winter 2010

inSights
the EarthScope newsletter

EarthScope News

The *Silvertones* David Bell, Ed Garnero, and Michael Wysession play in memory of Paul Silver during the WESP poster session. Event sponsored by Carnegie Institution of Washington.

- **Welcome to the first issue of inSights: the EarthScope Newsletter. inSights** developed from the need to provide the science community with a regular forum for news and exciting science from the EarthScope program. **onSite** will go back to its roots as a newsletter for landowners who graciously allow placement of EarthScope instruments on their property. The EarthScope National Office welcomes feedback (earthscope@coas.oregonstate.edu).

- **The UNAVCO Science Workshop** will be held March 8-11, 2010 in Boulder, CO. To learn more and stay informed about PBO-related and other topics at the workshop visit www.bit.ly/4KYa32.

- **The IRIS 2010 Workshop** will be held June 9-11, 2010 at the Snowbird Resort, UT. Visit www.iris.edu/iris_workshop for more information.

- **The New EarthScope Science Plan** is now available at www.earthscope.org/ESSP. The plan is the product of a community driven process that started with the Workshop for an EarthScope Science Plan (WESP) in October 2009 and included discussions held during an AGU Town Hall Meeting on an early draft followed by an

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Seismic Imaging of **Fault Zone Processes** on the San Andreas Fault near Parkfield

Earthquakes are caused by the sudden release of stresses along faults. Plate tectonics describes the long-term strain accumulation, but the specifics of stress release – what ultimately leads to fault failure and how failure manifests itself (as a small or large earthquake, as aseismic slip, or as non-volcanic tremor) – are still not well understood.

Current models of earthquake recurrence that assume constant loading rates and fixed fault strength are far too simplistic to describe exciting new observations of time-varying fault behavior. From among many examples (see online version for references), we present three recent discoveries of temporal changes in fault zone processes near Parkfield, CA. These discoveries were made possible by advanced borehole seismic recordings from the High-Resolution Seismic Network and the San Andreas Fault Observatory at Depth (SAFOD) drill holes and from EarthScope's USArray and PBO seismic and geodetic data recorded near the San Andreas Fault (SAF). Paul Silver (see tribute, page 2) was a collaborator and coauthor for much of this research.

1. In-Situ Velocity Changes Preceding Earthquakes. Stress-induced increases in microcrack density preceding rupture result in measurable seismic velocity changes that were observed in laboratory studies more than 40 years ago. However, source repeatability and the precision of travel-time measurements only recently became adequate to observe the effect of tidal and barometric stress changes on seismic velocities in the field. The SAFOD pilot and main holes provided an unprecedented opportunity for a continuous active-source cross-well experiment to measure velocity changes at seismogenic depth. We observed an excellent anti-correlation between S-wave travel-time through rock and barometric pressure. Two large travel-time excursions coincide with two earthquakes that are predicted to produce large coseismic stress changes at SAFOD (Figure 1). Interestingly, the excursions started approximately 10 and 2 hours before the earthquakes, suggesting they were related to pre-rupture stress-induced changes in crack properties, confirming, for the first time, the early laboratory observations.

2. Repeating Earthquakes Measure Changes in Fault Strength. Repeating earthquakes are a series of earthquakes that occur regularly on the same fault patch and thus produce nearly identical seismograms when recorded by the same station. Changes in any part of the seismograms can be attributed to temporal changes in medium properties making repeating earthquakes an ideal tool for monitoring changes in fault behavior. We identified robust temporal changes in the scattered wavefield following the strong regional 1992 Landers (M 7.3) and 2004 Parkfield (M 6.0) earthquakes, which indicate changes to a seismic scatterer within the SAF fault zone at ~3 km depth (Figure 2). This scatterer responded to both events and acted as an "in-situ" stress meter; it also changed its properties after the December 26,

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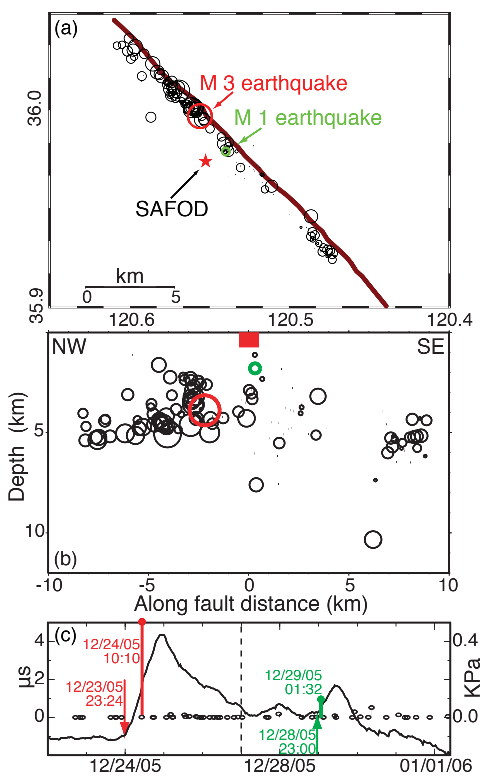

