data analysis has been undertaken and this constrains the depth extent of the FZC to around 1.5- 2 km. High-resolution earthquake locations now reveal that the seismicity begins at the base of the FZC. The in situ resistivity imaged with MT shows a significant correlation with velocities derived from seismic tomography.

While the shallow geoelectric structure at the SAFOD site is relatively well understood, the deeper structure at seismogenic depths is less well constrained. Synthetic inversion studies show that a longer MT profile could image features in the mid-crust that may be associated with crustal flow and deformation processes . It is possible that the width of a shear zone in the lower crust could be determined by a carefully executed MT survey.



Electrical resistivity structure at the SAFOD site, imaged with magnetotelluric exploration.

Subduction Potential at the Eastern Margin of North America

Suzan van der Lee
Northwestern University

Klaus Regenauer-Lieb
University Mainz

Dave Yuen
University of Minnesota

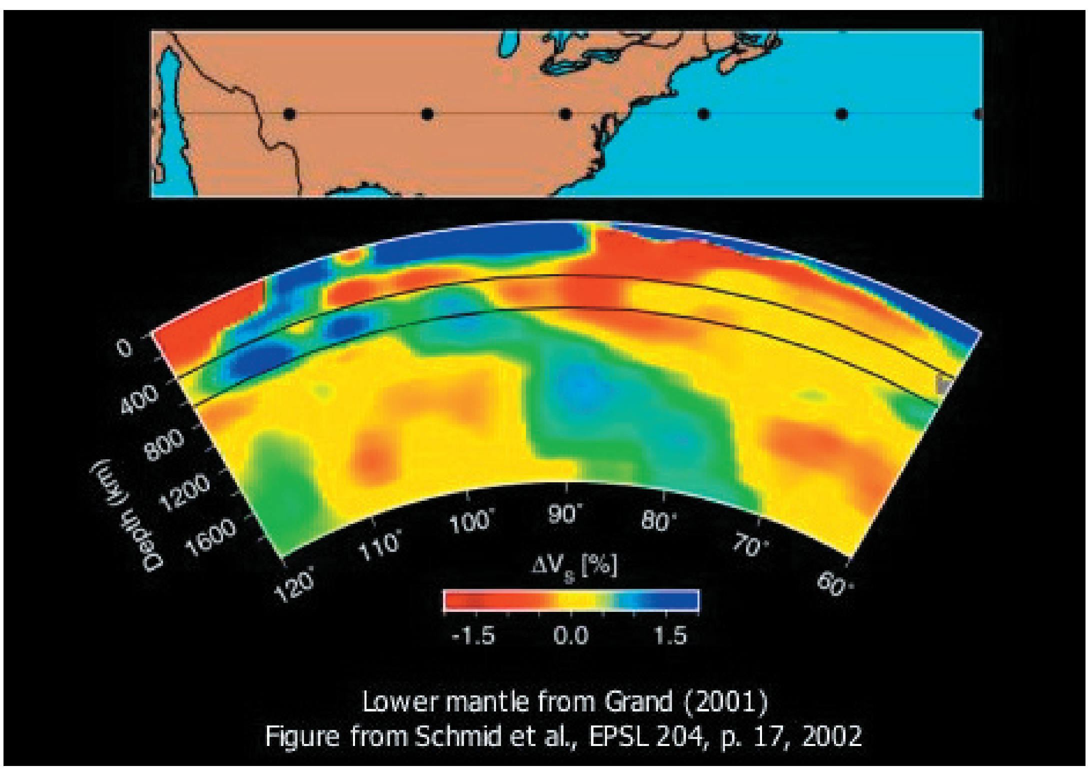
S. Mark Wang
University of Minnesota

Inferring the processes in and dynamics and evolution of Earth's interior is crucial for predicting how earthquake and volcanic activity will change in time and space. Three-dimensional models of S-velocity beneath North America combined with numerical simulations of forming lithospheric shear zones lead us to believe that a subduction zone on the US East coast could be incipient.

S-velocity models for the North American upper mantle show a giant dike of S-velocities about 0.1 km/s slower than the average upper mantle. Of temperature or relative content of iron, silicon, carbon dioxide, and water, we deem the latter the most likely explanation for the unusual S-velocity anomaly. Resolution tests, based on a recent set of over a thousand wave trains of continent-wide S and surface waves, show that the shape of the anomaly is resolved. However, S-velocities in the transition zone are underestimated. The low-velocity dike connects to a weak low-velocity zone at the top of the upper mantle in Grand's model (2001). The giant dike is east of and parallel to the Appalachians and to the strike of the Farallon slab in the top of the lower mantle (Grand, 2000). The dike most likely represents an upwelling. Past dehydration of subducted Iapetus lithosphere or more recent dehydration of the subducted Farallon plate are potential sources for the inferred wet rock in the low-velocity dike.

Geodynamic modeling shows that large-scale lithospheric faulting associated with subduction zones, can develop when the lithosphere is wet. Dry lithosphere such as that of the Atlantic Ocean thus needs to be hydrated to allow a new subduction zone to form on the US East coast. However, numerical modeling shows that a supra-lithospheric ocean cannot sufficiently hydrate the lithosphere and hence the source of hydration must come from below. The hydrous dike-shaped upwelling discussed above is the perfect candidate for such hydration and subsequent initiation of subduction. Under the sediment load off the US east coast the hydrated lithosphere will yield and can form a shear zone that cuts across the entire thickness of lithosphere. A new subduction zone is so initiated, up to half a billion years after a former subduction process provided the necessary ingredient, H_2O.

In the context of this abstract and many others, we are excited about the enormous amounts of new data that will be forthcoming in the next dozen years from the USArray. This data will both revolutionize the resolution with which we can image upper mantle structure at the eastern continental margin, and allow for potentially associated seismic activity to be monitored more closely. Arriving at the east coast, USArray might show us the driving mechanism for the Wilson Cycle.



Anomalous S-velocity in the North American upper mantle from seismic-tomographic imaging using S, multiple S, and surface waves. The upper-mantle column of low-velocity anomalies beneath the eastern continental margin presents a side view of the giant low-velocity dike.

EarthScope and You: What is the EarthScope Facility and How Can Researchers Use It?

Gregory van der Vink
EarthScope

The National Science Board approves funding for major research facilities such as EarthScope when it deems them "transformative in nature, [with] the potential to shift the paradigm in scientific understanding and/or infrastructure technology." There is broad recognition within the scientific community that Geoscience is on the verge of a paradigm shift, one that will come through multi-disciplinary approaches to addressing fundamental scientific questions that have stubbornly resisted traditional single-disciplinary work.

EarthScope is unprecedented in scope, scale, and ambition – taking a multi-disciplinary approach to understanding the tectonics of the North American continent at all scales: from the active nucleation zone of earthquakes, to individual faults and volcanoes, to the deformation along the plate boundary, and to the structure of the continent. With approximately $200 million in funding from the National Science Foundation's (NSF's) Major Research and Facility Construction account, EarthScope will be constructed over the next five years. Once complete, EarthScope is anticipated by NSF to be operating for an additional 15 years.

The North American continent is an ideal location for EarthScope, as no place else on Earth offers such a rich set of active geological processes so accessible for study. Available for observation is the full spectrum of plate boundary processes, ranging from plate convergence in the subduction zones of Cascadia and the Aleutians, to transform faulting along the San Andreas Fault, and intraplate extension of the Basin and Range. EarthScope has begun collecting multiple data sets that will allow us to study the transition from plate-scale tectonic interactions to small-scale system level processes such as individual faults and volcanoes, and how they interact. EarthScope is ideally suited to link traditional near-surface geology with deeper structure.

North America also provides a 3.5 billion year record of plate evolution and the assembly and break-up of a supercontinent, a process that occurred twice over the past 1.5 billion years. The resulting linear orogenic belts associated with supercontinent development reflect opening geometry transform faults, incorporation of island arcs and stray continental blocks in the ephemeral oceans, and the geometry of closing cratons.

From a "data collection" perspective, EarthScope is being implemented through the parallel construction of multiple observational systems. A four-kilometer deep observatory (SAFOD) bored directly into the San Andreas fault at Parkfield is providing the first opportunity to observe directly the conditions under which earthquakes occur, to collect fault rocks and fluids for laboratory study, and to monitor continuously with seismometers and strainmeters an active fault from within the earthquake zone. A network of continuously recording Global Positioning System receivers, borehole strain meters, and borehole seismic stations (PBO) is being installed along the western US plate boundary. A network of seismographic stations and magneto-telluric instruments (USArray) is being deployed to migrate slowly across the United States, eventually occupying 2,000 sites over the next ten years. Additional seismic and geodetic instrumentation will soon be available to individual PIs for high-resolution imaging in areas of special geologic interest. A key task for EarthScope is to provide seamless, single-point access to all EarthScope data so that the community may develop higher order data products, tools, visualizations systems, and portals.

Fulfilling the scientific promise identified by the National Science Board requires not only the construction of EarthScope, but also a comprehensive plan for its long-term operation – a plan that will continue to include a high level of management oversight and accountability. At the request of the National Science Foundation (NSF), EarthScope developed a detailed Operations and Maintenance Proposal with an exhaustive budget analysis that projects costs through 2011. The proposal, which is openly available on the EarthScope website or directly from the EarthScope Office, is undergoing a rigorous vetting process that includes the scientific community, NSF internal review, an independent cost review, and, finally, approval by the National Science Board.

The long-term funding requirements for EarthScope operations and maintenance are modest in terms of the overall capitalizations costs (approximately 20% per year), but are significant in terms of the Research and Related Activities Account of divisions with small budgets such as Earth and Atmospheric Research. Certainly, EarthScope can not achieve its goals if funding for its operation comes at the expense of the scientific and educational communities that it is intended to serve. At the same time, identifying additional funding within NSF's current budget environment will require decisions at the uppermost levels of the Foundation.

