

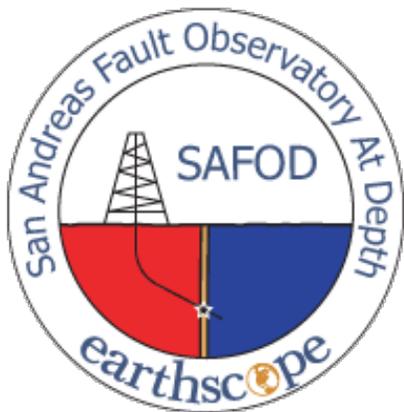
SAFOD: REVIEWING PAST PREDICTIONS, KEY RESULTS, AND FUTURE DIRECTIONS

EARTHSCOPE SYNTHESIS WORKSHOP

Room 101, Mitchell Building, Stanford University

(October 12-14, 2018)

The workshop's goals are to; 1) review the data/techniques that formed early predictions for the SAFOD project and their correctness, 2) synthesize the key scientific outcomes from SAFOD science, and 3) develop a plan to apply SAFOD data to existing concerns surrounding earthquake hazard along creeping faults and the physics of earthquake nucleation. Such a development would also consider possible future research utilizing SAFOD data and the SAFOD facility.



earthscope



Friday, October 12, Morning

Introduction, Current Status, and Past Predictions

8:30a.m.

BREAKFAST

9:00 - 10:15a.m.

Introduction and Current Status

(15-minute talks)

Bill Ellsworth
Elisabeth Nadin

Welcome
EarthScope Update and Outreach
Opportunities

Brett Carpenter

Meeting Layout and Goals

Steve Hickman
Kelly Bradbury

Current Status: SAFOD Borehole
Current Status: SAFOD Core

10:15 - 10:30a.m.

BREAK

10:30a.m. - 12:10p.m

Pre-drilling Predictions and Updates

(20-minute talks)

Mark Zoback
Diane Moore
Steve Roecker
Patrick Fulton
Cliff Thurber

Original Goals for SAFOD Drilling
Geologic Setting and Fault-zone Structure
Seismic and Resistivity Structure
Hydrologic and Thermal Structure
Target Earthquakes

12:10 - 1:30p.m.

LUNCH

Friday, October 12, Afternoon Key SAFOD Science Outcomes

1:30 - 2:50p.m. **Borehole and Earthquake Studies**
(20-minute talks)

Mark Zumberge	Strain in the SAFOD Borehole
Bill Ellsworth	Distributed Acoustic Sensing of the Seismic Wavefield at SAFOD
Rachel Abercrombie	Earthquake Source Properties
Peter Malin	Fault-zone Guided Waves and Their Implications

2:50 - 3:10p.m. **BREAK**

3:10 - 4:50p.m. **Core Studies**
(20-minute talks)

Kelly Bradbury	Structural and Geochemical Core Analysis
Ben van der Pluijm	The Timing and Properties of Fault-zone Clays
Genevieve Coffey	Seismic Slip in the SAFOD Core
Tamara Jeppson	Petrophysical Properties of SAFOD Core
Dave Lockner	Mechanical Properties of SAFOD Core

DINNER ON YOUR OWN

Saturday, October 13, Morning

Applications to Current Issues Future Directions

8:30a.m.

BREAKFAST

9:00 - 10:00a.m.

Applications to Current Issues
(20-minute talks)

Steve Hickman
Fenglin Niu

**SAFOD and Informing Seismic Hazard
Transient Velocity Changes and the EQ
Cycle**

Diane Moore

**SAFOD Structure: Application to Other
Faults**

10:00 - 10:30a.m.

BREAK

10:30 - 11:50am

SAFOD PHASE IV
(20-minute talks)

Brett Carpenter
Hiroki Sone

**Returning to SAFOD
Off-fault Deformation During the
Interseismic Period**

Taka'aki Tiara
Dave Lockner

**Continued Velocity Studies
Earthquake Nucleation and Propagation:
Current Status and Remaining Unknowns**

11:50a.m. - 1:00 p.m. LUNCH

Saturday, October 13, Afternoon

Group Discussions

1:00-4:00p.m. Discussions (Leader in BOLD)

Groups are encouraged to develop and discuss other critical questions related to the group's topic

1. Pre-drilling Predictions and Their Updates. What predictions and techniques panned out, which ones didn't? What were the surprises and why where they surprises? (Fulton, Malin, Moore, Roecker, Thurber, **Zoback**)
2. Key Outcomes. What are the key outcomes of the SAFOD project? Have the results be synthesized to present a complete story? What might this synthesis look like? What key results are missing? (Coffey, Ellsworth, Jeppson, Lockner, **Nadin**, Niu, **van der Pluijm**)
3. Application to Current Issues in Earthquake Processes and Seismic Hazards and Future Directions. How are lessons and results from SAFOD being applied elsewhere? What would SAFOD Phase IV look like? In the current climate, is Phase IV possible? What key science questions would drive Phase IV drilling? (Abercrombie, Bradbury, Carpenter, Hickman, **Sone**, Tiara, Zumberge)

2:30 - 2:45 p.m. BREAK (rotate groups after break)

1. Pre-drilling Predictions and Their Updates. (Carpenter, Ellsworth, Hickman, Taira, **Zoback**, Zumberge)
2. Key Outcomes. (Abercrombie, Bradbury, Moore, **Nadin**, Roecker, Thurber, **van der Pluijm**)
3. Application to Current Issues in Earthquake Processes and Seismic Hazards and Future Directions. (Coffey, Fulton, Jeppson, Lockner, Malin, Niu, **Sone**)

4:00 - 5:00p.m. Group Reports

6:00 - 8:00p.m. GROUP DINNER

Participants:

Brett M. Carpenter, University of Oklahoma, brett.carpenter@ou.edu

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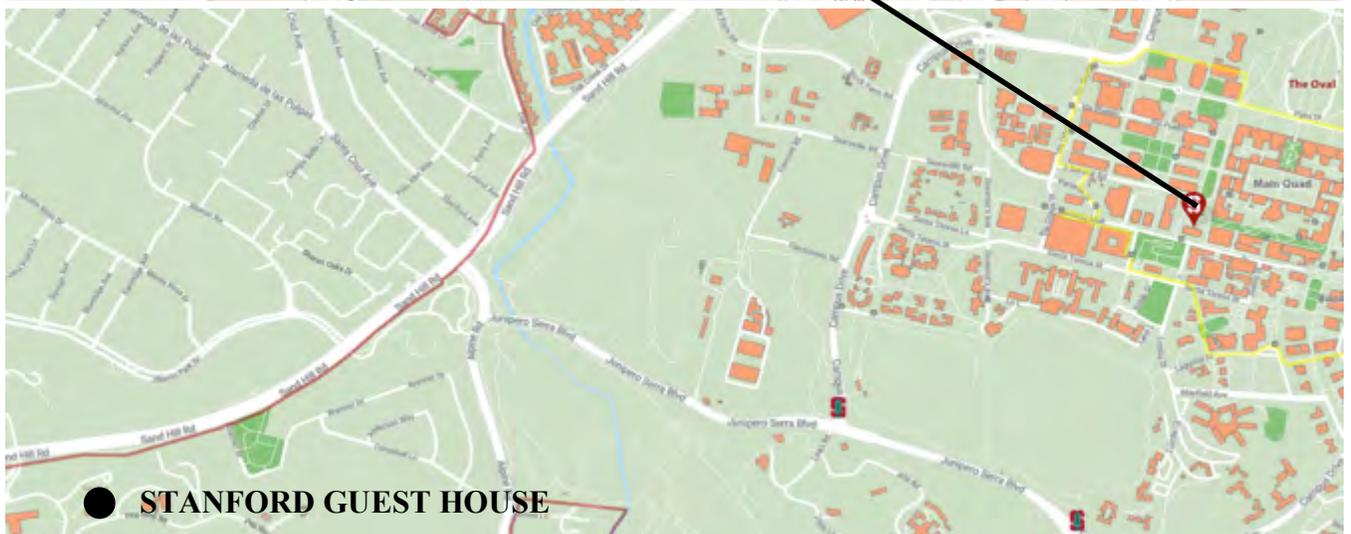
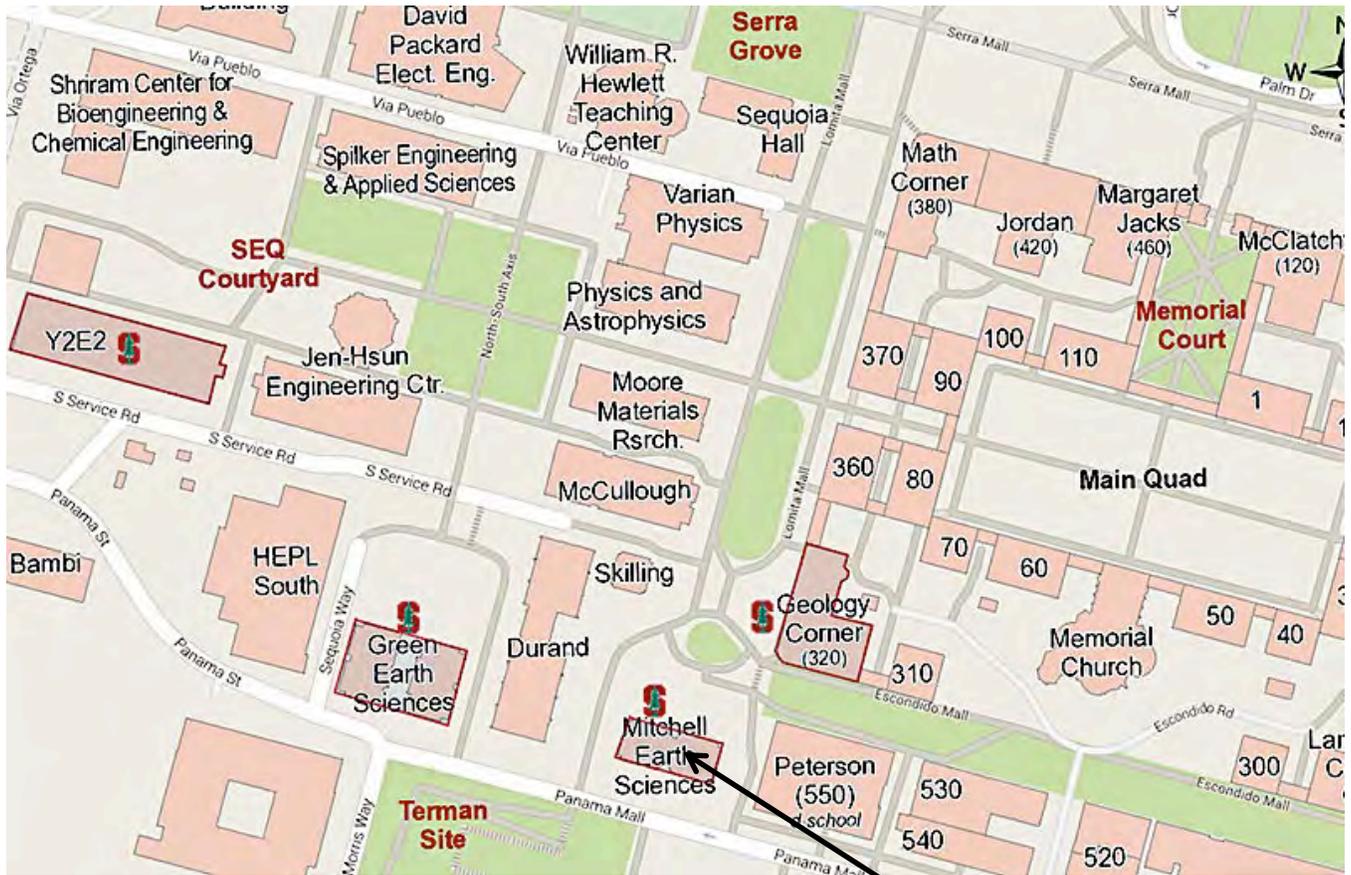
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Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predications, Key Results, and Future Directions

Conveners: Brett Carpenter, Clifford Thurber, Bill Ellsworth

Location: Stanford University

Date of Workshop: October 12-14, 2018

The SAFOD project recovered core samples from the Pacific-North America plate boundary and creeping patches of the San Andreas Fault, within about 100 m of a magnitude ~2 repeating earthquake patch. Data gathered on samples returned from depth have provided explanations for the weakness and aseismic behavior of the fault. Furthermore, samples collected from depth have shown the degree that fluid-rock interaction plays in the evolution of fault zone behavior. Finally, samples have also shown a past, seismic history for rock currently in the creeping section of the SAF. Borehole instruments have subsequently obtained a substantial archive of seismic data for earthquakes, tremor, and low frequency earthquakes along the San Andreas fault zone, as well as years of interferometric vertical strainmeter data. Borehole measurement results have highlighted the structure of the fault zone, that evolution of the state of stress approaching a plate boundary fault, and the role of crustal fluids in fault zone behavior. Finally, surface and borehole seismology studies have resulted in the detailed characterization of repeating earthquake clusters, the observation of preseismic velocity changes, and a better understanding of the 3D crustal structure surrounding the fault.

Overall SAFOD sampling, down-hole measurements and instrumentation at seismogenic depths have produced significant advances in our understanding of fault zone evolution, structure, composition and behavior. The project provided critical information on fundamental science goals in 2001 Earthscope Project Plan. SAFOD provided "the first look at the inner workings of a portion deep within an active geosystem - the San Andreas fault," and measured "subsurface conditions that give rise to slip on faults and deformation in the crust." However, a series of critical unknowns still exist.