Figure 1: (a) SAFOD site (star) and seismicity during the experiment (circles). (b) Earthquake depth distribution. Red square, red and green circles indicate the SAFOD site, and M 3 and M 1 earthquake hypocenters, respectively. (c) Predicted coseismic stress changes (circles, saturated for M 3 event) at SAFOD for earthquakes between December 22, 2005 and January 1, 2006. Velocity changes (arrows) started before the two earthquakes (solid lines) occurred.

MARGINS/EarthScope **Amphibious Array** in Cascadia

The National Science Foundation (NSF) EarthScope and MARGINS programs are joining forces in a comprehensive onshore-offshore initiative targeting the Cascadia subduction zone. The NSF Earth Sciences and Ocean Sciences divisions received funding through the 2009 American Recovery and Reinvestment Act (ARRA) for facility-related investments to support multi-disciplinary EarthScope and MARGINS science.

The initiative includes acquisition of new Ocean Bottom Seismographs (OBS's), deployment of additional USArray seismic equipment in the Cascadia forearc, and an upgrade of Plate Boundary Observatory GPS stations in the Pacific Northwest to high-rate sampling and real-time telemetry. The onshore and offshore seismic array is envisioned to be in place for at least 3 years, and all data will be publically available as soon as possible. A group of scientists and NSF officials met last summer at the Lamont-Doherty Earth Observatory to discuss primary science opportunities and critical objectives and to devise an initial implementation plan. A report and presentations are available at www.nsf-margins.org/Cascadia/09meeting/.

Implementation of the onshore part is well underway. More than 10% of the 232 GPS sites targeted for upgrade are currently streaming 1 Hz data with mean latency on the order of 1 second (www.pboweb.unavco.org/?pageid=107). Thirteen new broadband seismic stations in California and Oregon have been installed, and 14 additional sites will be installed in spring 2010. These sites have been seamlessly integrated with USArray Transportable Array data archiving procedures. Sites were chosen to complement existing permanent broadband seismic sites (from other institutions) and new sites being installed by the USGS as part of the ARRA program.

The most ambitious part is the offshore deployment. For continuous coverage across the subduction zone, many OBS's will have to be placed in shallow water where previous deployments indicate a need for shielding and possibly sensor burial to decrease perturbations by local biological activity and to protect the OBS's from trawlers. These requirements call for the development of a new generation of OBS with the first instruments planned for testing in 2010 and deployment in 2011. Details of the offshore deployment pattern are to be determined and community input is encouraged.

The ARRA-funded facility enhancement dramatically enhances geophysical observations in Cascadia and should lead to significant new discoveries. It also creates leverage for additional instrumentation and studies like onshore-offshore MT experiments and focused FlexArray seismic installations. Longer term, the initiative is a tremendous opportunity to launch subsequent integrated EarthScope-MARGINS studies along the Atlantic continental margin, around Alaska, and elsewhere. ■

Special **Tribute**

The EarthScope community lost two important guiding lights during the past year: John C. Lahr and Paul G. Silver. They will be missed. Through their warmth, generosity, and intellectual vigor, they touched and inspired many of us and will not be forgotten.

Everyone who met **John Lahr** was struck by his curiosity and desire to understand how things worked. As research geophysicist and project chief of the Alaska Seismic Studies Project at the USGS, John's work centered on investigating the seismicity and tectonics of Southern Alaska. He is known throughout the seismology community as the author of the widely used HYPOELLIPSE earthquake location program. After retiring, John enthusiastically focused on Earth science education; a field that he thought was seriously neglected by our educational system. John believed in hands-on learning, and he created many tools that show how "seismology works." Watching his gentle and caring approach with K-12 students, one could not help but notice how he was able to tickle their imagination and yearning for knowledge during demonstrations that were followed by a storm of questions. For a more complete tribute visit www.jclahr.com/tribute.html. The "John C. Lahr Educational Seismology Fund" (www.iris.edu/hq/sis/tribute) was established in John's memory to support "Seismographs in Schools" within the IRIS E&O program. ■

