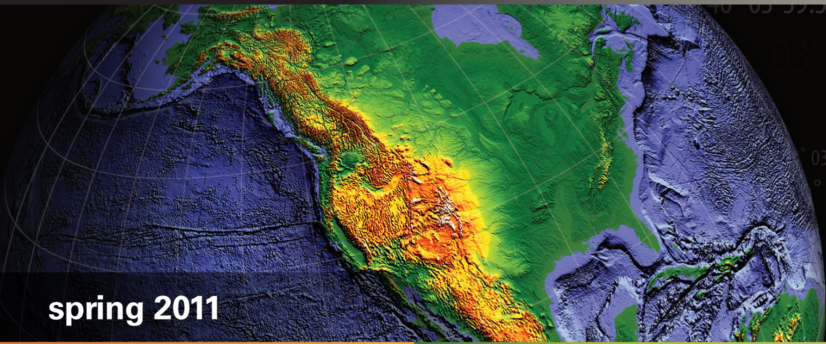


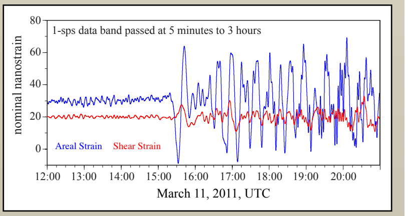
spring 2011

inSights
the EarthScope newsletter

EarthScope News

Participants and instructors at the recent EarthScope workshop for park and museum educators in the New Madrid-Central US region got a sneak preview of earthquake exhibits at the Marston Welcome Center on Interstate 55 just south of New Madrid, Missouri. For New Madrid Bicentennial activities visit http://newmadrid2011.org.

- The EarthScope **Institute on the Lithosphere-Asthenosphere Boundary** will be held September 19-21, 2011 in Portland, Oregon. For more information visit www.earthscope.org/workshops/lab11.
- This May, tune-in to "**X-Ray Earth**," a 2-hour special produced for National Geographic that features the Transportable Array and seismic tomography toward the beginning of the show.
- The borehole strainmeters of the Plate Boundary Observatory measured **strong crustal deformations caused by ocean loading from the tsunami** generated by the Tohoku M=9 earthquake. Station B012, located on Vancouver Island, Canada, recorded the tsunami onset almost 10 hours after the earthquake occurred, followed by a train of strain oscillations that continued for days as the tsunami waves bounced around the Pacific Ocean.



Fluid Pressure Spikes in SAFOD Rocks as Evidence of Microseismicity

The San Andreas Fault (SAF) deforms by permanent creep and microseismicity in central California. Higher-than-hydrostatic fluid pressures, which could explain low strength and creep, were not detected during the San Andreas Fault Observatory at Depth (SAFOD) drilling. Instead, aseismic creep is likely due to velocity-strengthening behavior of an intrinsically weak fault gouge in the active shear zones encountered by SAFOD. Creep of low-strength material, though, does not explain the observed repeating microearthquakes.

It has been suggested that repeated slip on hard (friction coefficient $\mu>0.2$) asperity patches of ~15-20 m radius controls seismic failure along the creeping SAF. Seismic inversion reveals such asperities in roughly strike-parallel clusters that make up 1% or less of the total SAF fault surface area. The asperities are surrounded by weak ($\mu<0.2$) velocity strengthening gouge. Based on microstructural evidence, we suggest that the asperity patches responsible for microseismicity are generated by cycles of crack sealing via intergranular pressure solution (IPS) creep in the SAF damage zone.

Whether structural geologists can use fault rock microstructures to identify seismic deformation has been debated since the 1970s. Direct evidence comes only from pseudotachylytes (solidified frictional melt). For other microstructures syntectonic formation has been difficult to establish. Syntectonic formation, however, is likely for microstructures observed in core samples from SAFOD lateral drill holes that were taken less than 100 m from a known cluster of repeating microearthquakes.

We present microstructural and analytical data from samples in the measured depth (MD) interval of 3188 m to 3194 m, only 2-3 m outside of an actively creeping shear zone. The samples show evidence of high fluid pressures (Figures 1 and 2) which provide a weakening mechanism to initiate seismic slip. For a dilation jog to remain open, fluid pressure in the jog must at least equal the lithostatic (overburden) pressure.