The workshop would bring together key participants with the following goals:

- 1) Synthesize the key scientific outcomes from SAFOD science
- 2) Review the data/techniques that formed early predictions for the SAFOD project and their correctness
- 3) Develop a plan to apply SAFOD data to existing concerns surrounding earthquake hazard along creeping faults and the physics of earthquake nucleation. Such a development would also consider possible future research utilizing SAFOD data and the SAFOD facility.

DRAFT: Earthquake Nucleation and Rupture at Unprecedented Detail

Rachel E. Abercrombie^{1a}, William L. Ellsworth²

²1. *Department of Earth & Environment, Boston University, Boston MA*

2. *Department of Geophysics, Stanford University, Stanford, CA, USA*

Monitoring earthquakes in the near field to improve understanding of earthquake nucleation and rupture was one of the two primary aims of SAFOD. Here we summarize the data acquisition, the analysis and results, the ongoing work, and suggest future directions.

The new seismic data acquired for SAFOD included increased local monitoring, as well as downhole instrumentation. The preparation for drilling the SAFOD holes included dense temporary surface deployments that greatly improved knowledge of the local velocity structure and earthquake locations – essential pre-requisites for more detailed earthquake source analysis. Also, two new permanent stations were added to the local, shallow-borehole, High Resolution Seismic Network (HRSN); the HRSN provides 30 years of high-frequency recording, enabling unprecedented long-term analysis of how seismicity and earthquake source processes vary with time. A string of instruments deployed at 32 depths in the Pilot Hole (PH), was followed by multiple deployments in the Main Hole (MH) and these have provided some of the shortest distance recordings of natural earthquakes (Zoback *et al.*, 2011). These include events in the three repeating sequences of M~2 earthquakes targeted by SAFOD, as well as members of other nearby similar repeating sequences. These different SAFOD seismic data have been used in many studies of earthquake rupture at Parkfield.

Imanishi & Ellsworth (2006) used the seismic array installed in the SAFOD PH to calculate the stress drop of over 30 small earthquakes, including ones in the repeating sequences targeted by SAFOD. Using the wide bandwidth, high frequency data they showed that small repeating earthquakes have similar source duration and stress release to more typical tectonic earthquakes, and that the moment-independent source scaling established for larger earthquakes holds down to earthquakes M<0. This work was only possible because of the low noise, low attenuation and high sample rates (2000 s/s) of the deep borehole data.

The repeating sequences targeted by the SAFOD drilling have been the subjects of further analysis by different groups. Dreger *et al.* (2007) used HRSN data to estimate the slip distributions of earthquakes in the M2.1 (SF) repeating sequence; they concluded that patches of relatively high slip and stress drop occurred within regions of more typical average stress drop. Abercrombie (2014) investigated whether the HRSN data could resolve temporal variation in the stress drop of the three targeted repeating sequences. She found that the largest sequence (SF) showed a clear decrease in stress drop following the M6 2004 Parkfield earthquake, and then a gradual recovery (Figure 1a). The M2 (LA) sequence revealed complex sources showing that small earthquakes exhibit spatially varying slip; Figure (1b) shows a nearby complex M2.7 earthquake. The smallest M sequence showed similar temporal behavior to the first, but limited by the resolution of the data. Kim *et al.* (2016) confirmed the results of Abercrombie (2014) for the M2.1 repeating sequence. Abercrombie (2015) used both HRSN and SAFOD PH data to investigate the resolution limits of small earthquake analysis. Progressively decimating the high frequency SAFOD PH data revealed the relatively poor resolution of surface, and even shallow borehole data, providing useful constraints for studies where no deep borehole data are available.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

Ongoing work is using the near-field deep SAFOD MH recordings to study the smallest earthquakes on the SAF, to characterize the microseismicity, and probe the earthquake nucleation process. Theoretical models of earthquake nucleation include a minimum source dimension and so the near-field SAFOD recordings provide an opportunity to constrain this. Over 6 months, 120 earthquakes, $M_w \geq -2.0$ were detected within 1 km by a seismometer installed in the SAFOD MH, 2550 m below the surface. These earthquakes exhibit a linear Gutenberg-Richter frequency-magnitude relation for $M_w \geq -0.5$. Below $M_w -0.5$, however, the G-R relation breaks down, as too few events were detected. Initial tests suggest the breakdown is not an artifact of incomplete detection of events, but rather reflects a change in earthquake population statistics. Combining the observed seismicity distribution with in-situ measurements of stress at SAFOD, statistical modeling suggests the nucleation size for dynamic rupture could be of the order of a meter at this location (Ellsworth, 2018). The high-frequency near-field recordings from the main hole can constrain the initial acceleration of the dynamic rupture with unprecedented resolution (Figure 1c).

In summary, SAFOD monitoring is enabling us to move beyond previous resolution limits and investigate earthquake rupture, source heterogeneity and nucleation in unprecedented detail.

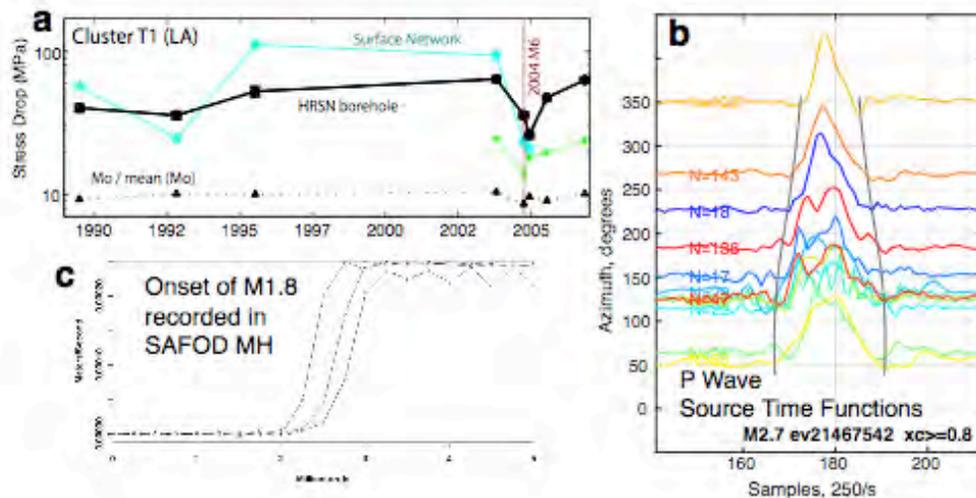


Figure 1: (a) Stress drop varying with time in LA Target Sequence; (b) Evidence for source complexity, subevents and directivity in a M2.7 earthquake, and (c) Fast onsets of a M1.8 recorded at 150 m distance.