EarthScope is committed to working with NSF through every part of this process: refining costs and management procedures through extensive reviews; maintaining transparency in schedules, costs, and progress; inviting continued community input and review; and working to identify possible methods for funding structures. Through this process and the continued support of the Geoscience community, we expect to secure sustainable funding for EarthScope, and to help set a positive precedent for the support of large facilities and the scientific and educational activities associated with them. At that point, the National Science Board's expectation may be met with both a quantum leap for our understanding of the Earth, and a positive model for the balance between individual research grants and community data collection enterprises necessary to support the next generation of scientists, educators, and students.

GPS Installation Progress in the Southern California Region of the Plate Boundary Observatory

Christian Walls
UNAVCO

Edward Arnitz
UNAVCO

Scott Bick
UNAVCO

Shawn Lawrence
UNAVCO

One of the roles the Plate Boundary Observatory (PBO), part of the larger NSF-funded EarthScope project, is the rapid deployment of permanent GPS units following large earthquakes to capture postseismic transients and the longer-term viscoelastic-response to an earthquake. Beginning the day of the September 28th, 2004, Parkfield earthquake, the PBO Transform Site Selection Working Group elevated the priority of two pre-planned GPS stations (P539 and P532) that lie to the south of the earthquake epicenter, allowing for reconnaissance and installation procedures to begin ahead of schedule. Reconnaissance for five sites in both the Southern and Northern California offices began the day following the earthquake and two permits were secured within three days of the earthquake. Materials and equipment for construction were brought along with the response team and within 4 days the first monument (P539) was installed.

Of the 875 total PBO GPS stations, 230 proposed sites are distributed throughout the Southern California region. These stations will be installed over the next 4 years in priority areas recommended by the PBO Transform, Extension and Magmatic working groups. Volunteers from the California Spatial Reference Center and others within the survey community have aided in the siting and permitting process. Currently the production status is: 24 stations built (12 short braced monuments, 12 deep drilled braced monuments), 35 permits signed, 46 permits submitted and 50 station reconnaissance reports. To date, Year 1 and 2 production goals have been met.

P600 Helicopter Installation Team. Left to right: Shawn Lawrence, Scott Bick, Ed Arnitz, Chris Walls.

The Electromagnetic View of Continental Dynamics: U.S. Experience and the Potential of EarthScope

Philip Wannamaker
University of Utah

Stephen Park
University of California Riverside

John Booker
University of Washington

Gary Egbert
Oregon State University

George Jiracek
San Diego State University

Alan Chave
Woods Hole Oceanographic Institute

Martyn Unsworth
University of Alberta

Electrical conductivity (or its inverse resistivity), is one of only a few physical properties with which we can understand Earth dynamics. EarthScope will implement new conductivity research potential at a vastly greater scale than the US community has been utilizing heretofore. Much of the field's credibility has been built up through prior projects supported by EMSOC (Electromagnetic Studies of the Continents). EMSOC is a multi-institutional facility, formally underwritten by the NSF since 1996, enabling EM studies of the Earth by maintaining and providing magnetotelluric (MT) equipment to U.S. institutions and their co-workers. EMSOC-supported experiments in the U.S., often a component of multidisciplinary studies, have mapped fluids and domains of probable weakness within the San Andreas fault zone, buoyant mantle supporting the High Sierra, lithospheric dismemberment and magmatism at the Great Basin-Colorado Plateau transition, and possible fossil suture zones and lithospheric delamination below the Southern Appalachians. EMSOC equipment has also exposed the MT method to nonspecialists at the NSF-supported field geophysical education and research program SAGE (Summer of Applied Geophysical Experience). Information about facility activities is available on the EMSOC web site emsoc.ucr.edu.

This abstract touches upon two existing studies, with additional project areas covered on the poster. A 400 km, detailed MT transect of the Great Basin-Colorado Plateau transition zone in southern Utah examines the mode of ongoing consumption of the Colorado Plateau by extensional processes of the Great Basin to determine the geometry of the deep transition (Figure 1a). Preliminary two-dimensional inversion shows two conductive, diapiric structures in the upper mantle project upward toward concentrations of low resistivity in the lowermost crust, which are interpreted to represent mantle melting, basaltic crustal underplating, and fluid exsolution from melts. Also seen is an interesting set of nested, whole-crustal detachment-like structures in the transition zone soling into the lower crustal conductor, although displacement is indeterminate. Colorado Plateau interior has only a slight, Moho-level conductor in keeping with its nearly stable state. From a 600 km transect across the Southern Appalachians (Figure 1b), essentially no low-grade sedimentary rocks are evident below the frontal Alleghanian thrusts toward the northwest. High conductivity zones in the lower crust below the Charlotte Terrane and New York Alabama Lineament probably are caused by underthrust graphitic metasediments in the fossil Taconic and Grenville sutures, largely hidden from the surface. The uppermost mantle of the Paleozoic oceanic terranes on land to the southeast is much more resistive than corresponding Laurentian upper mantle to the northwest, and is interpreted to reflect a Late Alleghanian delamination event with purging of volatile components. Below ~250 km depth, the resolved conductivity is approximately 1-D and compatible with dry peridotite and a geotherm near the average current mantle adiabat.

In the context of EarthScope, issues in active tectonism revealed well by electrical conductivity structure include: upper mantle melting, hydration state and rheology; crustal melt underplating and fluid exsolution; and lithospheric scale pathways linking deep fluids to the upper crust and potential ore deposits, and strongly affecting brittle regime strength. In fossil terranes, mapping of cryptic suture zones using MT via their entrainment of graphitized metasediments may shed light upon the controls by pre-existing structures on later deformation. Establishing a consistent difference between the lithospheres of Precambrian versus Phanerozoic terranes may imply a fundamental contrast in their petrological makeup, while otherwise would imply definition by specific tectonic events. In both active and fossil regimes, conductivity structure constrained by temperatures (e.g., from seismology) can provide degree of hydration in the upper mantle especially with anisotropy. A challenge to be addressed in formal joint seismic/MT inversion is the defining of constitutive relationships between velocity and conductivity.

