

featured science:

Insights into Frictional Behavior of Materials in and near SAFOD

The San Andreas Fault Observatory at Depth (SAFOD) offers an opportunity to understand the state of stress in the lithosphere and the strength of major tectonic faults. Several lines of evidence imply that the San Andreas Fault (SAF) is weak, however, the issue remains controversial. Indeed, a primary justification for drilling into the fault was to obtain samples for detailed laboratory studies of fault zone physical properties. Although the core from Phase III drilling, which penetrated the active fault zone, has not yet been released for friction studies, we conducted experiments on samples collected at the surface that are representative of the rocks in and around the SAFOD borehole (Figure 1) including (a) material from SAFOD drilling; (b) outcrop samples of lithologic units surrounding the fault at depth, but not crossed by the borehole; and (c) synthetic fault gouges composed of **talc**, **serpentinite**, and quartz. Our results provide information about frictional strength of major wall rock units (from which fault gouge likely is derived), strength of fault material, and abundance of weak minerals (such as talc or serpentine) required to lower the **friction coefficient** (μ) sufficiently to satisfy weak fault models.

We performed laboratory shearing experiments to document frictional strength and constitutive behavior for rocks in and around SAFOD (Figure 2). SAFOD borehole samples of wall rock, including granodiorite, arkosic sandstone, and siltstone, are all frictionally strong ($\mu = 0.56 - 0.66$). Similarly, sand and clay-rich lithologies from outcrops have friction coefficients of $\mu = 0.56 - 0.68$. Both groups are consistent with a strong crust ($\mu = \sim 0.6$) surrounding the SAF.

Natural serpentinite, sampled from an outcrop in the New Idria region, is thought to abut the SAF at depth, and previous work suggested that serpentinite could explain the fault's apparent weakness. We found low friction ($\mu = 0.18 - 0.26$) for this serpentinite. An important result comes from comparing serpentinite friction with results for synthetic mixtures of weak (talc or serpentinite) and strong (quartz) materials (Figure 2). For synthetic gouge mixtures, friction is low only when large amounts (>50% by weight) of weak phases are present. Our findings for frictional strength of naturally occurring serpentinite and talc, thought to influence the SAF's mechanics, indicate entrainment of these materials in the fault zone could partially explain its mechanical weakness. However, these materials are not sufficiently weak to completely explain the inferred effective friction coefficient on the SAF if the weak phase is distributed homogeneously within the fault zone. Our results for synthetic mixtures indicate serpentinite and/or talc would need to be much more abundant than is observed.

(continued on page 3)

From the EarthScope National Office

This issue follows on the heels of the very successful 2009 EarthScope National Meeting. Approximately 300 scientists and students gathered at the Centre on the Grove in Boise, Idaho, on May 12, for a day of field trips, planning workshops, and software training classes. The main meeting kicked off with a reception in the Stueckle Sky Center at Boise State University, which offers a panoramic view of Boise and the surrounding mountains. This was followed by 2½ days of talks, posters and discussions on recent results. The presentations highlighted the dramatic increase in knowledge enabled by the EarthScope facilities. During the post-meeting field trip to Yellowstone National Park, participants were treated to a rare and spectacular hydrothermal explosion in Biscuit Basin (http://www.earthscope.org/es_doc/en/Hydrothermal_YellowstoneNP.pdf).

As we start the summer, we embark on another ambitious project – updating the 2001 EarthScope Science Plan. Since this plan was published, new phenomena have been discovered that have important implications for understanding earthquakes, climate change and other topics of broad scientific interest and societal relevance. The EarthScope National Office is working with program managers at the National Science Foundation and with the EarthScope Steering Committee to organize an open community workshop, October 7-9, at the Snowbird Resort, Utah, to identify new opportunities for EarthScope. The outcome of the workshop will be an updated science plan that looks forward to the potential impact of EarthScope on our understanding of the atmosphere and hydrosphere as well as the solid Earth.