- Abercrombie, R. E., 2015. Investigating Uncertainties in Empirical Green's Function Analysis Earthquake Source Parameters, *J. Geophys. Res.*, doi:10.1002/2015JB011984.
- Abercrombie, R. E., 2014. Stress Drops of Repeating Earthquakes on the San Andreas Fault at Parkfield, *Geophys. Res. Lett.*, 41, 8784–8791, doi:10.1002/2014GL062079.
- Dreger, D., R. M. Nadeau, and A. Chung (2007), Repeating earthquake finite source models: Strong asperities revealed on the San Andreas Fault, *Geophys. Res. Lett.*, 34, L23302, doi:10.1029/2007GL031353
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- Imanishi, K., and W. L. Ellsworth, (2013) Source Scaling Relationships of Microearthquakes at Parkfield, CA, Determined Using the SAFOD Pilot Hole Seismic Array, *Earthquakes: Radiated Energy and the Physics of Faulting*, (81-90).
- Kim, A., D. S. Dreger, T. Taira, and R. M. Nadeau (2016), Changes in repeating earthquake slip behavior following the 2004 Parkfield main shock from waveform empirical Green's functions finite-source inversion, *J. Geophys. Res. Solid Earth*, 121, 1910–1926, doi: 10.1002/2015JB012562.
- Zoback, M.D.; Hickman, S.H.; Ellsworth, W.L.; SAFOD Science Team (2011): Scientific Drilling Into The San Andreas Fault Zone - An Overview Of SAFOD's First Five Years. -doi:10.2204/iodp.sd.11.02.2011, Scientific Drilling 11 14-28.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

Sampling and Current Status of the SAFOD Core

Kelly K. Bradbury^a and James P. Evans^a

^aUtah State University, Dept. of Geology, Logan, UT 84322

In 2007, ~40 m of whole rock core was collected across an actively creeping trace of the San Andreas Fault as part of Phase 3 of the San Andreas Fault Observatory at Depth (**SAFOD**) Borehole, one of Earthscope's three main facilities. Every centimeter of this extremely valuable SAFOD core represents a rare view into an active plate boundary fault at ~3 km depth. Thus, it is critical to rigorously and comprehensively examine the core in order to decipher the processes that influence seismic slip and aseismic creep. While *in situ* SAFOD samples have revealed much about the nature of the San Andreas Fault, to date, a systematic analysis of micro-scale composition, structure, and geochemical alteration of the entire Phase 2 and 3 cores remains incomplete. In addition to the core, well cuttings and associated wireline log analyses provide insights into the nature of the fault and related damage zone near where small earthquakes nucleate, and perhaps reveal evidence for mechanisms of fault creep.

As EARTHSCOPE reaches its end, we aim to complete an integrated, robust analysis of the core, address several of the key questions posed in the SAFOD effort, collate the key results of research performed on the core and cuttings, and we hope, to develop new questions that utilize the rocks sampled in the SAFOD borehole. New insights into fault zone behavior(s) based on theoretical, laboratory, *in situ*, and exhumed analogs suggest that the community conduct new structural and geochemical analyses, and reevaluate previously collected data and interpretations to address questions that were not posed at the onset of the SAFOD planning process nearly 25 years ago. Our group at Utah State University (USU) is focused on studying the structural and permeability architecture at SAFOD, and in fault zones more broadly, through the examination of variations in composition, microstructures, deformation mechanisms, physical rock properties, and mineralogical alteration and geochemical signatures of fluid-rock interactions.

The SAFOD core is currently housed at the IODP Gulf Coast Repository (GCR) at Texas A&M. A new digital core viewer is accessible and contains the original core images, current state of the core images, and histograms of the remaining core quantities for each core section. At least 25% of each core section is preserved and saved for archiving. We hope to work with all current and past PIs and active research groups of core and cuttings analyses projects in order to integrate previous and new analyses to recognize patterns within the fault structure, fluid-rock interactions, and rock properties that relate to the larger context of understanding active fault zone processes and to contribute to the development of more realistic constraints on earthquake source physics within active faults.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

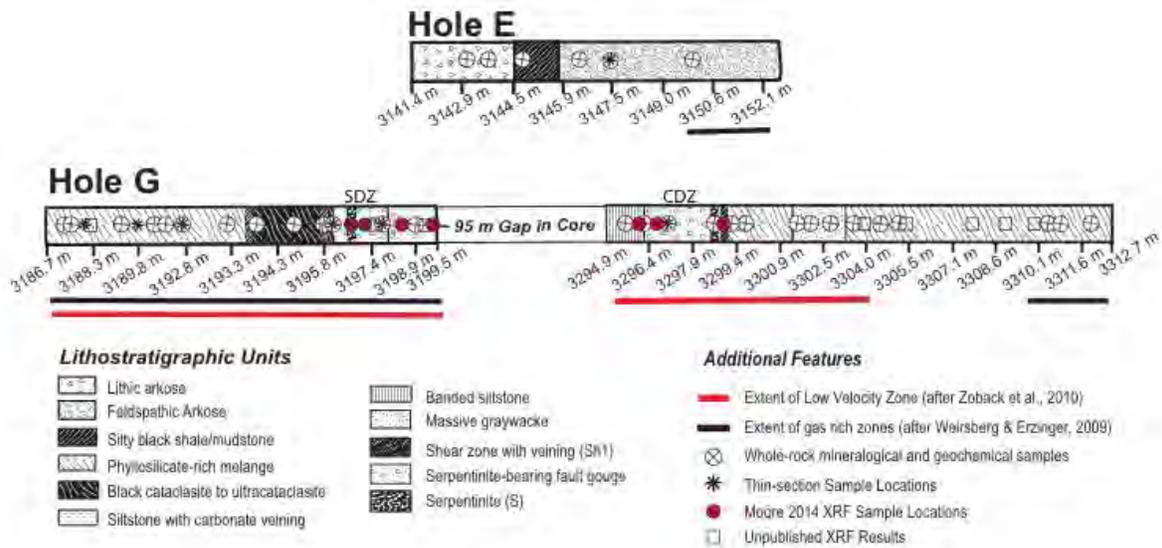


Figure 1. Lithologic Units and Structure of Phase 3 core identified previously with current mineralogical and whole-rock geochemical sampling locations noted.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

STRUCTURAL AND GEOCHEMICAL ANALYSES OF SAFOD CORE

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We examined rock composition and properties from SAFOD using the available range of cuttings, sidewall cores, whole-rock core, and downhole geophysical logging data from the SAFOD Scientific Borehole. The main focus of our on-going work has been to characterize the *in situ* composition and structure of the whole-rock core obtained in 2007 during Phase 3 drilling to further the understanding of the subsurface structure and physical and chemical processes that may occur in the San Andreas Fault at depth.

The SAFOD core continues to provide a rare opportunity to rigorously examine *in situ* fault-rock samples. Our recently funded Earthscope project involves the systematic integration of microscopy and geochemistry, which enables us to understand structural diagenesis in dynamic, complex, and heterogeneous fault zones. Remnants of extensive alteration during fluid-rock interactions, and complex microstructural changes during deformation are difficult to resolve without diverse techniques at various scales. Our proposed interdisciplinary approach uses high-resolution microscopy, geochemistry, and evaluation of rock properties spanning a wide range of scales and methods and will further contribute to our ability to decipher the physio-chemical processes that influence slip and fluid migration at the microscopic scale in faults.