Figure on Page 261 >

Philip Wannamaker
University of Utah

Stephen Park
University of California
Riverside

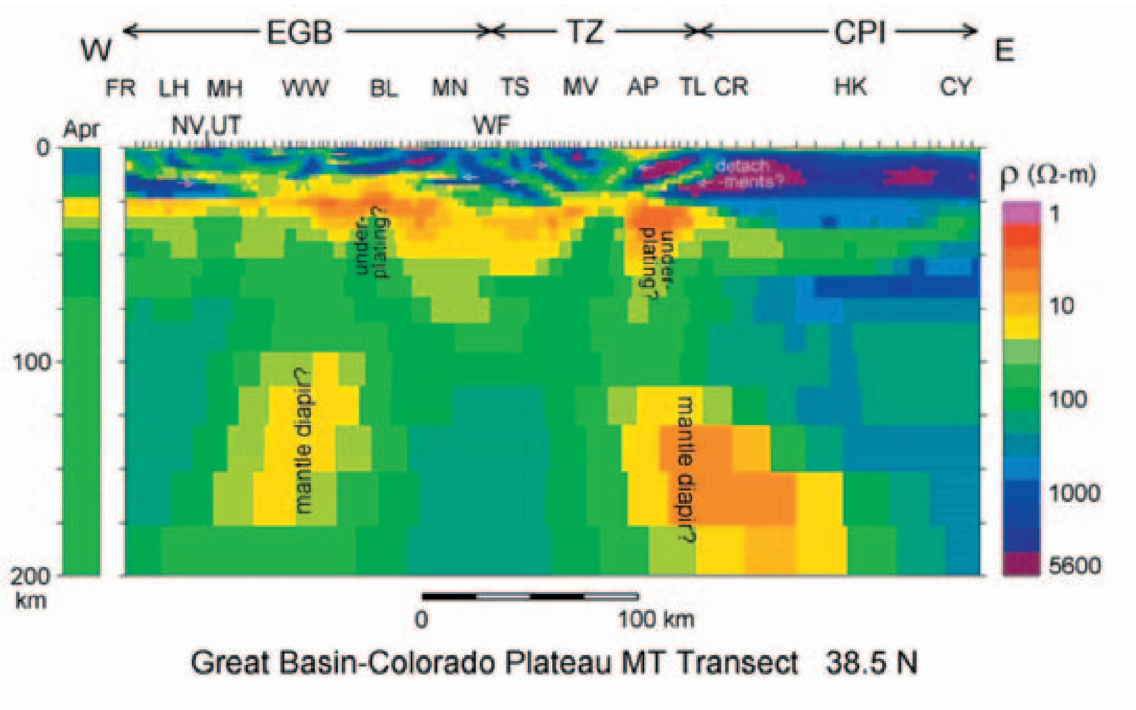
John Booker
University of Washington

Gary Egbert
Oregon State University

George Jiracek
San Diego
State University

Alan Chave
Woods Hole
Oceanographic Institute

Martyn Unsworth
University of Alberta



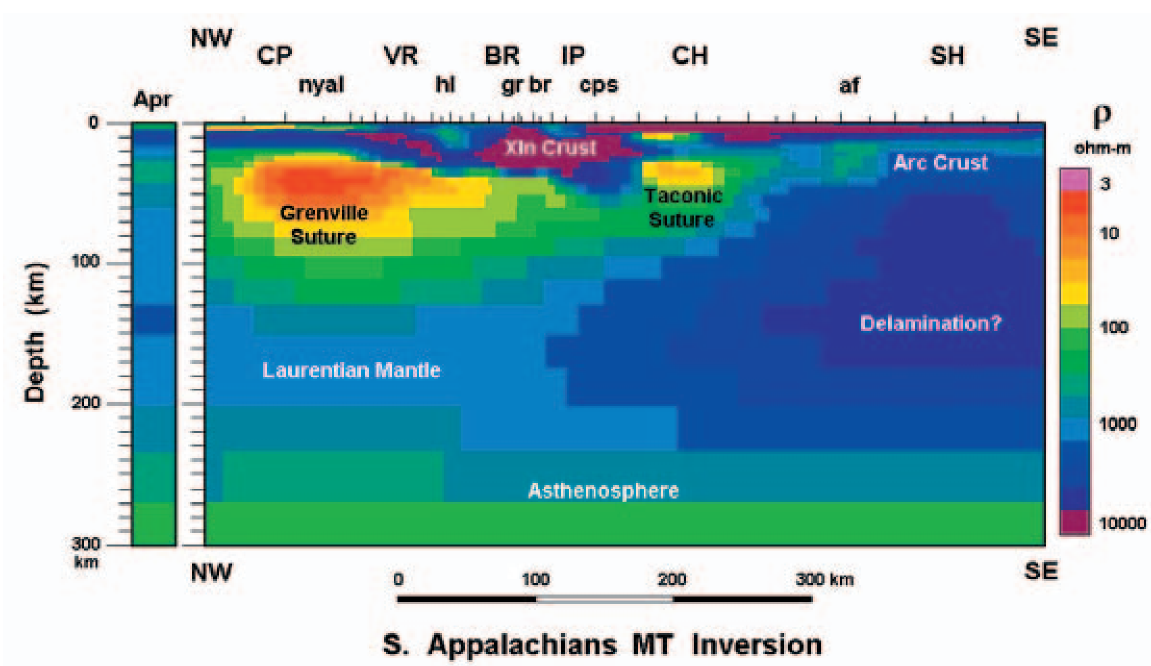


Figure 1. Left (a); Resistivity inversion of new MT profiling by Wannamaker mainly in S Utah at latitude 38.5N of 108 MT sites over period range 0.01 – 13000 s. Main physiographic features include Wah Wah Mtns (WW), Tushar Mtns (TS), Thousand Lake Mtn (TL) and Hanksville (HK). Provincial divisions are eastern Great Basin (EGB), Transition Zone (TZ), and Colorado Plateau Interior (CPI). White arrows in upper crust point to possible low-angle normal detachments. Right (b); Resistivity inversion of MT data in Wannamaker et al. (1996, EOS) across the S Appalachians in a NW-SE profile over similar period range. Main physiographic features include Cumberland Plateau (CP), Blue Ridge (BR), and Spring Hope terrane (SH). Graphitic mechanisms probably dominate Moho level conductivity, while hydration and low melting components affect the lower lithosphere properties.

Increasing Satellite Monitoring of Volcanic Activity by Achieving SO_2 Flux Measurements from Small Low-altitude Volcanic Gas Plumes: Ambrym Volcano, Vanuatu as an Initial Case Study

Lois Wardell
McGill University

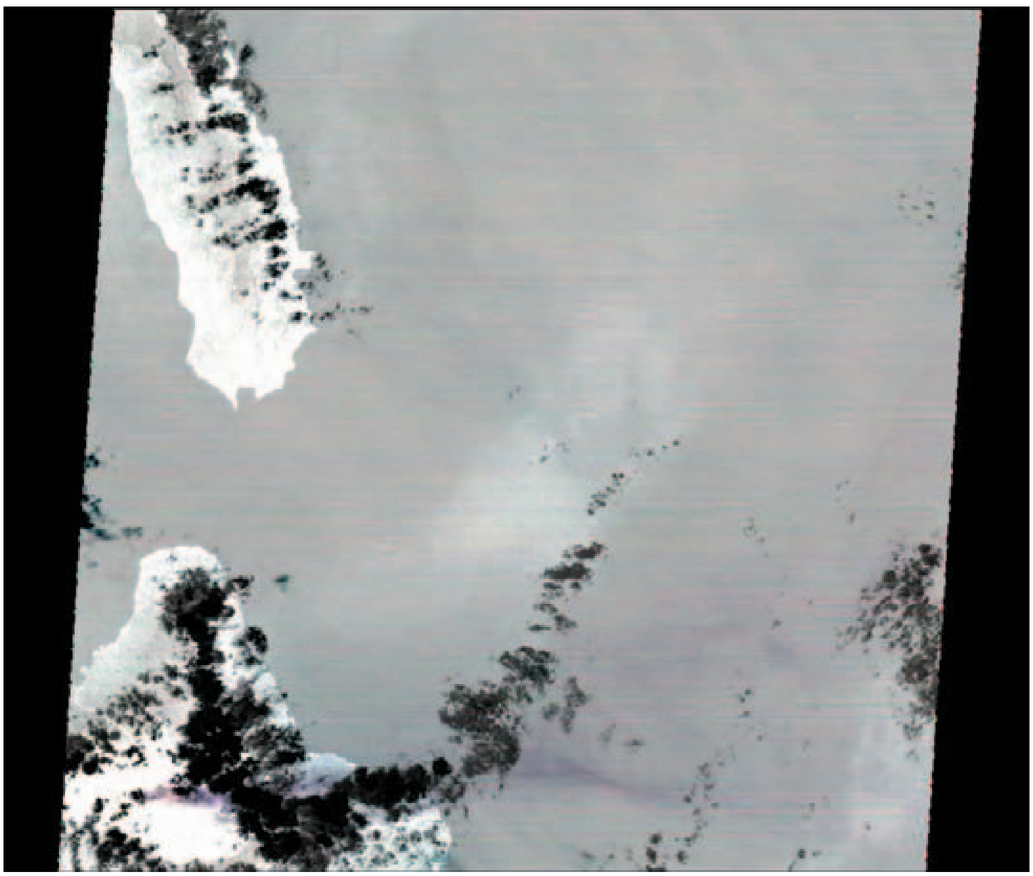
Matt Watson
Michigan Tech

Vince Realmuto
NASA

John Stix
McGill University

The value satellite remote sensing of volcanic SO_2 emissions is well documented and has been achieved by a number of satellites and techniques (e.g. TOMS and OMI). However, mainly due to the resolution, the remote sensing of SO_2 from volcanic activity has been limited to large eruption plumes or high-altitude volcanoes with significantly large emission rates. Retrieving the high resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data, on the Terra EOS satellite, manipulation of the thermal bands may allow quantification of volcanic gas plumes that are small (<1000 tonnes per day) and at low altitude. This tool could allow remote gas monitoring of changes that may be occurring in active volcanoes prior to eruption.

Ambrym volcano, Vanuatu was used as an initial case study. The 1334 meter-tall island volcano in the New Hebrides Island Arc is known for having a persistent gas plume although little work on volcanic gas emissions has been conducted at this volcano. Calculations using an algorithm on images taken from ASTER of the gas plume on 01 November 2000 resulted in a SO_2 flux value of 6 to 15 kg/s (500 to 1300 Mg/d), (based on estimated wind speeds of 2 to 5 m/s), supporting the important potential for the ability to use ASTER data in monitoring degassing volcanoes. By quantifying SO_2 in downwind plume transects, agreement could be achieved for total SO_2 in each transect, showing the rate of dispersal of SO_2 for these cross-sections at several distal locations.



This is an ASTER image of Ambrym volcano (lower left) with the SO_2 gas plume seen in purple.

Geodetic Determination of the Eastern Terminus of the Pacific-North America Plate Boundary Zone

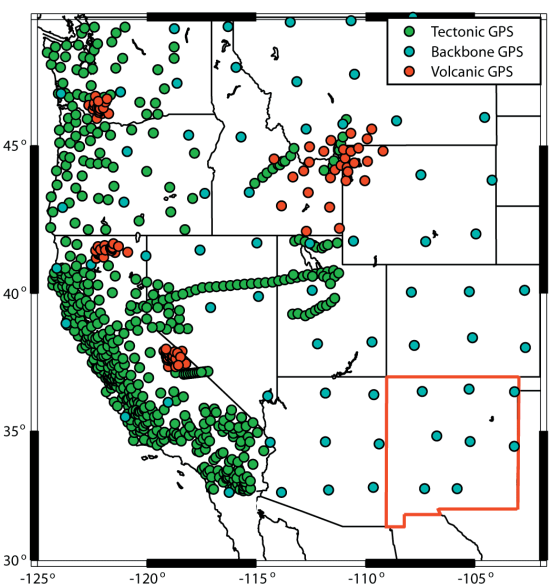
Shimon Wdowinski
University of Miami

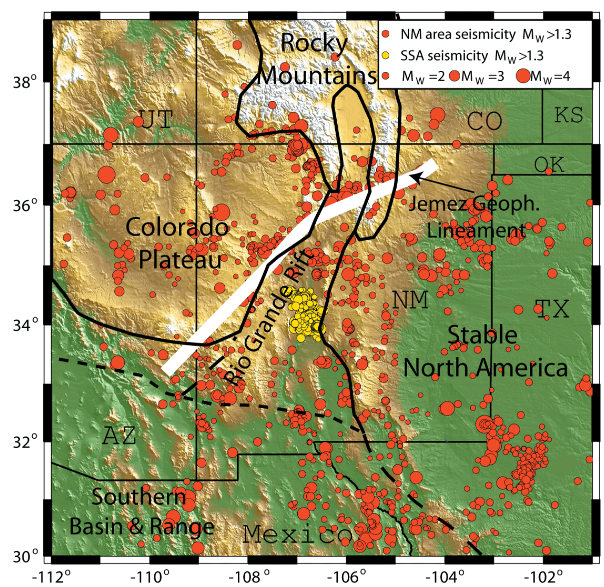
Andrew Newman
Los Alamos National Laboratory

The Pacific-North America diffuse plate boundary extends over a1000 km wide region, from near the Pacific coast in the west to beyond the Basin and Range Province (SBR), Colorado Plateau (CP) and the Rio Grande Rift (RGR) in the east. Though much work has been done in the west, where high strain rates cause frequent earthquakes, little is known about the eastern portion of the deforming plate boundary. We suggest that it is necessary to soon begin an expansive geodetic study of the eastern terminus of the Pacific-North America diffuse plate boundary, in order to constrain the slow deformation (likely < 3mm/yr) in the life-cycle of the EarthScope Program. A proposed study should incorporate data from the PB-backbone, already existing continuous GPS and establish and occupy a network of campaign GPS benchmarks that transect the RGR, SBR, CP and select regional volcanic bodies. It is essential to begin the campaign portion of this sort of study to begin the temporal baselines necessary to answer key questions about this boundary.