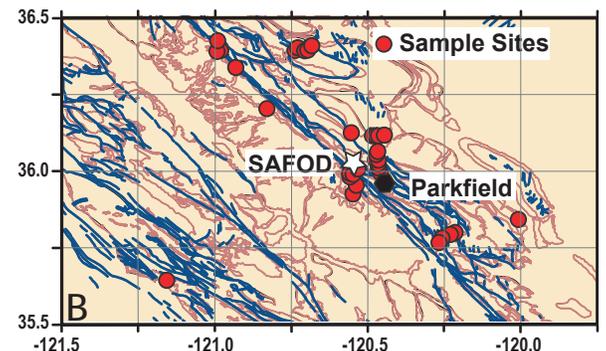
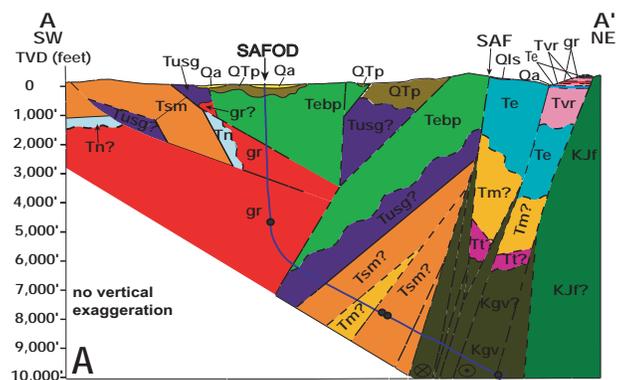
This summer will bring upgrades to continuous GPS sites, installation of new seismometers onshore and offshore in the Pacific Northwest, USArray station siting, and investigator-driven Flexible Array programs.

Enjoy this issue! As always, we encourage feedback (earthscope@coas.oregonstate.edu).



Anne Tréhu and the staff of the EarthScope National Office

Figure 1: Panel A. Geologic cross section at the SAFOD borehole. Black circles indicate location of cuttings used in this study. Panel B. Location of outcrop samples (red circles) on topographic map (pink lines) with faults (blue lines). A-A' (Panel A) is perpendicular to the fault and crosses it at the SAFOD site (white star in Panel B).



Please Note

Starting with this issue, featured science articles that contain references, expanded content, or both are available at <http://www.earthscope.org/science> in the Thematic Working Group sections.

featured science:

Receiver Function Images of the Western US Lithosphere

The tectonically active western United States can be divided broadly into several physiographic/tectonic provinces. Although most provinces have a strong pre-Cambrian and Paleozoic tectonic imprint, all have been greatly modified by and owe their current structure to large-scale Mesozoic-Cenozoic interactions of the Farallon and Pacific plates with the North American plate. The deep structure of continental lithosphere beneath each province and its response to changes in tectonic motions are not clearly understood. The USArray Transportable Array data uniformly sample the tectonic provinces in the western US with the large number of recorded teleseismic earthquakes allowing construction of lithosphere-scale structural images.

Using Transportable Array **teleseismic data**, we have made **common conversion point** (CCP) stacked PdS and SdP receiver function image volumes to determine the crustal thickness and the depth to the **lithosphere-asthenosphere boundary (LAB)** beneath the western US.

Receiver functions can be made with two types of scattered waves: P converted to S at an interface at depth d (PdS) and,

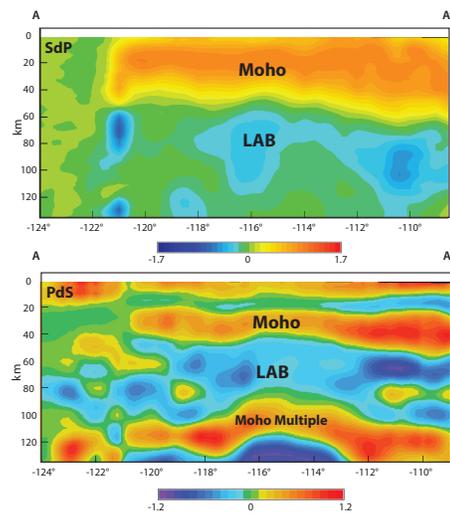


Figure 1: Cross sections through the SdP (top panel) and PdS (bottom panel) volumes along 34.5°N (see Figure 2 for location).

similarly, S converted to P (SdP). Receiver functions isolate converted waves resulting from seismic velocity and density layering beneath a station that appear in the P coda for PdS, or preceding the S arrival for SdP. Individual receiver functions can be converted to depth and laterally "migrated" to their conversion point using a reference velocity model with redundant signals stacked for signal enhancement. The use of both PdS and SdP allows for independent models of the same area and provides different frequency bands and ray paths to image crust and upper mantle structure.