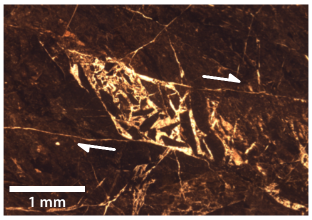


Figure 1: Optical plane polarized image of a calcite-filled dilational jog. The blocky calcite crystals and suspended angular fragments of clay gouge indicate crystallization in a space created by a rapidly opening shear fracture under higher-than-hydrostatic fluid pressures. Shear sense is indicated by arrows. Core sample is from 3189.94 m MD.

We argue that the observed microstructures result from earthquakes that originate in the damage zone rather than in the actively creeping zone because the latter lacks vein networks and mainly consists of almost cohensionless phyllonitic gouge. To relate microstructures to microearthquakes we ask: Are high fluid pressure events episodic? And what are possible controlling mechanisms for seismic failure?

Reworked dilation jogs support episodic fluid pressure events. The dilation jog in Figure 3 has been stretched and fractured by a combination of

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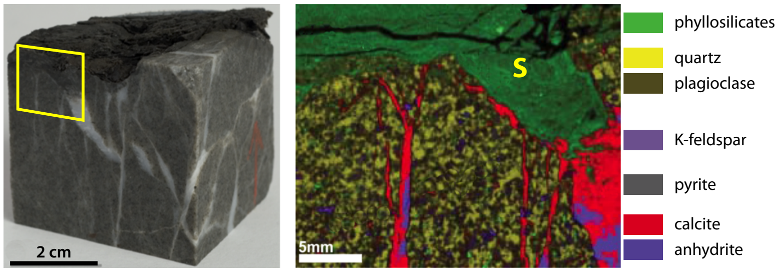

Figure 2: The X-Ray Fluorescence chemical map (right) from the section face indicated on the sample block (left) shows injection microstructures at the shale-sandstone gouge boundary. Shale, labeled S, has intruded a calcite/anhydrite vein opening in sandstone. The injection is possibly the result of high fluid pressure build-up in fault gouge. Core sample is from 3193.67 m MD.

EarthScope **News**

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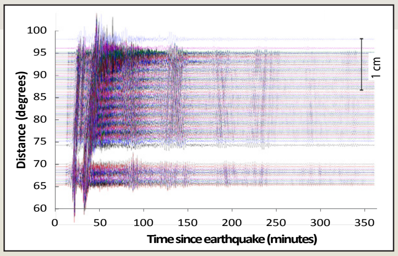
- The IRIS DMC has released two new products showing **USArray data.** Event Plots include USArray seismic record sections that are automatically generated following M 6+ earthquakes. Ground Motion Visualizations use USArray data to illustrate how seismic waves travel across the US.



Record section (20-125 s period) from the March 11, 2011 M = 9 Tohoku earthquake recorded by the USArray.

- The **Transportable Array** certified its first station on the eastern side of the Mississippi River, Station 345A, about 15 miles northwest of Columbia, Mississippi.

Inter-Lab Friction Correlations of SAFOD Samples

When two laboratories measure frictional properties of the same rock sample, will they obtain the same results? The core obtained from Phase III of SAFOD – drilling through the actual San Andreas Fault zone and retrieving core samples was completed in 2007 – is diverse in composition, texture, fabric and scale as shown in Figure 1. It is thus expected that frictional properties will vary considerably. At the same time, procedures and experimental apparatuses vary significantly between laboratories, potentially leading to widely different results for core samples taken from the same location. To calibrate measurements and aid interpretation, SAFOD instituted a pre-requisite: laboratories had to determine friction coefficients (μ) on standard materials under given conditions before obtaining core samples. This article summarizes the results of this study; a complete description will be published elsewhere.

Seven laboratories in the US and Europe participated in the friction tests. Sample rocks were selected to represent a possible spectrum of frictional responses that might be encountered in a fault zone. They ranged from ground up granite, representing strong rock adjacent to an active fault, and ground up quartz sand, as material that might be incorporated into a fault zone from disturbed strata, to mixtures of quartz and montmorillonite (clay) as observed in other fault zones. Talc and SAFOD shale cuttings were included as weak end members.

Friction coefficients of μ≈0.8 represent brittle rocks capable of stick-slip behavior and release of significant seismic energy. Low values of μ=0.3-0.4 have been measured for clays and halite, which are ductile and usually show continuous displacement by stable sliding. Values in between are expected to show stick-slip, stable sliding, or transitions from one to the other depending on rock and other conditions.