The overall scientific goals would be:

1. Determine the eastern terminus of the Pacific-North America diffuse plate boundary zone.
2. Measure extension and uplift rates across the Rio Grande Rift and Southern Basin and Range and determine how strain is partitioned between them.
3. Measure and model volcanic/magmatic induced deformation likely associated with the RGR over the Socorro Magma Body and the Valles Caldera.
4. Measure uplift and rotation of the eastern Colorado Plateau and determine its role in concentrating strain on the Rio Grande Rift and the Basin and Range.





[Left] Proposed PBO continuous GPS stations across the western United States. New Mexico is highlighted in red to identify geopolitically, our region of interest. [Right] Tectonic framework of the Eastern Terminus of the Western North America Diffuse plate boundary zone. Shown here are recorded regional (Red) and volcanic earthquakes (yellow; over the Socorro Magma Body) greater than Mw 1.3 between 1962 and 1998 [Sanford et al., 2002].

SAFOD Products:
Monitoring Data, Downhole Measurements, and Physical Samples

Charles Weiland
Stanford University

Stephen Hickman
U.S. Geological Survey

William Ellsworth
U.S. Geological Survey

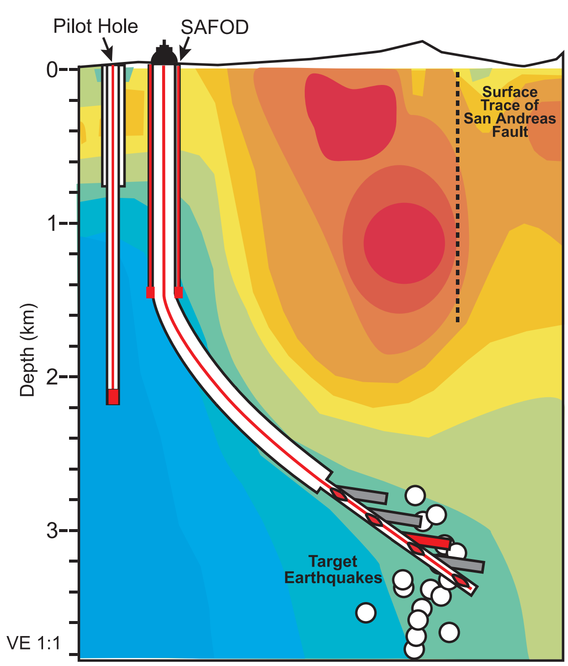
Mark Zoback
Stanford University

The major data products from the San Andreas Fault Observatory at Depth (SAFOD) are physical samples (core, cuttings and fluids) exhumed from the fault zone and surrounding crust, geophysical measurements within the borehole, and monitoring data collected from the multi-stage observatory being constructed within and adjacent to the active fault zone. This paper presents the acquisition, storage and distribution plan for SAFOD data products.

Monitoring data streams will include seismic velocity and acceleration, fluid pressure, temperature, strain and tilt. With an anticipated 100 channels at up to 4000 samples per second, data management becomes a significant challenge. Our intention is to manage the data in ways that minimize storage costs and promote easy data access while maximizing the scientific return from these data. Consequently, there are 3 main streams of seismic monitoring data that will flow from the SAFOD site into the EarthScope Integrated Data Access System: real time, event trigger, and complete continuous.

The real time data will include 6-10 channels decimated to 200 - 500 samples per second, sufficient for monitoring and easy to transmit with an expected latency of less than 1 minute. For the event trigger data, we anticipate approximately 10,000 triggers per year with full recording on all channels. Automatic processing will yield preliminary hypocenters and magnitudes. These events will be transported via the Internet as bandwidth permits, with an expected latency of less than 24 hours.

Continuous transmission of all SAFOD data channels would be prohibitively expensive. Instead, complete continuous data will be written to tape at the SAFOD site. The tapes will be shipped to the Northern California Earthquake Data Center once a month, where they will enter an online buffer with the capacity for 90 days (6 TB) of data. Researchers will be able to access the online buffer using standard EarthScope seismic request tools. After 90 days (+1 month), data can be restored to disk on an as-requested basis.



In addition to data anticipated from SAFOD, seismic data from ~5600 events already recorded with the Pilot Hole array from Sept 2002 to May 2004 are now available at http://quake.geo.berkeley.edu/safod/.

Some of the most important products coming from SAFOD will be the core, cuttings and fluid samples exhumed from the San Andreas Fault Zone and country rock. These samples will be stored at the Gulf Coast Repository (GCR) of the International Ocean Drilling Program at Texas A&M University. Use of SAFOD core, cuttings and fluid samples will be governed by NSF and EarthScope policies for physical samples. Cutting samples are plentiful: small samples are collected at 3m intervals, with larger volumes collected every 30m, and still larger volumes every 100m. During Phase 1 (2004) drilling we collected 20 m of core at measured depths of 1.5 and 3.1 km. Photos of the core and cuttings are available on the web at http://www.icdp-online.de/sites/sanandreas/public/public.html. During Phase 2 (2005) drilling we will collect four, 10m spot cores. Our primary coring effort will occur during Phase 3 (2007), when we will continuously core four, 250-m-long multilaterals directly within and adjacent to the San Andreas Fault Zone.

In addition to the monitoring and sampling programs, SAFOD also has an extensive program of borehole measurements to further address questions pertaining to the physical properties and chemical process controlling faulting. During Phase 1 we conducted an extensive suite of wireline geophysical logs, first in the vertical section of the hole (from 610m to 1445 m depth), and later in the deviated section (from 1360m to 3050m measured depth) After the logging results from Phase 1 are processed and quality controlled they will be distributed via the web at http://www.icdp-online.de/sites/sanandreas/public/public.html The Pilot Hole logging data are now available at the same URL.

The figure summarizes the drilling and monitoring plan for SAFOD. Drilling (white) through the fault zone will be complete in 2005. The pilot hole was completed in 2002. Multilateral cores (gray) in the fault zone will be taken in 2007. The three monitoring systems (red) include: 1) seismic and deformation in the Pilot Hole, 2) behind casing optic fiber interferometric strainmeter, 3) multi-level monitoring array inside casing including, seismic, pore pressure, deformation and temperature sensors.

Seismic Wave-equation Migration Methods and EarthScope

Lianxing Wen
State University of New York at Stony Brook

Ling Chen
Chinese Academy of Sciences

Tianyu Zheng
Chinese Academy of Sciences

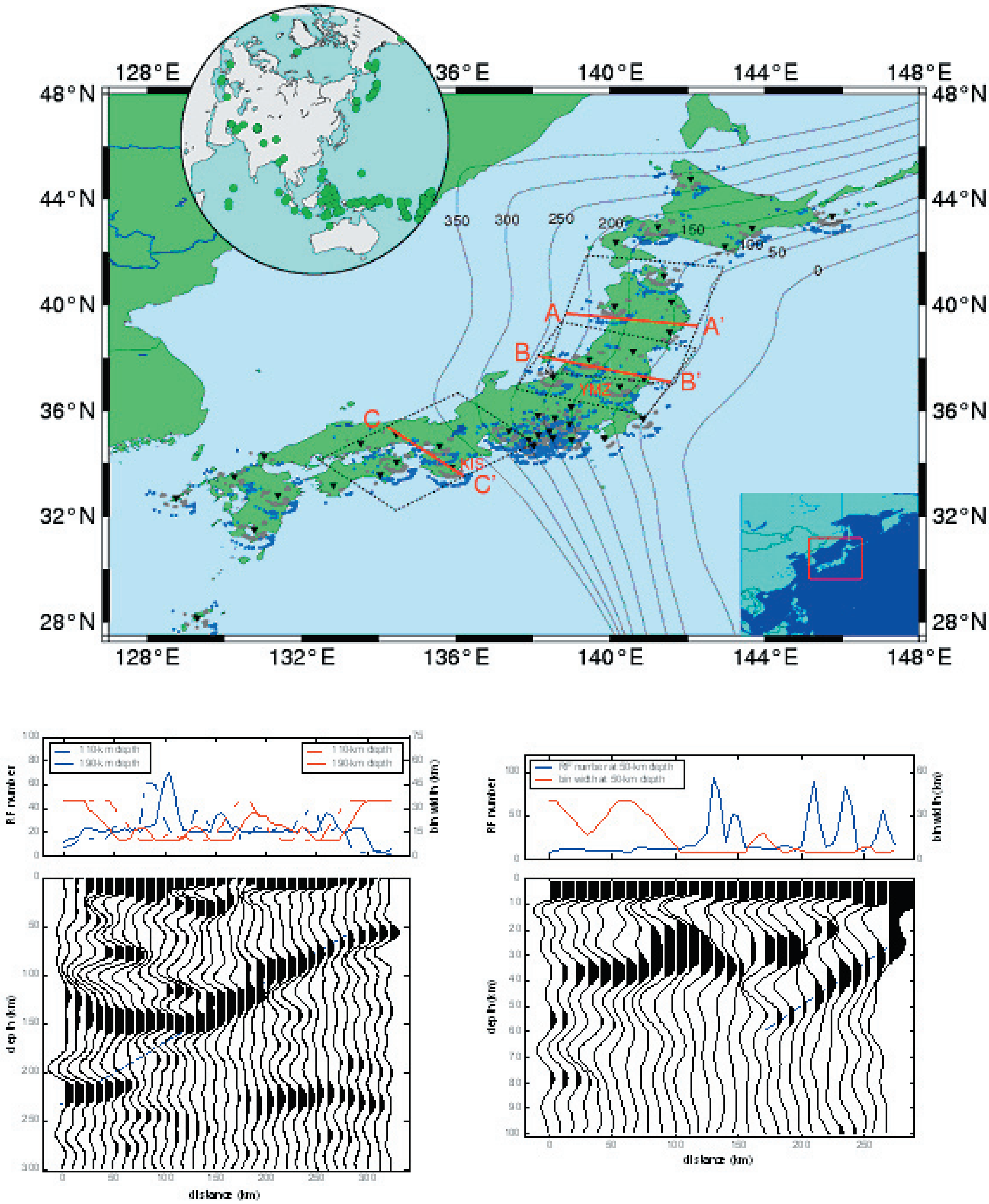
Dense seismic data will soon be available from the EarthScope. Such dense observations provide an opportunity to employ methods in exploration seismology to image seismic structure in high resolution. We develop a wave equation based poststack depth migration method to image the Earth's internal structure using teleseismic receiver functions. By utilizing a frequency-wavenumber domain one-way phase-screen propagator for wavefield extrapolation in the migration scheme, the common conversion point (CCP) stacked receiver functions are backward propagated to construct the subsurface structural images. The phase-screen propagator migration method takes into account the effects of diffraction, scattering, and travel time alternation caused by lateral heterogeneities, and therefore, is particularly useful for imaging complex structures and deep discontinuities overlain by strong shallow anomalies. Synthetic experiments demonstrate the validity of the migration method for a variety of laterally heterogeneous models and show considerable improvement of the migration method over the CCP methods in recovering model features. We discuss one application of our migration method to the studying of the subsurface structures of the Japan subduction zone using the FREESIA broadband data and possible applications using the EarthScope data. We choose three profiles in the subsurface imaging of the seismic structures beneath the Japan subduction zone, two in northeast (NE) Japan to study the subducting Pacific plate and one in southwest (SW) Japan to study the Philippine Sea plate. The descending Pacific plate in NE Japan is well imaged within a depth range of 50 – 150 km. The slab image exhibits a little more steeply dipping angle (~32°) in the south than in the north (~27°), although the general characteristics between the two profiles in NE Japan are similar. The imaged Philippine Sea plate in eastern SW Japan, in contrast, exhibits a much shallower subduction (~19°) and is only identifiable at the uppermost depths of no more than 60 km. Synthetic tests indicate that the top 150 km of the migrated images of the Pacific plate is well resolved by our seismic data, but the resolution of deep part of the slab images becomes poor due to the limited data coverage. Synthetic tests also suggest that the breakdown of the Philippine Sea plate at shallow depths reflects the real structural features of the subduction zone, rather than caused by insufficient coverage of data. The observed seismicity in the region confirms the geometries inferred from the migrated images for both subducting plates. Moreover, the deep extent of the Pacific plate image and the shallow breakdown of the Philippine Sea plate image are observed to correlate well with the depth extent of the seismicity beneath NE and SW Japan. Such a correlation supports the inference that the specific appearance of slabs and intermediate-depth earthquakes are a consequence of temperature-dependent dehydration induced metamorphism occurring in the hydrated descending oceanic crust. We will also discussed possible scientific targets and influences of several factors on the image quality of the poststack migration, including inter-station spacing, noise level of the data, velocity model used in migration and earthquake distribution, in the context of the EarthScope data.