Our PdS wave volume contains ~11,000 receiver functions from 70 earthquakes and our SdP wave volume has ~5,000 receiver functions from 45 earthquakes. At present, the image volumes extend from the Pacific continental margin to ~108°W and from Mexico to Canada to approximately 200 km depth. S-wave receiver functions were depth converted, spatially repositioned, and common conversion point stacked using a 1-D reference model based on MC35 and an average western US crust. The travel times for PdS image volumes were computed using linear tomography corrections for 3-D velocity models constructed from Crust2.0 and the mantle model of van der Lee and Fredericksen (2005) before converting to depth.

The current images sample the lithosphere and asthenosphere beneath most tectonic provinces of the western US: the Pacific-North American plate boundary (PPB), Sierra Nevada (SN), Cascadia subduction zone (CAS), Snake River Plain (SRP), Basin and Range (BR), and Colorado Plateau (CP). Both the P- and S-wave receiver function stacks show a nearly continuous, although variable strength, Moho, identified as a positive (red) polarity event (Figure 1). The P- and S-wave receiver functions also image deeper features, such as the LAB. The LAB is a negative polarity feature (blue) with significant topographic variation between tectonic provinces and, unlike the Moho, cannot be described as a single surface (Figure 1).

In the BR, CP, and Transverse Range provinces, the PdS and SdP estimates for

both the LAB and the Moho depths are in good agreement (Figure 1). Figure 2 is a crustal thickness map interpreted from the PdS receiver functions. The map illustrates the thin crust of the coastal terranes of the PPB, thicker crust under much of the SN, thin crust in the BR, and then rapid crustal thickening beneath parts of the CP.

The Transportable Array is providing a voluminous dataset to study the lithospheric structure beneath the US. As the footprint of the array moves east, we plan to produce updated crust and LAB images of the Rocky Mountains, the central plains and craton in the interior, and the eastern US. The crustal thickness and LAB maps and data are available online at <http://terra.rice.edu/departments/faculty/levander/downloads/>. ■

By Meghan S. Miller, University of Southern California and Alan Levander, Rice University.

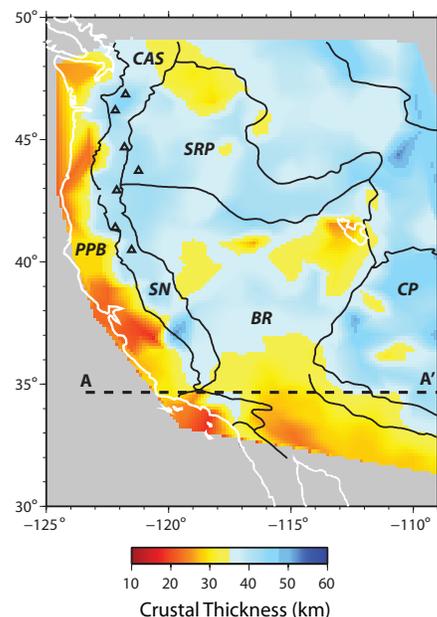


Figure 2: Depth to Moho map based on the PdS receiver function image volume. White lines are coastlines and black lines are the tectonic provinces as defined in text. A-A' illustrates cross section location in Figure 1.

Glossary

Common conversion point: Back-projects receiver functions along the signal's path, thus placing the signal at the location where it originated. Stacking is adding signals from many observations — earthquakes and seismic stations — for each element of the 3-D volume; stacking increases the strength of the coherent signal resulting in clearer images.

Lithosphere-asthenosphere boundary (LAB): An important rheological boundary in the Earth. Lithosphere consists of Earth's crust and uppermost mantle and is quite rigid. Lithosphere plates move on top of lower viscosity asthenosphere, which over long-time intervals is flowing. LAB thickness is one measure of tectonic plate thickness.

Receiver functions: Time series computed from three-component seismograms by deconvolving one trace by another to emphasize the signal generated at interfaces (layer boundaries) below a seismic station. For an overview, see <http://eqseis.geosc.psu.edu/~cammon/HTML/RftnDocs/rftn01.html>. For a comparison of Moho-depth results for USArray sites, visit the EarthScope Automated Receiver Survey website (<http://ears.seis.sc.edu/>).