Laboratory tests under triaxial compression, rotary shear, and torsion were conducted at room temperature on brine-saturated samples that were subjected to 3 to 5 MPa pore pressure under effective normal stresses of 3, 10 and 100 MPa to mimic fault conditions.

Triaxial tests consist of a cylinder with a saw cut inclined ~35° to the long loading axis. The gouge material is distributed evenly along the saw cut and shear displacements are generally limited to 10 mm or less. Friction coefficients, measured at Penn State, Texas A&M, and the USGS, were remarkably consistent. Friction coefficients for Ottawa quartz sand and ground Westerly granite ranged from 0.57 to 0.70, and for talc from 0.22 to 0.30. For a 50/50 mix of quartz sand and montmorillonite, μ generally ranged from 0.19 to 0.30. Similar variability was observed for SAFOD Phase III drill cuttings, where μ ranged from 0.59 to 0.71, with one set at 0.35 which most likely reflects the variability in the cuttings. In all cases stable sliding was observed.

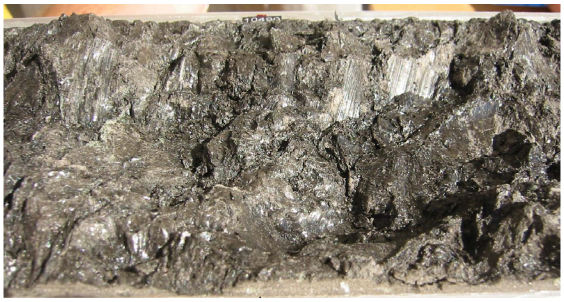


Figure 1: Close up of foliated fault gouge from Hole G Run2 Section 8 of the SAFOD core. The oblique view shows scaly fabric and striations. Image from the Phase III Core Photo Atlas V.4 (www.earthscope.org/es_doc/data/safod/Core Photo Atlas v4.pdf).

For rotary shear tests samples are placed between two rotating discs that also apply normal stress. Displacements may range up to 50 mm. At lower normal stresses, μ ranged from 0.33 to 0.64 for quartz sand, ground granite, and SAFOD Phase III cuttings. At 100 MPa normal stress, samples compact and the spread in μ narrowed to 0.52 to 0.64. For talc and the sand/montmorillonite mix, μ ranged from 0.11 to 0.30. Notably, stable sliding was the prevalent deformation mode except when loading was momentarily stopped and resumed, which sometimes caused small stress oscillations (stick-slip). Rotary shear tests resulted in a wider but not excessive spread for μ considering the different experimental equipment and sample configuration at the labs in Utrecht, Padua, Bremen, and Brown University.

The inter-lab tests have been a successful exercise to calibrate results from measurements of frictional properties obtained at different labs. They are not meant to assess rock properties at SAFOD or to speculate on San Andreas Fault slip mechanisms, which will have to wait until actual measurements on SAFOD samples are completed. A major effect is increased communication within the international rock-friction laboratory community. While result variability is still large for some samples and conditions, improved communication is already leading to an assessment of procedures and more standardization, and to an exchange of ideas on how to harmonize experimental apparatuses that promises to reduce inter-lab differences significantly in the future. Inter-lab communication and exchange of ideas has long been sought in the rock mechanics community and it is the importance of the SAFOD cores that has finally brought this to fruition. ■

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Fluid Pressure Spikes as Evidence of Microseismicity