Figure on Page 266 >

Lianxing Wen
State University of New York at Stony Brook

Ling Chen
Chinese Academy of Sciences

Tianyu Zheng
Chinese Academy of Sciences



Top: the Japan subduction zone, seismic sampling and three cross-sectional profiles (red lines A-A', B-B' and C-C'). Migrated images of two profiles (B-B' and C-C') are presented below. Receiver functions are obtained from the seismic data recorded at the 44 FREESIA broadband stations in Japan (triangles) for 185 teleseismic events (green circles). Piercing points at 110- and 210-km depths for P-to-S converted phases are shown as gray and blue dots, respectively. Depth contour lines mark the depths of the subducting Pacific plate. The block rectangles mark the areas where the receiver functions are stacked for the three profiles. Map inset in lower right shows the location of the study area in the northwest Pacific region. Bottom: receiver function migration images of the subducting Pacific plate for profile B-B' (left) and of the Philippine plate for profile C-C' (right), along with the numbers of receiver function in the bins (blue traces) and bin widths (red traces) used in the CCP stacking.

Proterozoic Growth and Stabilization of Continental Lithosphere: Southern Laurentia as a Key Type Section

Steven Whitmeyer
University of Tennessee

Karl Karlstrom
University of New Mexico

The continental lithosphere of the U.S. was assembled and repeatedly modified during the Proterozoic, so EarthScope's goal of understanding the evolution of continental lithosphere will require an integration of geologic, geochronologic, and geophysical studies of the Proterozoic basement. From ~1.9 to 1.0 Ga, Laurentia grew by the successive addition of oceanic terranes and magmatic arcs to a long-lived "southern" compressive/transpressive plate margin. Understanding the growth of the southern Laurentian portion of Rodinia during the Paleoproterozoic requires an understanding of the geometry and history of accretion of juvenile terranes during several key time slices. This sequential look at the growth of Laurentia allows us to examine the processes that transform initially thin crust and lithospheric mantle of juvenile arcs into stable continental lithosphere.

The Archean cratons of Canada and the northwestern U.S. had stabilized as continental lithosphere prior to 2.5 Ga, were rifted about 2.1 Ga, then assembled into a large continental mass during 2.0-1.8 Ga Trans-Hudson orogenesis. Juvenile terrane accretion to southern Laurentia initiated with the Penokean orogeny at ~1.88-1.83 Ga, in which Archean basement and Paleoproterozoic supracrustal rocks were deformed and metamorphosed during collisions with oceanic arc terranes. This was followed by the successive accretion of NE-trending juvenile terranes, including the 1.78-1.68 Ga Mojave province (which incorporates reworked Archean and Paleoproterozoic basement), the 1.8-1.7 Ga Yavapai province and the 1.67-1.65 Mazatzal province. These provinces likely were comprised of a complex series of juvenile arc terranes (similar to the present-day Banda Sea region) that accreted to the southern and eastern margins of Laurentia during extended orogenic cycles.

An important and still enigmatic tectonic event was the addition of 1.5-1.3 Ga juvenile crust that now underlies much of the mid-continental U.S. from Texas through eastern Canada. This was likely a complex magmatic arc system linked to voluminous ~1.45-1.35 Ga A-type magmatism that intruded and helped stabilize the older Proterozoic provinces. Accretion of juvenile crust to southern Laurentia culminated with the 1.3-1.0 Ga Grenville orogeny, which extends from Maritime Canada to western Mexico. This collisional event represents the final stage in the growth of southern Laurentia and facilitated the assembly of most significant continental landmasses into the supercontinent of Rodinia. Collapse and breakup of Rodinia was a multi-stage process that initiated along the western margin of Laurentia at ~0.8-0.7 Ga and was followed by rifting along the eastern margin of Laurentia at ~0.55 Ga.

A principal focus of the new sequence of southern Laurentia maps is the extent and ages of granitoid magmatism within the progressively assembled Proterozoic orogens. With each addition of juvenile crust, granitoid magmatism outlasted shortening deformation and invaded across province boundaries (defined by Nd data) to stitch young juvenile crust with older basement. This process is hypothesized to enhance cratonization through several mechanisms. These include 1) stabilization of lithospheric mantle via thickening and de-densification due to basalt extraction, 2) strengthening of the lower crust via differentiation and development of a mafic residue, and 3) mechanical strengthening of the middle crust via pluton emplacement and reduction of anisotropy.

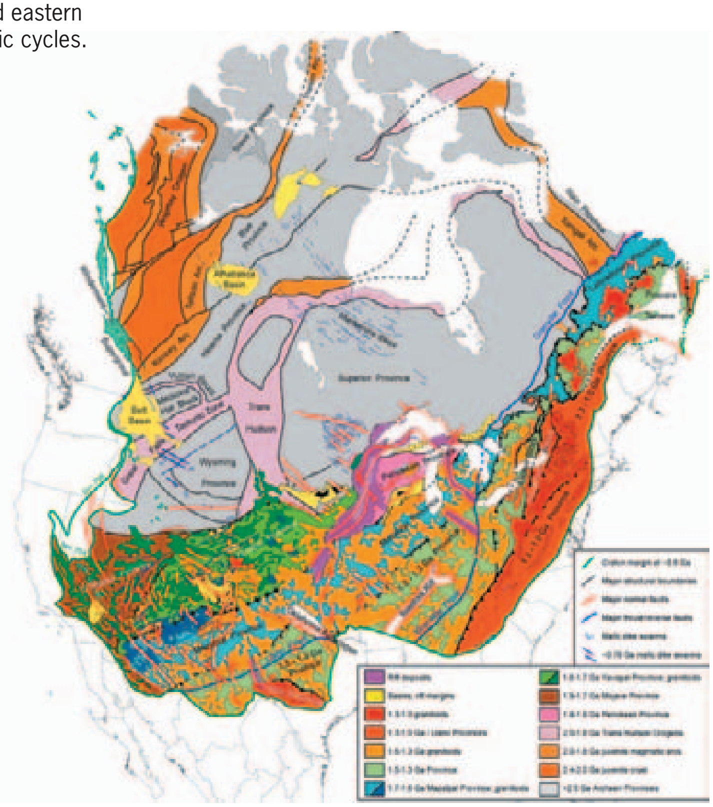


FIGURE 1. Simplified geologic map of Laurentia at the time of Rodinia breakup (about 0.55 Ga). The Archean cratonic core (gray) comprises most of present-day Canada and the northwestern U.S. Proterozoic juvenile terranes (brighter colors) were accreted to the southeastern margin of the expanding Laurentia continent, beginning with the Penokean province at ~1.9 Ga and followed sequentially by the Mojave, Yavapai, Mazatzal, 1.5-1.3, and the 1.3-1.0 (Grenville) and Llano provinces. Several episodes of voluminous granitoid plutonism that stitch province boundaries are also apparent.