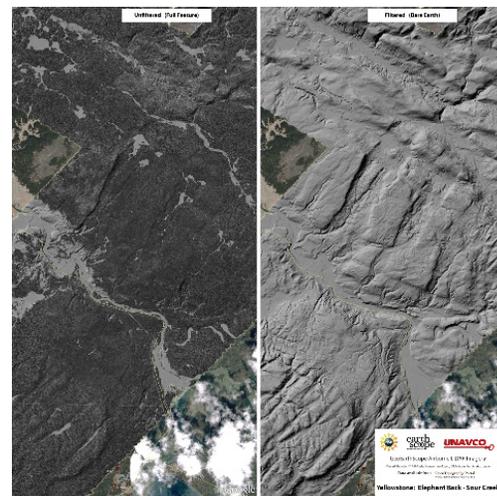
Teleseismic data: Seismograms recorded at stations more than 3000 km from an earthquake source. The seismic waves traveling through the Earth are nearly vertical (less than 20° from vertical) when they are detected at the recording site.

EarthScope News

- A new EarthScope Science Plan!** NSF is requesting an update to the original, almost eight-year-old science plan. The update will identify high-priority, new and emerging areas of scientific exploration over the next five to ten years emphasizing transformative and interdisciplinary science. A community workshop is being held October 7-9, at the Snowbird Resort, Utah, to develop the plan. Visit <http://www.earthscope.org> for updates. See you at the planning workshop!
- Nearly 200 people attended the **EarthScope Symposium and Reception** on Capitol Hill to acknowledge the contributions of the National Science Foundation and other organizations that have helped make the first five years of EarthScope a resounding success. Visit <http://www.iris.edu/hq/>

[earthscope_symposium_and_reception](#) for a summary and photos.

- New GeoEarthScope airborne LiDAR** (Light Detection and Ranging) data are available at <http://opentopography.org/> for the tectonically active regions of Utah and Wyoming, including Yellowstone and Grand Teton National Parks and the southern Wasatch fault. GeoEarthScope thanks the National Park Service for support and collaboration. GeoEarthScope acquired aerial and satellite imagery (including LiDAR) and geochronology data to enhance scientists' abilities to examine the strain field beyond the time scales available from other PBO components (<http://pboweb.unavco.org/>).



LiDAR imagery of the Elephant Back-Sour Creek area in Yellowstone National Park showing (left) unfiltered "full feature" and (right) filtered "bare-Earth" hill shades at 1-meter resolution with a 315° illumination angle.

featured science: Insights into Frictional Behavior of Materials in and near SAFOD

(continued from front)

The dependence of friction (μ) on shear velocity is crucial to the stability of fault slip. Velocity strengthening frictional material leads to fault creep, whereas velocity-weakening material is necessary for fault rupture. Serpentinite, with its velocity-strengthening behavior, could be partially responsible for the creeping behavior along this section of the SAF. Sand and sandstone, which comprise most borehole and outcrop samples, tend towards velocity neutral to slightly velocity strengthening behavior, whereas clay-rich samples are generally velocity strengthening. The gouges from rocks surrounding the SAF can support both seismic rupture and aseismic creep for experimental conditions investigated.

Our results indicate that (a) serpentinite exhibits low strength and could be a cause of observed fault behavior; (b) all other samples are consistent with a strong fault and crust; and (c) if the SAF is weak ($\mu \leq 0.2$) due to serpentinite or talc, these minerals would need to constitute over 50% by weight of the shear zone. Future work on SAFOD cuttings and core will illuminate further controls of fault behavior. ■

By Brett Carpenter, Chris Marone, and Demian Saffer, Department of Geosciences and Energy Institute Center for Geomechanics, Geofluids, and Geohazards, The Pennsylvania State University.

Glossary

Friction coefficient (μ), or coefficient of sliding friction: The ratio of shear force to normal force as one surface slides past another. Common values are: Sand (angular quartz) = ~ 0.6 ; granite = ~ 0.6 ; some clays ~ 0.3 ; and talc = ~ 0.2 .

Friction rate parameter: $a-b$ is a term derived from rate-and-state friction equations. The parameter $a-b = \Delta\mu/\Delta\ln V$ indicates a material's response to a change in sliding velocity V . For $a-b > 0$, material is velocity strengthening (stable sliding), a condition required for aseismic creep. For $a-b < 0$, material is velocity weakening (stick-slip), necessary for seismic rupture (earthquakes).