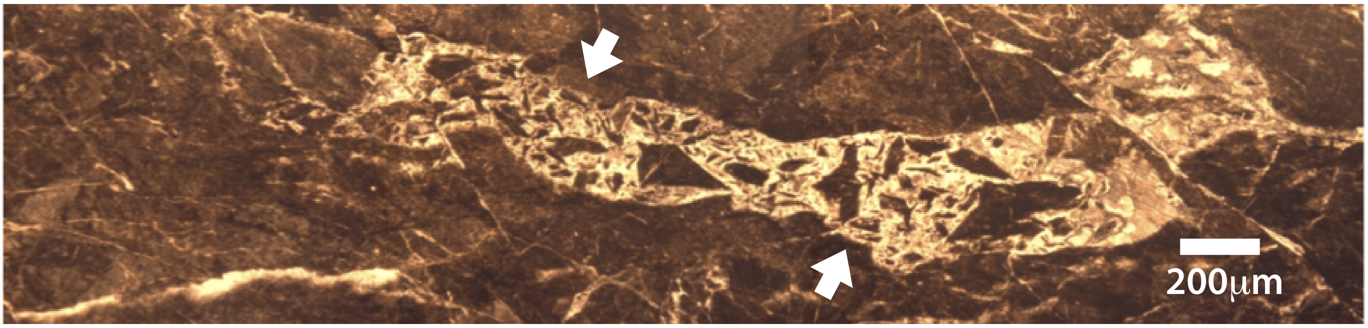

Figure 3: Deformed (reworked) calcite-filled dilation jog indicates that cyclic pore pressure spikes are intermittent with periods of aseismic creep. Note sharp incursions of clay gouge against the jog borders (arrows) probably resulting from dissolution by pressure solution creep and distributed fracturing (cataclastic flow) in the gouge. Sample and image type as in Figure 1.

IPS and cataclastic flow (distributed fracturing), which have been identified as interseismic creep deformation mechanisms based on other SAFOD core sample studies. We discuss two mechanisms for developing asperity patches, noting that local fluid pressure that exceeds hydrostatic pressure is a mechanical requirement for seismic slip on a velocity weakening patch within an otherwise velocity strengthening fault zone.

Fluid pressure build-up requires flow to the site of seismic failure. The SAF, like many other mature fault zones, acts as a hydrologic barrier limiting flow across the fault zone. Fluids primarily flow along-strike and up-and-down dip. Porosity measurements (Figure 4) from clay gouge show that fluid flow through the foliated fault rock may not occur smoothly. The local variations in porosity across the foliation indicate a strong likelihood of local sealing and build up of high fluid pressures in the creeping clay gouge. As IPS dissolves hard minerals like quartz and feldspar at impingement points, the insoluble residues such as clay minerals accumulate at a right angle to the normal stress acting across the fault. The soluble products such as calcite often precipitate and seal off nearby transgranular cracks parallel to the normal stress. This process results in a banding fabric with a highly variable porosity and permeability distribution. The distance dissolved material travels from dissolution to precipitation site (diffusion distance *d*) determines the rate of deformation by IPS. For *d* close to the average transgranular crack length (~10 – 100 μm), steady-state aseismic pressure solution creep could accommodate the entire SAF creep rate of ~20 mm/year. Uneven porosity and permeability could cause extensive crack sealing, locally impeding the solute diffusion (at *d* >100 μm) so that stresses do not relax. Such local gouge restrengthening may cause microseismicity. The possibility of rupture assisted by transient high fluid pressures in the damage zone is also supported by evidence of anhydrite and calcite vein sealing found in the same injection event (Figure 2), suggesting a breach of barriers between isolated fluid sources.

An alternative explanation involves the spatial distribution of material contrasts within the damage zone. The two active creep zones in the SAFOD main hole are ~100 m apart and are expected to vary in width and spacing with a tendency to pinch, branch, and converge along strike within the damage zone. Field evidence and modeling suggest that undulations of the embedded active zones could result in a non-uniform stress distribution and pore pressure build-up in structural boundary regions resulting in microseismicity.

The evidence of extensive IPS in the SAF damage zone and the possible role of pressure solution creep in generating microseismicity are exciting new findings. This microstructural study serves to constrain parameters and state variables of mechanical models of faulting. The complexity and variety of structural deformation prompt us to emphasize that a significant amount of microstructural information remains to be extracted from the SAFOD cores and to be integrated in the development of more realistic deformation models for the SAF. Core and cuttings samples from SAFOD drilling have provided the Earth science community with unique opportunities for firsthand, direct observations of an active plate boundary fault. ■

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See online version for expanded article with references.

Visit www.earthscope.org/observatories/safod for more on SAFOD, to retrieve the SAFOD Core Photo Atlas, and to access the SAFOD core viewer.