Enhancing the EarthScope Image: A View of Deep and Middle Crustal Processes in Isobarically Cooled Terranes

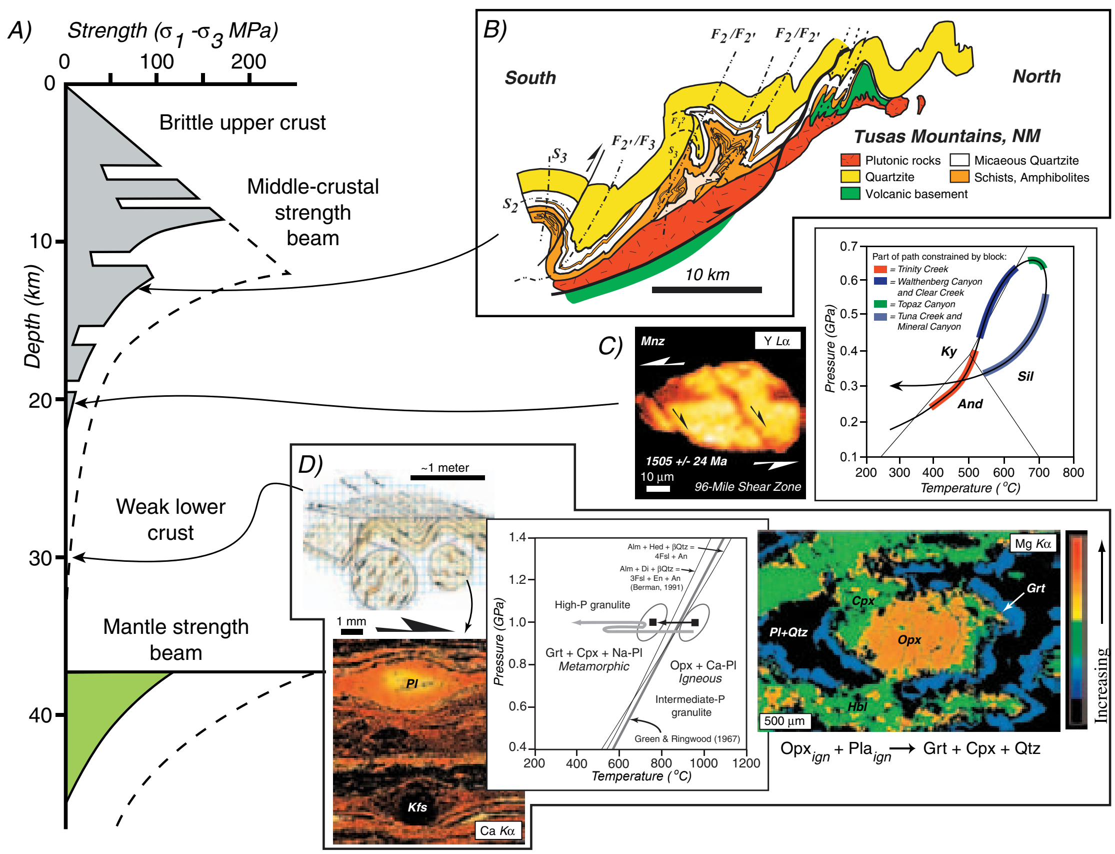
Michael Williams
University of Massachusetts

Kevin Mahan
University of Massachusetts

Michael Jercinovic
University of Massachusetts

Karl Karlstrom
University of New Mexico

Isobarically cooled (IBC) terranes provide information that is difficult to glean from remote data sources about compositional relationships and structural and metamorphic processes in the mid and deep crust. These terranes allow lateral relationships and scales of heterogeneity to be evaluated for specific crustal levels. The granulite facies East Athabasca area, Saskatchewan, is an example of an isobarically cooled terrane that resided in the deep crust (1.0-1.2 GPa) from ~2.5 Ga to at least 1.9 Ga. Proterozoic rocks in the southwestern USA may have been in the middle crust (0.4-0.6 GPa) from at least 1.65 Ga to 1.4 Ga. The single overwhelming characteristic of both regions is the extreme heterogeneity, at all scales, in lithology, structure, and tectonic history. At the largest scale, both regions have a block architecture with lithologically and structurally distinct blocks or domains. Domains in the granulite facies, East Athabasca area are dominated by tonalite, charnockite/granite, felsic gneiss, or deformed migmatite. Locally abundant swarms of mafic dikes document heat and mess transfer from mantle to crust. Most rocks are restitic to some degree, showing evidence of melt loss to higher levels of the crust. Mid-crustal rocks in the SW-USA are dominated by amphibolite facies metasediments and granitoids. Mafic dikes are much less common, as are migmatites. Instead, most regions record the emplacement of large volumes of felsic magma (plutons, dikes, pegmatites). Both terranes, deep crustal and mid-crustal, have a similar structural signature with early, shallowly dipping fabrics overprinted by domains of intense upright fabric. The shallow fabric may reflect early collisional processes or alternatively, it could reflect crustal flow events that postdate continental assembly. Understanding the two fabrics, at the two crustal levels, has great implications for a range of crustal process and characteristics, particularly rheology through time, that are also key to interpreting EarthScope images. In-situ monazite geochronology, combined with detailed petrologic and structural analysis is proving to be a powerful tool for deconvoluting the multi-phase P-T paths in the IBC terranes. Once distinguished, each part of the history can provide significant insight into the nature of modern continental crust and modern crustal processes.



Crustal processes from isobarically cooled (IBC) terranes. A) schematic strength profile, modified from Karlstrom and Williams (1996). B) cross-section of the mid-crustal Tusas Mountains (ca. 0.4 GPa) showing early shallow fabric overprinted by upright fabric. C) Monazite crystal and P-T path from the Upper Gorge of Grand Canyon (0.6 GPa). D) Relationships from the East Athabasca area, Saskatchewan (1.0-1.2 GPa). Early shallow fabric overprinted by steep fabric. Many regions show progressive growth of garnet and clinopyroxene (densification) during deep crustal cooling. Together these IBC terranes provide a model for the middle and deep crust during and after orogenesis.

Results from the LA RISTRA Seismic Array: Implications for the EarthScope Flexible Seismometer Array

David Wilson
University of Texas Austin

Rick Aster
New Mexico Institute of Mining and Technology

Steve Grand
University of Texas Austin

James Ni
New Mexico State

We present results from the Colorado Plateau/Rio Grande Rift/Great Plains seismic transect (LA RISTRA) experiment, a 950 km-long PASSCAL broadband seismic line with approximately 18 km station spacing deployed during 1999-2001 from Lake Powell, UT to Pecos, TX. LA RISTRA was designed to combine geophysical techniques with geological and geochemical information in order to investigate fundamental relationships between regional tectonic provinces and crust and upper mantle structure, and is a representative experiment addressing scientific issues appropriate for the Flexible Array component of USArray (LA RISTRA had 1/4 the number of broadband seismometers that will be available with the Flexible Array). Receiver function results show crustal thickness ranging from 45 to 50 km beneath both the Colorado Plateau and the Great Plains, thinning to a minimum of 35 km centered beneath the Rio Grande rift (RGR) axis. Inversion of surface wave data and tomographic inversion of teleseismic body-wave delay times show a broad low velocity region, also centered beneath the rift axis. These observations suggest that the lower crust and mantle lithosphere of the RGR have deformed symmetrically about the rift axis, indicating an essentially pure shear mode of lithospheric deformation. Upper mantle receiver function images show relatively flat discontinuities at 410 km and 670 km, indicating there is not a large-scale, deep-seated thermal anomaly beneath the rift. However, small-scale variations in upper mantle velocity, seen both in body wave tomography and surface wave analysis, indicate unexpected localized thermal or compositional variations that may influence small-scale convection and may be common in western U.S. upper mantle.

Crustal-scale Tectonic Wedging in Eastern New England: Target for the Flexible Array

Robert Wintsch
Indiana University

John Aleinikoff
U.S. Geological Survey

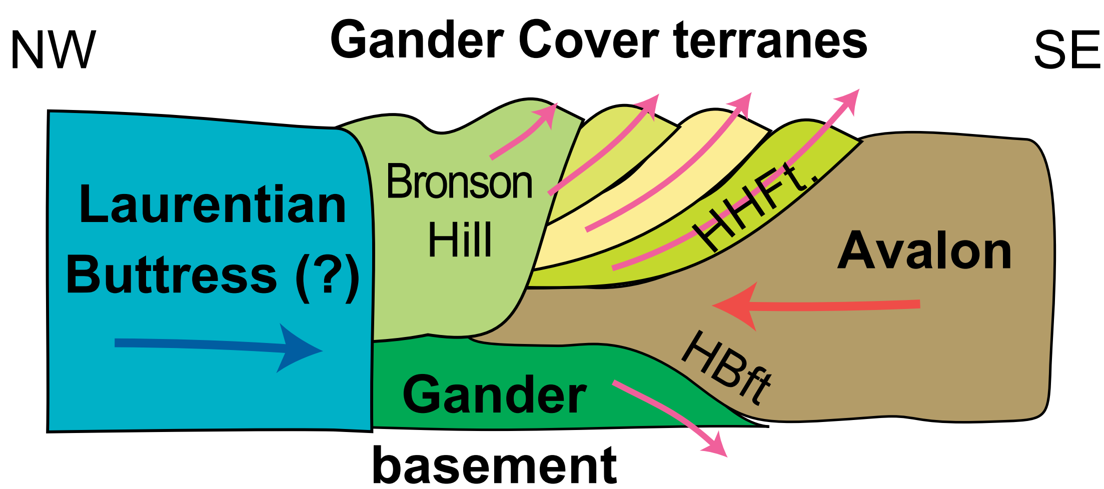
Daniel Unruh
U.S. Geological Survey

Greg Walsh
U.S. Geological Survey

While models of crustal delamination have received increasing support from the interpretations of geophysical data, delamination has rarely been observed and demonstrated in the field. The geology of eastern New England now provides an unprecedented opportunity to examine and test crustal-scale delamination by tectonic wedging. Here tectonic wedging of the Gander zone basement from its cover by Avalon zone rocks has recently been identified in surface exposures. These structures are exposed in a north-plunging structure within 20 km of the coast of Connecticut. The wedge plunges progressively deeper to the north where it is overlain by thickening slabs of Gander-zone cover terranes. A Flexible Array experiment could cross New England in E-W traverses testing for increasingly deep reflections to the north from the upper and lower mylonitic surfaces of the tectonic wedge.