Serpentinite: A metamorphic rock composed mostly of minerals from the serpentine group (antigorite, chrysotile, lizardite) and formed by alteration of mafic and ultramafic rocks.

Talc: A fine-grained mineral from the phyllosilicate group known for their sheet-like structure. Talc has a soft, soapy feel and often occurs near metamorphosed serpentinites.

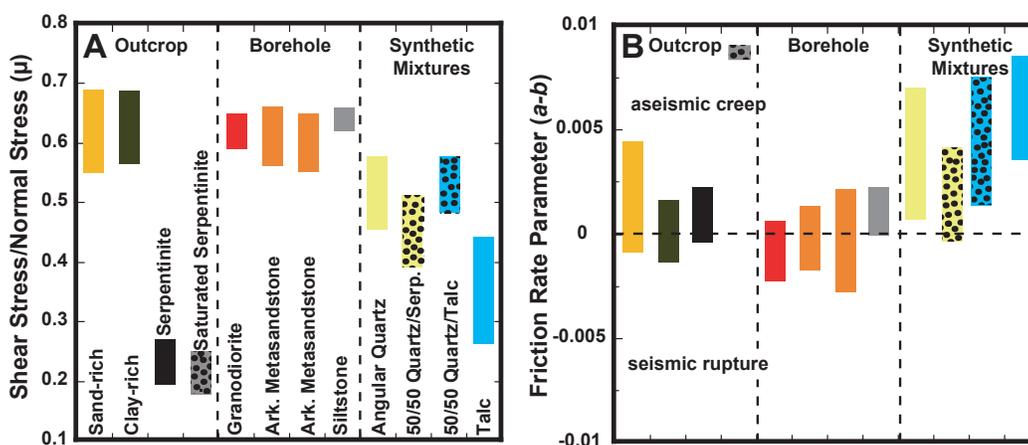


Figure 2: Frictional strength (A) and velocity dependence (B) of outcrop samples, borehole samples, and synthetic mixtures separated by vertical dashes. Horizontal dashed line indicates velocity-neutral behavior ($a-b = 0$). Note the different behavior of serpentinite compared to other outcrop rocks sampled near the fault, as well as the amount of serpentinite or talc that would be required to lower the fault strength significantly in synthetic mixtures. Samples investigated can support both seismic rupture and aseismic creep.

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EarthScope facilities are funded by the National Science Foundation and are being operated and maintained as a collaborative effort by UNAVCO Inc. and the Incorporated Research Institutions for Seismology with contributions from the US Geological Survey and several other national and international organizations. The EarthScope National Office at Oregon State University is supported by Grant No. EAR-0719204. This material is based upon work supported by the National Science Foundation under Grants No. EAR-0733069, EAR-0443178, EAR-0732947, EAR-0323700, EAR-0323938, and EAR-0323704. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

EarthScope onSite is published four times a year by EarthScope (www.earthscope.org)

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Students Present Research at EarthScope National Meeting

Forty-three students from 32 academic institutions participated in the 2009 EarthScope National Meeting in Boise, Idaho. Winners of the student poster competition included a tie for first place between Jayne Bormann of the University of Nevada-Reno and Jamie Farrell of the University of Utah. Second place went to Anna Foster of Columbia University. The best undergraduate poster was presented by Samuel Pacheco of the University of Puerto Rico-Mayagüez, and the best face-to-face presentation award went to Abhijit Ghosh of the University of Washington. Honorable mentions were earned by Patrick Brennan (Purdue University), Chinaemerem Kanu (Indiana University), Janine Buehler (University of California at San Diego), Julie Elliott (University of Alaska-Fairbanks), John West (Arizona State University), Yun-Ruei Chuang (Indiana University), Steven Hansen (University of Wyoming), and Chunpeng Zhao (Arizona State University). Special appreciation is extended to Emma Hill of the Harvard-Smithsonian Center for Astrophysics for organizing the poster competition and judging! ■



Emma Hill (left) with winners Samuel Pacheco, Abhijit Ghosh, Anna Foster, Jayne Bormann, and Jamie Farrell.



Jamie Farrell presents his award-winning poster at Yellowstone Lake during the post-meeting field trip.