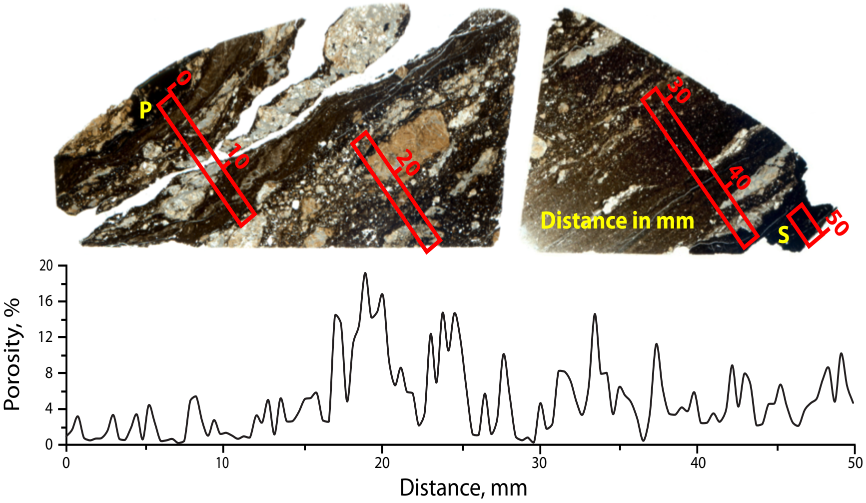

Figure 4: Top: Optical plane polarized image of typical foliated siltstone-shale gouge from 3188.97 m MD. Red boxes on the image indicate exact position of Backscatter SEM image tracts used for 2D porosity measurements. Tracts were offset to widen the coverage. **Bottom:** Variations in maximum porosity across the gouge. Siltstone-rich foliation bands show a higher porosity than clay-rich foliation bands. The porosity traverse begins in a deformed pyrite mass (P) and ends in host rock shale (S).

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Inside this issue...

EarthScope facilities are funded by the National Science Foundation and are being operated and maintained by UNAVCO Inc. and the Incorporated Research Institutions for Seismology with contributions from the U.S. Geological Survey and several national and international organizations. The newsletter is published by the EarthScope National Office at Oregon State University. The content of the newsletter material represents the views of the author(s) and not necessarily of the National Science Foundation.

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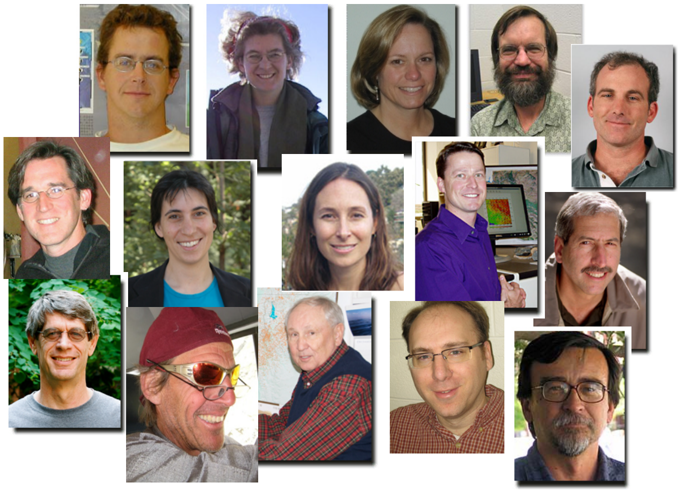
The EarthScope Speaker Series

The EarthScope Speaker Series was initiated in 2008 to present EarthScope research to faculty and students in departmental seminars at colleges and universities across the country. The 15 distinguished speakers (www.earthscope.org/speakers) to date have represented a broad spectrum of science that draws from data collected by EarthScope's three observatories and campaign experiments. The objectives of the Speaker Series are to increase EarthScope visibility, to make scientists, students, and the public more aware of the relevance of EarthScope science, and to share the excitement of the latest EarthScope discoveries.

The current speakers are Kaj Johnson (Indiana University), Meghan S. Miller (University of Southern California), Gary Pavlis (Indiana University), Harold Tobin (University of Wisconsin-Madison), and Steve Wesnousky (University of Nevada-Reno). Previous speakers were Gene Humphreys (University of Oregon), Bob Smith (University of Utah), Emily Brodsky (University of California at Santa Cruz), Mark Zoback (Stanford University), Ramon Arrowsmith (Arizona State University), Judi Chester (Texas A&M University), Matt Fouch (Arizona State University), Tim Melbourne (Central Washington University), Suzan van der Lee (Northwestern University), and George Zandt (University of Arizona).



The EarthScope Speaker Series is committed to reaching diverse audiences and to establishing links to organizations and communities that engage underserved populations. During the first three years, presentations have been given at 64 colleges and universities. As the series expands in the future, presentation venues may include community colleges, civic organizations, state and national parks, museums, and local community programs. ■