Surface exposures in coastal Connecticut involve rocks formerly mapped as fold nappes in the Avalon terrane. In addition to Avalonian rocks derived from juvenile sources, our pilot study of Nd and Pb isotopes in these Late Proterozoic plutonic rocks has identified the structurally lowest of them to be derived from ancient crustal rocks that correlate with the Gander terrane in Maritime Canada. Regional map patterns can now be interpreted to show that rocks of the Avalon terrane are sandwiched between basement and cover rocks of the Gander terrane. Thus this map plan defines the geometry of a north-plunging tectonic wedge. This interpretation has precedence in the subsurface of eastern Newfoundland, where single and even double delamination between the Gander and Avalon zones has been interpreted from seismic reflection data

A Flexible Array experiment in eastern New England would be unparalleled in the study of active mountain belts, because regional Mesozoic tilting to the north and subsequent exhumation has exposed a 30 km deep indenter that is completely inaccessible in active mountain belts. An experiment could be designed to identify major reflections where geological ties to surface exposures could lead to confident geological interpretations. Interpretations of progressively northern seismic profiles could build on those well constrained by surface exposures in the south. The results of the experiment would thus be two fold. First, and most immediately, it provides a test of the use of surface exposures to refine interpretations of shallow- to moderate-depth seismic imaging. More significantly, however, it tests whether crustal thickening during continental convergence could be caused by tectonic wedging and crustal delamination at the scale of ~1500 km along this belt of rocks from southern New England to Newfoundland.



Crustal-scale delamination and stacking of Gander cover terranes (yellow-green including the Bronson Hill terrane) from Gander Basement (dark green) by tectonic wedging of Avalon terrane rocks (brown) along the Honey Hill and Hunts Brook faults against a buttress of relatively strong Laurentian crust (blue).

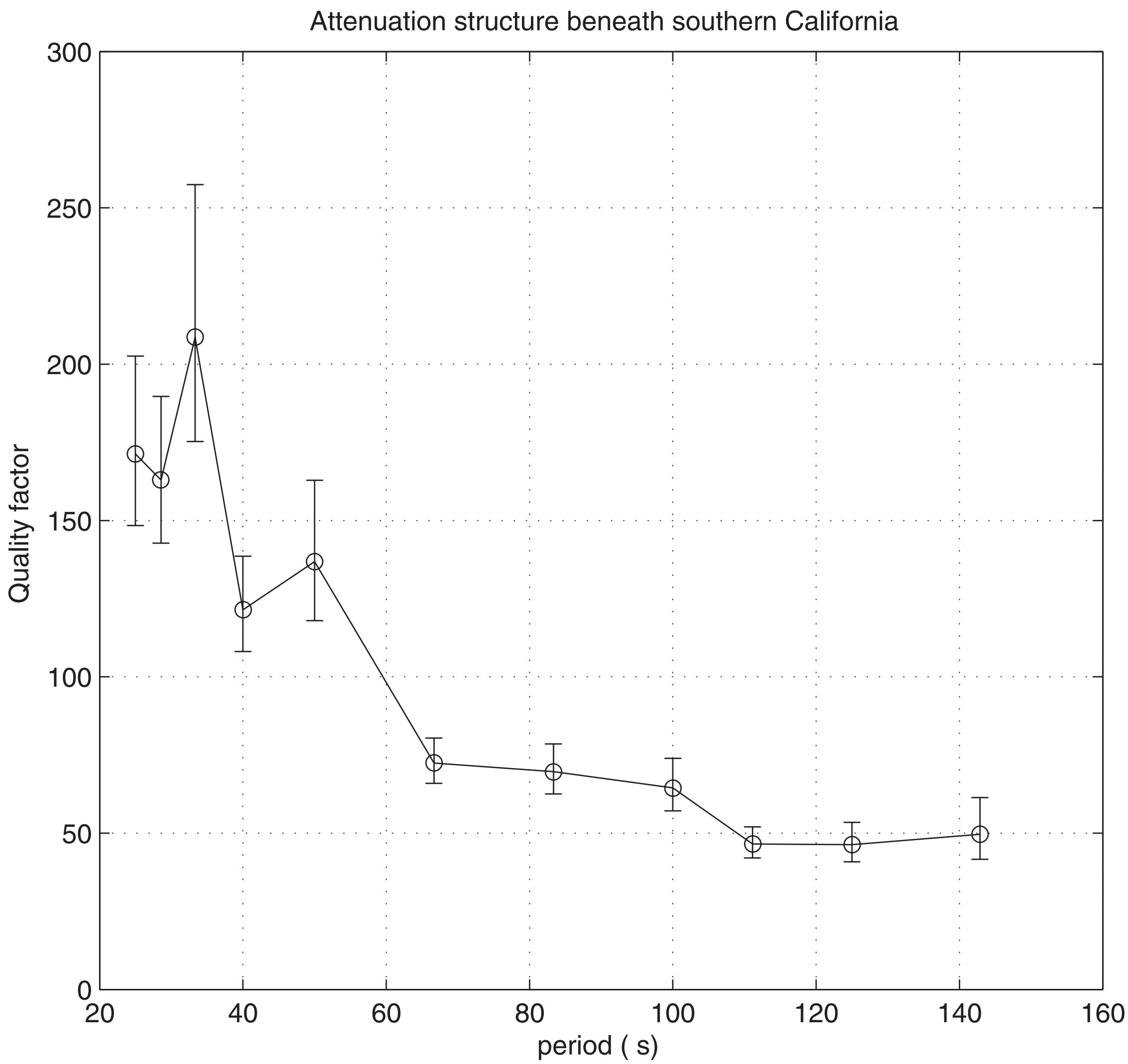
Regional Attenuation Structure from Surface Wave Tomography

Yingjie Yang
Brown University

Donald Forsyth
Brown University

Seismic attenuation has been long neglected in traditional seismic tomography since attenuation effects on amplitude are hard to be separated from other effects such as focusing, defocusing and scattering. However, attenuation is an important property of Earth's materials and can provide us additional knowledge other than elastic velocity about temperature, fluid content, phase changes, and density of solid-state defects in the crust and mantle.

Fundamental mode surface wave studies at different periods allow us to constrain regional and vertical variation of the quality factor Q. We use 2-D sensitivity kernels for surface waves based on single-scattering (Born) approximation to account for the effects of elastic structure on amplitude in regional surface wave studies. The kernels can accurately predict the variation of amplitude caused by the heterogeneous structure. We invert phase and amplitude data of fundamental mode Rayleigh waves for phase velocity and attenuation structure simultaneously in couple different tectonic regions. Inverted attenuation variation at different periods in each region is presented.



Q value in southern California for Rayleigh waves at a number of periods. One standard error bars are shown.

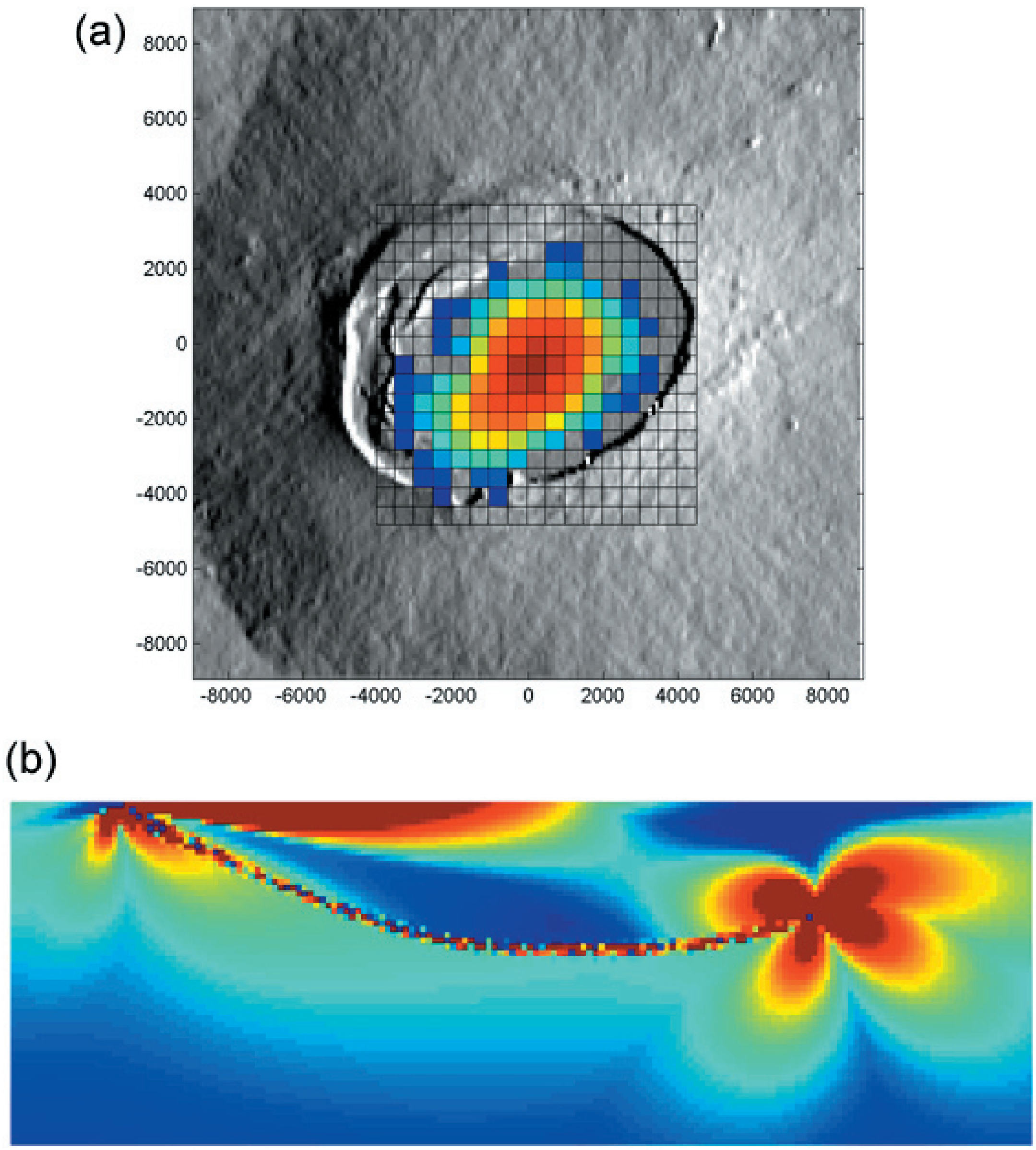
Mechanical Modeling of Sierra Negra Volcano, Galapagos Islands, Based on InSAR Observations