New directions for our research using the SAFOD whole-rock core aim to: 1) examine the mechanisms of deformation and slip localization, the grain- to fault-scale nature of fluid-rock interactions within the fault zone; 2) to determine the origin, nature, and role of carbonaceous matter in the fault zone; 3) test our hypothesis that the carbon-bearing fault rocks may serve as indicators for earthquake induced fluid migration and may influence slip weakening and localization; 4) couple new results on fault zone composition and structure with borehole-based data to assist in refining the elastic properties of the fault zone, to examine the nature and significance of time-dependent chemical and physical fault zone processes, and to relate the material properties to key elastic parameters that affect the energy distributions in and near fault zones; 5) Identify the nature of protolith compositions and microstructures; and 6) synthesize our new results and re-evaluate all published and accessible results by numerous research groups related to the geology, geochemistry, and rock properties of SAFOD to develop a more comprehensive compositional database and refined subsurface model of fault zone structure and permeability architecture.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

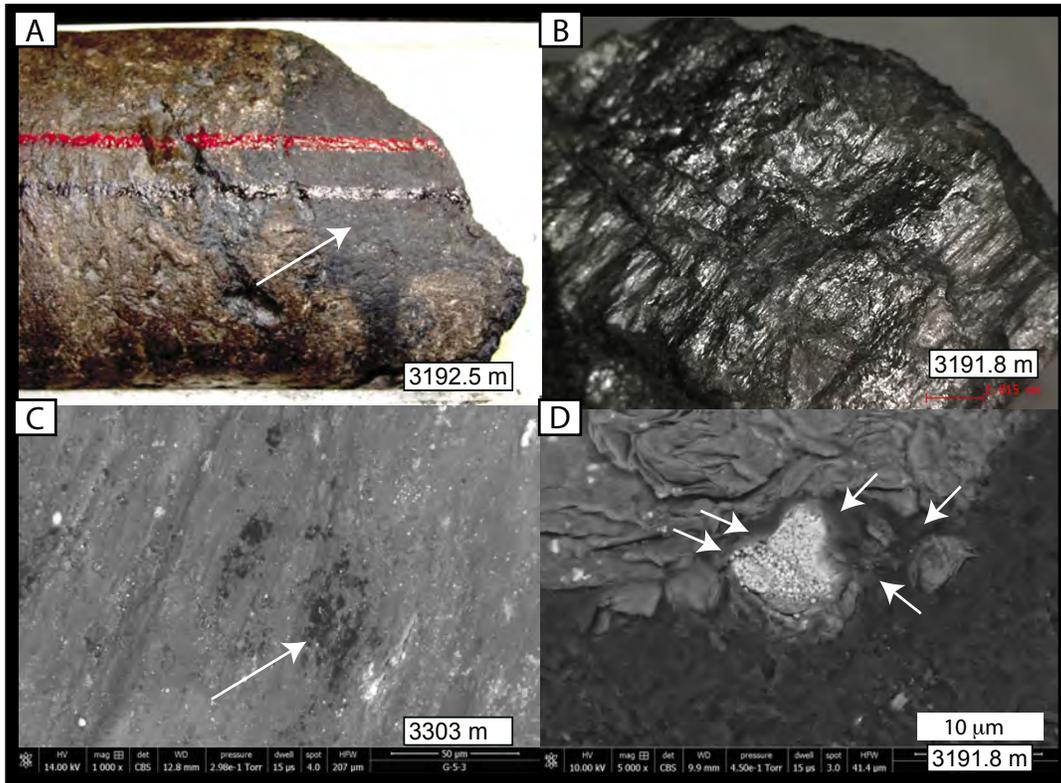


Figure 1. A current focus of our research involves the micro-scale examination of carbonaceous matter identified at several localities within the SAFOD core: A) Black carbonaceous matter adjacent to fractures at 3192.5 m MD; B) Slip surface at 3191.8 m MD with 1.22 wt.%TOC; C) SEM image of slip surface on a rock chip sampled at 3303 m MD where nearby samples have 1.5 – 1.9 wt. % TOC; and 4) Pyrite framboid enveloped by carbonaceous-rich matter and scaly clays at 3191.8 m MD.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predications, Key Results, and Future Directions

**Capturing the Seismic Cycle: Installing a Seismic
and Geodetic Observatory Directly within an Earthquake Nucleation Patch**

Brett Carpenter^a, Judith Chester^b, Stephen Hickman^c, Jeff McGuire^d, Clifford Thurber^e, and Hiroki Sone^f

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Sampling, down-hole measurements and instrumentation of active faults at seismogenic depths throughout the world have produced significant advances in our understanding of fault zone evolution, structure, composition and mechanical behavior. These efforts have advanced our understanding of the physics of faulting and earthquake generation by addressing the following key questions of Earthscope, GeoPRISMS, ICDP, IODP and US Scientific Drilling: *How do earthquakes start, propagate and arrest? How do fault zone structure and composition evolve over time, including during the seismic cycle? What is the absolute strength of faults? What are the mineralogy, deformation mechanisms and constitutive properties of fault rocks? What are the processes that lead to spatial and temporal variations in slip behavior, including the transition from creeping to locked (seismogenic) behavior? What are the physical and chemical processes that control faulting and earthquake recurrence?* These questions are especially relevant for large, plate-boundary faults capable of producing damaging earthquakes. It is critical that future SAFOD drilling builds off previous efforts and bridges the gaps that remain in our understanding of fault-slip behavior over all spatial and temporal scales.

In light of the above, future SAFOD drilling should target one of the accurately located, repeating seismogenic (nucleation) patches at the well-characterized SAFOD site where new observations from recovered material, downhole measurements and monitoring can be directly compared to previous studies. Only by studying the composition, properties and in-situ behavior of a known seismic patch through multiple earthquake cycles can we begin to tie laboratory data and rupture dynamics models to observations of fault behavior. The SAFOD borehole (Fig 1.) provides one of the best and only opportunities to sample a repeating earthquake nucleation patch, located within an otherwise creeping segment of the San Andreas Fault (SAF). In this region, three repeating microearthquake clusters are located in the vicinity of the borehole (Fig. 1), with the Hawaii cluster located ~100 m beneath the main SAFOD borehole and within reach of a multilateral core hole. Although the original intent of SAFOD was to core through both the creeping SAF and one of these repeating microearthquakes, drilling difficulties only allowed for the completion a core hole and installation of the SAFOD observatory in the creeping fault. The extensive work completed to date has defined the geophysical and geologic conditions in the SAFOD borehole and surrounding region to an unprecedented extent, and through exhaustive studies of SAFOD downhole measurements and recovered core, led to fundamental discoveries about fault zone structure and evolution and the physical and chemical processes responsible for fault creep. The existing SAFOD borehole has also enabled near-field observations of these repeating microearthquakes using removable seismic instruments, which made it possible to define the locations and rupture properties of these events to an extent heretofore impossible.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predications, Key Results, and Future Directions