Without **Paul Silver**, EarthScope would probably not be what it is today. Paul, with a strong interest in advancing Earth science infrastructure, was an early leader in proposing a plate boundary observatory of seismic and geodetic instruments across western North America. His community service includes chairing the boards of UNAVCO and IRIS. A researcher at Carnegie's Department of Terrestrial Magnetism, Paul was an eminent scientist pioneering new applications of seismic observations to infer the flow field of Earth's mantle and the mechanics of fault zones. This issue's featured science article showcases one of his many collaborations and interests. Paul also left a lasting impact on many young researchers he mentored at Carnegie. In many cases this was only the beginning of long-lasting collaborations. Another facet of Paul's life was his love for music - he and his band provided entertainment at scientific meetings (e.g. 2008 IRIS Workshop) as well as in clubs in Washington, DC. A tribute to Paul was published in EOS (90(45), 10 November 2009). The "Paul G. Silver Postdoctoral Fellowship" (www.ciw.edu/silver_fellowship) was established at CIW's Department of Terrestrial Magnetism to honor his extraordinary contributions. ■

EarthScope News

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open comment period. The planning and writing teams did an outstanding job synthesizing high-priority, new, and emerging areas of exploration for the EarthScope Program that emphasize transformative interdisciplinary science. To obtain a printed version please contact earthscope@coas.oregonstate.edu.

- **PBO at GSA 2009**. A major EarthScope objective is to use multiple data types to resolve North American tectonics. At the Geological Society of America meeting, Evelyn Roeloffs (USGS) reported that borehole strainmeters of the Plate Boundary Observatory (PBO) recorded shear strain transients during the January 2007, May 2008, and May 2009 Cascadia Episodic Tremor and Slip events, confirming that tremor and strain both originate from a single underlying process. Kyle McDonald (Oregon State University) and colleagues showed heat flow data from boreholes drilled during PBO strainmeter installation in California that will lead to a better understanding of the temperature field near the San Andreas Fault. Ray Weldon (Univ. of Oregon) presented water level records from NOAA tide stations that show uplift rates identical to those inferred from modeling horizontal PBO GPS data.

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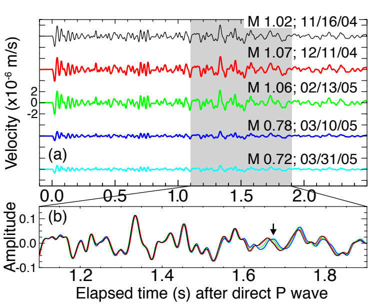
Seismic Imaging of **Fault Zone Processes** on the SAF near Parkfield

2004 (M 9.1) Great Sumatra Earthquake. Coincident with scatterer changes, the repeating events occurred more frequently and with reduced sizes. These systematic variations are consistent with a slip-predictable model for earthquake occurrence in which size and occurrence are governed by the failure strength of a fault and a constant minimum stress. The local response to the distant Sumatra earthquake implies that dynamic stress changes such as the passage of large-amplitude surface waves can induce movements of fault-zone fluids that cause structural changes in the fault zone through variations in pore pressure and a reduction in fault strength. Thus, the very largest earthquakes may globally influence the strength of Earth's fault systems.



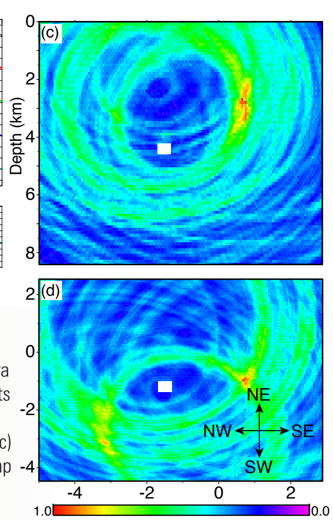


Figure 2: (a) Vertical seismograms at a borehole station near Parkfield for 5 repeating earthquakes. Event size became minimal ~3 months after Sumatra earthquake. (b) Normalized waveforms. Arrow points to waveform change after Sumatra earthquake corresponding to changes in fault zone properties. (c) Cross-section parallel to SAF and (d) 3 km depth map view showing location of responding scatterer (red) relative to repeating earthquakes (white square).