Sang-Ho Yun
Stanford University

Howard Zebker
Stanford University

Paul Segall
Stanford University

In the last 10 years, Sierra Negra volcano, on the island of Isabella in the Galapagos, has experienced rapid uplift, trapdoor faulting (Amelung and Jonsson et al., Nature 2000), renewed inflation, and subsidence (Geist et al., JVGR in press). Inversion with boundary element calculations based on InSAR observations constrains the magma chamber geometry and excess magma pressure at Sierra Negra (Yun et al., JVGR in press). It is possible to use the stress state from the inversion results as an initial stress condition for the following events. Using this approach we model the mechanical interaction between two events at Sierra Negra, which are flank eruption in 1979 and trapdoor faulting occurred sometime in 1997-1998. Each of the two events seems to encourage the other by perturbing the stress field so that it becomes conducive to the other event. Our results will have important implications for the stress state within the volcano, the mechanics of induced faulting and dike propagation, and may lead to better forecasts of future behavior.



(a) Deformation source from inversion and (b) Coulomb stress field from the simulation of flank eruption and trapdoor faulting.

Sierra Nevada EarthScope Project (SNEP): A Study of Active Foundering of Continental Lithosphere Beneath the Sierra Nevada, California

George Zandt
University of Arizona

Hersh Gilbert
University of Arizona

Thomas Owens
University of South Carolina

Craig Jones
University of Colorado

Foundering of ultramafic and mafic composition mantle lithosphere has been used to account for processes in both continental tectonics and the compositional evolution of continental crust. Despite widespread appeals to this idea, the scarcity of good resolution observations of ongoing removal has left a collection of untested hypotheses. Recent seismological and related geologic studies of the Sierra Nevada batholith in eastern California have revealed that eclogite and peridotitic mantle lithosphere under the range since the Mesozoic were removed by about 3.5 Ma and now sinks beneath the southern Great Valley and is viscously dragging a cone-shaped piece of crust into the mantle. Removal of the batholithic root may have led not only to the rise of the Sierran crest but also to subsidence of its western foothills, Quaternary volcanism and extension in Long Valley and along the eastern edge of the Sierra, and perturbations to the stress regime of the San Andreas-Eastern California Shear Zone plate boundary. Because of the young age of this event, we can pose a number of questions that bear on the general process of removal of lower continental lithosphere:

1. Does the eclogite root founder by a true delamination process or as a convective instability?
2. How does the remaining lithosphere “heal” from this removal process?
3. What are the tectonic and magmatic consequences of this process?
4. What conditions facilitate removal of lithosphere?

We will address these questions in part with new seismological data to be acquired by a recently funded Flex Array deployment of 40 broadband seismometers for 30-months in the central Sierra Nevada. The instruments will be deployed in two separate arrays occupying 80 sites, and the timing of these deployments takes advantage of the Transportable Array (Bigfoot) component of USArray. The first array covers an area extending north from the previous Sierran Paradox experiment to just south of Lake Tahoe. The concurrent deployment of our dense arrays with Bigfoot provides a common framework for all three deployments and decreases station spacing from the ~70 km Bigfoot spacing to ~25 km; this will improve our sampling in the depth ranges of interest and allow us to combine spatially and temporally distinct datasets. Next, the same 40 instruments will be redeployed in a dense (~5 km spacing) transect to study the critical crust/mantle zone with greater resolution.

This data will be processed to separate areas underlain by melt laden, low-velocity, seismically anisotropic asthenosphere from those retaining resistive, cold, high-speed, seismically isotropic eclogite. Our results will also constrain variations in Moho topography and finite strains affected by the flow of the drip as recorded by seismic anisotropy. Coordinated proposal(s) will complement the new seismological data with examination and analysis of volcanic rocks along the Sierra, the xenoliths that they carry, changes in post-Miocene sedimentation in the Central Valley of California, geomorphic expressions of recent changes in topography, seismotectonics above the drips, and numerical experimentation. These will constrain the lateral extent of lithospheric removal and the time-space-composition evolution of the upper mantle beneath the Sierra Nevada during the Late Cenozoic.

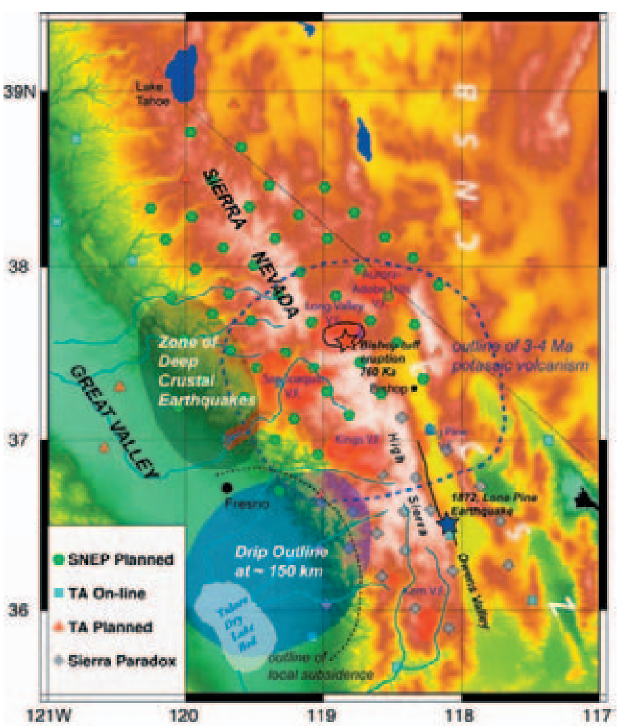


Figure 1. Map of planned 40+ station SNEP network (green hexagons), EarthScope Transportable Array (TA) stations (blue squares are operational, red triangles are planned), and 1997 Sierra Paradox sites (grey diamonds). Major geographic and tectonic features, Miocene-Recent volcanic areas (shaded orange), 1872 Lone Pine earthquale (blue star), and Bishop Tuff eruption (red star) shown on a shaded relief map of southern California and western Nevada. Drip at 150 km depth is shaded blue. ECSZ, Eastern California Shear Zone. CNSB, Central Nevada Seismic Belt.

Proterozoic Rhyolite-quartzite Syntectonic "Cover" Assemblages and Their Importance for Understanding Orogenic Assembly of SW Laurentia

Austin Zinsser
University of New Mexico

Amy Luther
University of New Mexico

Karl Karlstrom
University of New Mexico

Michael Williams
University of Massachusetts

The success of EarthScope hinges on multidisciplinary collaboration to integrate diverse datasets into a 4-dimensional view of the continental lithosphere. EarthScope will provide a snapshot of the final juxtaposition and geometry of orogenic provinces assembled during the Proterozoic. Understanding the time dimension of this picture requires the application of structural analysis and geochronology to key localities. The association between widespread deposition of quartz arenite successions and regional tectonism has emerged as one key focus for understanding the polyphase tectonic history and P-T-t-D evolution of continental lithosphere.

Proterozoic rocks of the Southwest contain a distinctive association of high silica, alkali rhyolite and ~ 1-km-thick quartz arenite. They overlie a volcanogenic basement that was previously deformed and metamorphosed. Pre-quartzite tectonism is documented in the Needle Mountains (high temperature deformational fabrics in the basement not present in the quartzite), Mazatzal Group (basal angular unconformity), Blue Ridge Quartzite (basal regolith on granite), and Gunnison areas (lower strain in quartzite than in basement). Quartzite successions fall into two age ranges: (1) 1.7-1.69 Ga (Hondo Group, NM, Mazatzal Group, AZ, Uncompahgre Group, Blue Ridge Quartzite, and Coal Creek Quartzite, CO) and (2) 1.66-1.65 Ga (Manzano Group, NM; White Ledges quartzite, AZ; Chino Valley quartzite, AZ). Dating efforts are underway to provide new timing constraints on the each of the two suites. This will allow us to test the idea of short-lived syntectonic basins and adjacent orogenic uplifts.

Rhyolite- quartzite successions are clearly syntectonic in a regional sense (both at 1.70-1.69 and 1.66-1.65 Ga) because volcanism and deposition were occurring at the same time as plutonism and deformation nearby. Thus, we do not interpret them to represent a shelf sequence or rifted margin, but rather as syntectonic basins, developed on stabilizing crust. They appear to mark unroofing of middle crustal rocks prior to and during their deposition. Basal angular unconformities are interpreted to record collisional exhumation of upthrust blocks and related deposition in small foreland basins. Their importance for understanding crustal evolution is underscored by their complex P-T-t-D paths, with multiple loops: 1) Volcanogenic basement was unroofed from middle crustal depths in the Yavapai orogeny. 2) Quartzites were deposited during continued thrust convergence in late stages of the Yavapai orogeny. 3) 1.70-1.69 Ga quartzites (and their basement) were buried (re-buried) to depths of 5-15 km via thrusting during the Mazatzal orogeny at 1.65 Ga and additionally shortened at 1.45-1.35 Ga. 4) similar rhyolite-quartzite successions were deposited syntectonically during the Mazatzal orogeny. 5) Both suites of rhyolite-quartzite assemblages were variably deformed and metamorphosed in the middle crust (5-15 km) at 1.45-1.35 Ga before being exhumed to the surface by ~ 1.25- 0.5 Ga.