We propose that an additional multilateral borehole be drilled off the main SAFOD borehole to penetrate the Hawaii repeating earthquake patch. Before such a project can be undertaken, however, a multi-level seismic array should be installed in the current SAFOD borehole to total depth. This array would allow for wide-aperture observations and accurate absolute location of the HI target earthquake, as needed to ensure that a new multilateral core hole would penetrate the seismogenic rupture patch. Sampling of fault and country rocks, downhole measurements and long-term fluid pressure, deformation and seismic monitoring within this new multilateral would provide unique information on the composition, physical properties and deformational behavior of a repeating earthquake patch, for direct comparison with similar samples and observations already obtained in the creeping SAF directly overhead. With the infrastructure now in place from SAFOD, we could then test numerous hypotheses explaining the existence of these isolated, repeating earthquakes within the San Andreas Fault zone. Previous studies suggest that these repeating microearthquakes may reflect variations in fault zone geometry/width, fault-gouge composition and/or fluid pressure. The opportunity to penetrate, sample and instrument a repeating earthquake-generating patch from SAFOD would allow us to realize one of the original goals of SAFOD and EarthScope, providing an unprecedented window into the SAF and enabling us to answer fundamental answers about the physics and chemistry of earthquake generation

References: Hickman et al., (1995), *EOS* 75:137; Collaborative Research: Earthscope-Acquisition, Construction, and Facility Management – *MREFC Proposal* 2003; Hickman et al., (2004), *Geophys. Res. Lett.* 31:L12S01; Tobin et al., (2006), *Scientific Drilling* 1:5; Walton et al., (2009) *DOSECC Workshop Publication* 1:35; M. Zoback et al., (2011), *Scientific Drilling* 11:14; http://www.icdp-online.org/front_content.php?idcat=310; <http://www.geoprisms.org/deformation-geodynamics.html>;

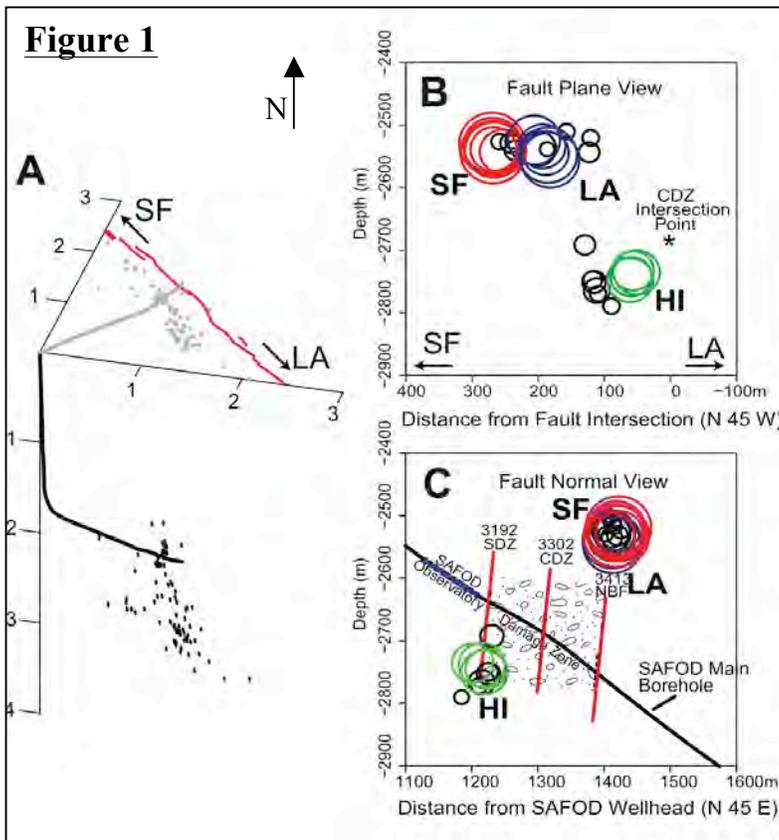


Figure 1: Repeating earthquake clusters in the SAFOD target zone. (A) Three-dimensional view of the volume surrounding the SAFOD borehole, with microearthquakes shown as black dots. Axes are in km. (B) Location of repeating microearthquakes within the plane of the SAF, showing the borehole intersection point (asterisk). The three patches, SF-San Francisco, LA-Los Angeles and HI-Hawaii, produce regular and nearly identical microearthquakes (M~2) every few years. (C) Cross-sectional view of the same microearthquake clusters looking parallel to the SAF. The two active fault traces that deform the SAFOD wellbore are the Southwest Deforming Zone (SDZ) and the Central Deforming Zone (CDZ). The HI cluster occurs on the downward extension of the SDZ about 100 m below the borehole whereas the LA and SF clusters appear to occur on the upward extension of the NBF. The SDZ and Northern Boundary Fault (NBF) mark the edges of the SAF damage zone (Zoback et al., 2011).

The Search for Coseismic Slip in SAFOD using Biomarker Thermal Maturity

Genevieve L. Coffey^a, Heather M. Savage^a, Pratigya J. Polissar^a

^aLamont Doherty Earth Observatory, Columbia University, Palisades, New York 10964

Faults exhibit a range of different deformation styles from slow aseismic creep to fast earthquake slip. Creeping faults are thought to be unable to nucleate large earthquakes, but what remains less clear is whether large earthquakes initiating elsewhere can propagate through these stable sections of a fault. This is of particular importance along the San Andreas Fault, where the locked northern and southern sections flank the central, creeping section. Determining whether an earthquake can rupture into the central San Andreas fault has significant implications for earthquake hazard in California. SAFOD has provided us with a valuable opportunity to search for evidence of coseismic slip within rock from the central San Andreas Fault.

We can determine where coseismic slip has occurred by looking for evidence of temperature rise. During an earthquake, work done to overcome frictional resistance can lead to the generation of very high temperatures. Temperatures reached during slip depends on various fault and earthquake properties, allowing us to not only use temperature rise to identify where an earthquake has occurred, but also to better understand aspects of earthquake properties like energy dissipation. Here we use biomarkers to identify regions that have experienced coseismic heating within SAFOD. Biomarkers are organic molecules produced by living organisms that accumulate in sediments over time. They are useful as paleothermometers because when heated, their structure is systematically altered to more stable configurations. This allows us to use the ratio between stable and unstable biomarkers to quantify thermal maturity of the sediment and model temperature rise.

Biomarker thermal maturity analysis was completed on a total of 40 samples from SAFOD, over two stages. Initially samples were collected at regularly spaced intervals along the core, including the two actively deforming zones, in order to gain an understanding of the background thermal maturity and identify any regions of interest. A region of high thermal maturity was observed immediately west of the southern deforming zone (3193 – 3196.5 m) and during the second stage of sampling we focused on more densely sampling that region. This region of high thermal maturity spans a width of 3.5 m and drops back down to background maturity abruptly to the west and into the southern deforming zone towards the east. This region was previously identified through structural analysis as a particularly deformed, indurated section of the core (Bradbury et al., 2011, Holdsworth et al., 2011).