3. Non-volcanic Tremor at a Transform Plate Boundary. A densification of seismic stations in the Parkfield region, initiated by EarthScope, aided in the discovery of non-volcanic tremor on a non-subducting plate boundary: the SAF near Cholame, CA. Using 8 years of data we monitored and located tremor activity below the seismogenic zone of the SAF at ~15-30 km depth. Tremor activity significantly increased following the regional 2003 San Simeon (M 6.5) and 2004 Parkfield (M 6.0) earthquakes (Figure 3). A distinct fore-tremor episode was observed ~3 weeks prior to the Parkfield event. The Parkfield event also affected post-seismic tremor. Since the event, tremor episodes appear to be quasi-periodic, long-term activity has increased, and tremor was initiated in a previously dormant creeping section of the SAF near Monarch Peak (the epicentral region of the 1857 Ft. Tejon M 7.8 earthquake). The persistent tremor changes could signal a shift in the process of deformation and stress accumulation beneath the SAF. Tremor variation due to the two regional events and to tidal forcing implies that changes in shear stress dominate changes in normal stress, indicating near-lithostatic fluid pressure in the lower crust. The post-seismic tremor changes also correlate with changes in fault zone deformation and ambient seismic noise velocities, attributable to post-seismic relaxation processes following the events.

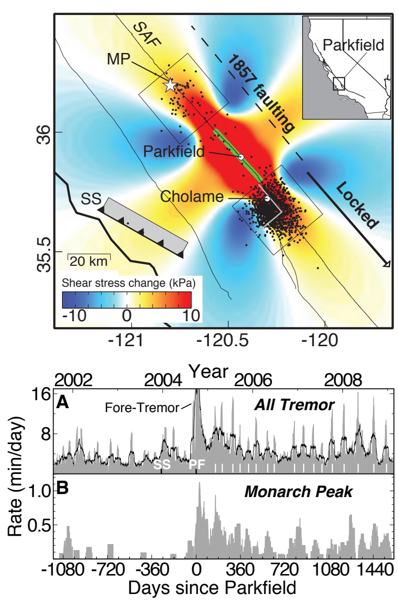


Figure 3: (Top) Study region with 1250 well-located tremors (black dots). Boxes define Cholame and Monarch Peak (MP) tremor zones. Color contours represent Parkfield earthquake (PF, green line) static shear-stress change at 20 km depth. The San Simeon earthquake (SS) is shown as a grey rectangle. Grey lines in Cholame box bound the western quadrant where quasi-periodic episodes dominate. White star is epicenter of 1857 Ft. Tejon earthquake. (Bottom) (A) Fifteen-(grey) and 45-day (black) smoothed tremor rates. SS and PF mark event occurrence. Intense fore-tremor activity occurred ~3 weeks before PF. White bars are times of quasi-periodic episodes. (B) Tremor in the MP zone (45-day smoothed) transitioned from near dormant to active following the Parkfield mainshock.

These examples illustrate how improved monitoring has led to significant discoveries about fault zone processes, their temporal variations, and fault interdependence. That pre-seismic velocity changes can be measured is encouraging for the development of earthquake warning systems. Increased tremor activity, fore-tremor and activity in previously dormant zones may signal changes in deformation processes on the fault below the earthquakes. The interplay of tremor, transient slip, and earthquakes near and far is exciting and is shifting our paradigm about how deformation in the Earth's crust is accommodated. ■

By Robert M. Nadeau, University of California at Berkeley, Fenglin Niu, Rice University, and Taka'aki Taira, University of California at Berkeley.

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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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Active Earth Display

The Active Earth Display (AED) is a low-cost, simple-to-implement interactive display conceived by IRIS consisting of a set of web pages. IRIS, together with UNAVCO and EarthScope, has developed two regional modules that tell a story about tectonics, earthquakes and volcanoes in Cascadia and the Basin and Range Province. Additional modules are planned in association with a series of workshops for interpretive professionals organized by the EarthScope National Office (www.earthscope.org/eno/parks) and are designed to appeal to a diverse audience. The flexible web format allows customization and addition of pages and modules. For information and to apply for an account visit www.iris.edu/hq/programs/education_and_outreach/museum_displays/active_earth. AED kiosks are already located at many museums, universities, park visitor centers, NSF Headquarters and the Amundsen-Scott South Pole Station! ■

E&O workshops target Southwest US

A teacher workshop, "Exploring Southwest Geology and Geophysics through the EarthScope Program" organized by Arizona State University, UNAVCO and IRIS, was held September 26-27, 2009 in Flagstaff, AZ. Through exploration of EarthScope learning activities, teachers expanded their geoscience foundation and obtained ready-to-go hands-on activities for classroom use. Workshop materials are available through UNAVCO's Community Workspace (www.bit.ly/6rn4FH) and workshop postings can be found at the E&O Blog (www.bit.ly/4K3STp). The fourth installment in the popular EarthScope workshop series for informal educators (www.earthscope.org/eno/parks) was held October 26-28, 2009 in Albuquerque, NM. More than 40 interpretive professionals from parks and museums explored how to convey the tectonic story behind the dynamic landscape of the Colorado Plateau-Rio Grande Rift region. ■