Given the width of the thermal maturity anomaly, as well as results from previous studies that demonstrate that coseismic heating is localized along very narrow layers, our results suggest that the core at SAFOD has hosted multiple earthquakes. Future work on refining earthquake temperatures and slipping zone thickness will help us determine whether these earthquakes reflect intermediate-sized events like the Parkfield earthquake that rupture a small part of the creeping section or larger events. Furthermore, future work will also focus on ruling out other sources for the maturity anomaly, namely migrated petroleum and hydrothermal fluids.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

Distributed Acoustic Sensing of the Seismic Wavefield at SAFOD
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An OptaSense Distributed Acoustic Sensing (DAS) model ODH3.1 was used to record local, regional and teleseismic earthquakes for one month at SAFOD using an optical fiber cemented behind casing. The fiber was interrogated between the surface and 800 m depth (top of basement). With this recording geometry, the DAS system captures the full vertical wavefield between the basement interface and free surface, revealing direct, converted and refracted waves. Both P- and S- strain waves are clearly visible in the data. The main borehole at the San Andreas Fault Observatory at Depth (SAFOD) contains optical fibers cemented in place in between casing strings from the surface to just below the top of the basement. The fibers are under tension of approximately 1 N and are housed in a 0.9 mm diameter stainless steel tube. Earth strain is transmitted to the fiber by frictional contact with the tube wall. One fiber has been in use as a vertical strainmeter since 2005, measuring the total strain between 9 and 740 m by laser interferometry. The OptaSense DAS laser interrogator measures the strain over a gauge length with a set spacing between gauge intervals. For this experiment we set the gauge length to 10 m with 1 m spacing between gauges. Including the surface run of the fiber, this gives us 936 channels measuring the vertical strain at a sample interval of 0.4 msec (2500 samples/s). The incident and surface reflected wavefields can be separated by frequency-wavenumber filtering due to the large-aperture and fine spatial and temporal sampling. Up- and downgoing strain waves illuminate the subsurface within the sensor array's depth range. Accurate arrival time determinations of the initial arrival phase are possible due to consistent wave forms recorded at 1 m spatial intervals that can be used for fine-scale shallow velocity model estimation.

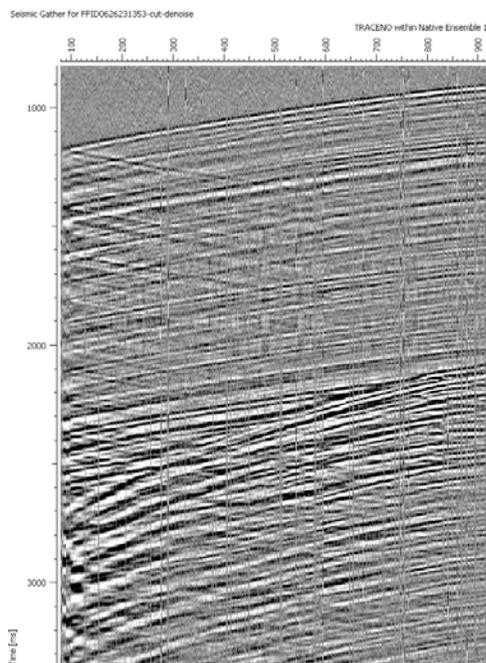


Figure shows seismic wavefield recorded by the DAS for a M 1.5 earthquake located almost directly beneath SAFOD at a depth of 15 km. The horizontal axis is distance along the fiber in meters with the surface at the left and bottom at the right. Time in milliseconds increases from top to bottom. Note the surface reflections from the first arrival P-waves and P-wave coda. Note also the S-to-P conversion at approximately 800 m distance. Note also the complexity of the S-wave and early coda, particularly at and near the surface.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

Insights into Hydrologic and Thermal Conditions within the San Andreas Fault from the SAFOD project and Associated Studies

Patrick Fulton

A major scientific motivator of the SAFOD project was the potential to resolve questions regarding the San Andreas stress / heat flow paradox, a long-standing conundrum associated with stress and heat flow observations and the long-term shear strength of the San Andreas Fault. The paradox is founded upon two sets of observations along the San Andreas Fault: First, a lack of a pronounced heat flow anomaly across the fault from frictional heating, suggesting the fault slips with an average friction coefficient < 0.2 , far less than laboratory-derived estimates of static friction at the time and measurements of absolute stress in deep-boreholes suggestive of values closer to ~ 0.6 [e.g., Brune, 1969; Henyey and Wasserberg, 1971; Lachenbruch and Sass, 1980]. And secondly, the orientation of the maximum principal stress in the crust adjacent to the San Andreas fault inferred from inversions of earthquake focal mechanisms or directly from borehole breakout measurements is at a very high angle to the fault in central California. This implies that the active fault zone must be a very weak plane relative to the surrounding crust [e.g., Mount and Suppe, 1987; Zoback et al., 1987]. Together these observations have led to the hypothesis that the San Andreas Fault is frictionally weak, supporting very low shear stresses.

Provocative arguments, however, were made suggesting that these observations were misinterpreted and that the San Andreas could indeed be strong such it has high friction and supports large shear stresses [Scholz, 2000; Scholz and Hanks, 2004]. Scholz [2000] argued that the fault could be as strong as predicted with friction near 0.6, but that the stress orientation data are affected by effects of regional fold structures that have subsequently been rotated relative to the strike of the SAF in Central CA or are affected by the effects of adjacent subsidiary faults, as in the case of the Cajon Pass borehole measurements. With regards to the heat flow data, the hypothesis was made that the long-term conductive heat signal from millions of years of frictional heating during slip could perhaps be washed away by fluid advection, particularly that resulting from topographically-driven groundwater flow away from the fault zone.

In preparation and anticipation for SAFOD drilling, a concerted effort was made to reanalyze the available data and assess these arguments. On the thermal side, efforts were made to reprocess the original raw temperature-depth data from a variety of studies around the Parkfield area around the SAFOD site and re-compute heat flow data considering full 3D terrain corrections including the effects of solar insolation now possible with modern computers and digital elevation maps [Fulton et al., 2004; Williams et al., 2004]. The reanalysis ensured that the data were all processed in a similar manner and allowed for error bars to be considered based on available thermal conductivity data. The results reduced the scatter amongst the data but still did not result in a resolvable near fault anomaly. In addition, numerical modeling studies were conducted to test the hypothesis of whether topographically-driven groundwater flow

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

could reasonably wash away or obscure the frictional heat signal from a strong SAF considering the available data, particularly around the SAFOD site in Parkfield [Saffer et al., 2003; Fulton et al. 2004; Popek and Saffer, 2011]. In short, no; groundwater flow cannot explain the lack of a frictional heat signal. Trends in heat flow versus elevation constrain the amount of topographically driven groundwater flow to models that are unable to obscure the heat signal from a strong fault and are most consistent with very little to no long-term frictional heat generation on the fault [Saffer et al., 2003; Fulton et al. 2004; Popek and Saffer, 2011]. Simulations that could perhaps allow for the advective disturbance of frictional heat require large recharge rates and produce spatial variations in heat flow far beyond those observed in the data [Fulton et al., 2004].

Fulton and Saffer [2009a] also evaluated the effects of uncertainties in assumptions regarding the regional background heat flow and conductive effects resulting from thermal conductivity contrasts. That study found that much of the remaining scatter in the data after terrain corrections could potentially result from thermal refraction effects, but that these effects too would not hide the signal expected from long-term frictional heating along a strong fault.

Together these studies, and others that evaluate the potential effects of buoyancy driven fluid flow [Williams and Narisimhan, 1989] reject the hypothesis that either advection or conductive refraction effects are able to easily obscure the signature of a strong SAF in a manner consistent with the available observations. New heat flow measurements in the SAFOD pilot and main holes, at depths much greater than most of the other data in the region and very close to or within the fault zone, are also most consistent with models with a weak rather than a strong fault [Williams et al., 2004; 2005].

Meanwhile, on the mechanical side, Townend and Zoback [2001] conducted careful focal mechanisms inversions of maximum principal stress direction in Central and Southern California. When compared with borehole breakout data from existing wellbores they show consistently high angles between the maximum principle stress and the San Andreas fault far beyond the theoretical lock-up angle of 60° and as high as 85° in some areas [Townend and Zoback, 2004]. These steep orientations were later confirmed by borehole breakout data and other inferences of stress orientation from the SAFOD pilot and main boreholes very close to the fault further suggesting that the fault acts as a weak plane within a strong crust [Hickman and Zoback, 2004; Zoback and Hickman, 2005; Boness and Zoback, 2006].

The SAFOD project has led to a better recognition and understanding that the SAF indeed does act as a weak plane within a stronger crust. The question therefore has now focused on “why?” Possible explanations may involve either low friction material or high pore fluid pressures localized within the fault zone, or perhaps a combination of both [Rice, 1992; Fulton and Saffer, 2009; Tembe et al., 2009]. From a hydrologic point of view, high pore pressures at first seemed unreasonable, as the steep stress orientations require large localized pore pressures with pore pressure values greater than lithostatic values. Rice [1992] however presented a theoretical model for how fault zones may allow for such a scenario without hydrofracture due to

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

differences in rheologic properties within the fault core causing the fault core to experience both increased total stresses and reduced differential stress. Faulkner et al., [2009] later illustrated this mechanism considering variations in elastic properties consistent with values obtained from fault damage zones and laboratory measurements.

As the SAFOD project progressed forward, core samples provided insight into potential geologic and frictional controls on the strength on the fault, while efforts to understand whether large localized pore pressure could potentially be generated and sustained within the SAF were also tested. Rice [1992] proposed a potential means for creating large localized overpressures within the fault zone by having low permeability crustal rocks trap large fluid pressures at depth and pressure-dependent permeability within the fault zone allowing for these high pressures to propagate up a fault acting as a permeable conduit such that the fault zone conduit would transiently maintain large localized pore pressure.

In practice, a fault acting as conduit all the way to the surface drains fluid pressures and does not easily localize excess fluid pressures [e.g., Fulton et al., 2009]. In addition, observations directly from the SAFOD main hole and surroundings find that the SAF around Parkfield tends to act as a barrier to fluid flow, at least laterally across the fault zone. Inside the SAFOD main hole, Erzinger and Wiersberg [2007] report reduced gas flux within the fault zone suggesting that it has lower permeability. In addition, a sharp change in mantle helium content is observed across the fault with meteoric values on the SW side and increasing mantle signatures on the NE side [Erzinger and Wiersberg, 2007; Wiersberg and Erzinger, 2007], consistent with regional observations [Kennedy et al., 1997; Kharaka et al., 1999] and the fault sealing off different hydrologic regimes. Similarly, well data from both sides of the fault find a contrast in pore pressure across the fault with subhydrostatic pressures to the SW and 12 MPa of overpressure at 1.5 km depth in the Varian well 1.4 km to the NE of the fault [Johnson and McEvilly , 1995; Zoback and Hickman , 2005], which is also consistent with large-scale regional trends [Berry, 1973].

Sources of large pore pressures and mechanisms for trapping them within the fault have been long-hypothesized. For example, Irwin and Barnes [1975] on the basis of geologic mapping and the distribution of CO₂ rich springs suggested that regional metamorphic dehydration may create a fluid source that is trapped beneath the Coast Range ophiolite or other subsurface seals abutting the SAF. Fulton et al. [2009] computed theoretical fluid source estimates and evaluated the potential for overpressure development from crustal dehydration following the Mendocino Triple Junction migration and the creation of the San Andreas Fault. They found that these sources are relatively small and short-lived such that large overpressures were not generated nor maintained in numerical modeling simulations considering a range of potential fault zone architectures and hydrologic scenarios. Whereas crustal dehydration is small and short-lived, Fulton and Saffer [2009b] found a potentially large and long-lived source of fluids may result from dehydration of formerly serpentinized upper mantle following the transition from subduction to strike-slip tectonics. This hypothesis was first proposed by Kirby et al, [2002] and later expanded upon in Kirby et al. [2014]. When these fluid sources are included in fluid

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

flow and heat transport models, Fulton and Saffer find that they could create large sustained overpressures. For certain particular scenarios that may result in large localized pressures within the fault zone acting as a hydrologic barrier in a manner consistent with the range of geochemical, thermal, mechanical, and hydrologic observations from the SAFOD boreholes and surroundings.

These models are intriguing, but the question remains as to whether fluids are involved in faulting at the SAFOD site. Analysis of rock samples from SAFOD core suggest that the fault zone is very low permeability, consistent with the reduced gas flux observations and suggestions of the fault acting as a hydrologic barrier to fluid flow [Rathbun et al., 2010; Marone et al., 2010]. In addition, analysis of veins and microstructures within the SAFOD phase III cores have been interpreted to suggest evidence of repeated transient increases in pore pressure over time [Mittempergher et al., 2011]. Direct long-term measurements of pore pressure were not made in the SAFOD boreholes. The lack of observable mud kicks during drilling is often referred to as perhaps evidence suggesting a lack of overpressures within the fault [e.g., Zoback et al., 2010]. However, calculations and analysis by Wang [2011] illustrate how the signature of large overpressures would be unresolvable during drilling if the effective permeability is quite low. In addition, the modeling results of Fulton and Saffer [2009b] show that the greatest overpressures, and those that may most greatly affect the overall strength tend to develop at depths deeper than the reach of either of the two SAFOD boreholes. This result comes from the combination of likely lower permeability and a greater diffusive distance to the surface with increasing depth. Further insights into the potential role of fluids are likely to result from future borehole studies that either allow for direct constraints on hydrologic conditions or permit indirect inferences from high-resolution seismological observations of triggered tremor or other phenomena [e.g., Thomas et al., 2009].

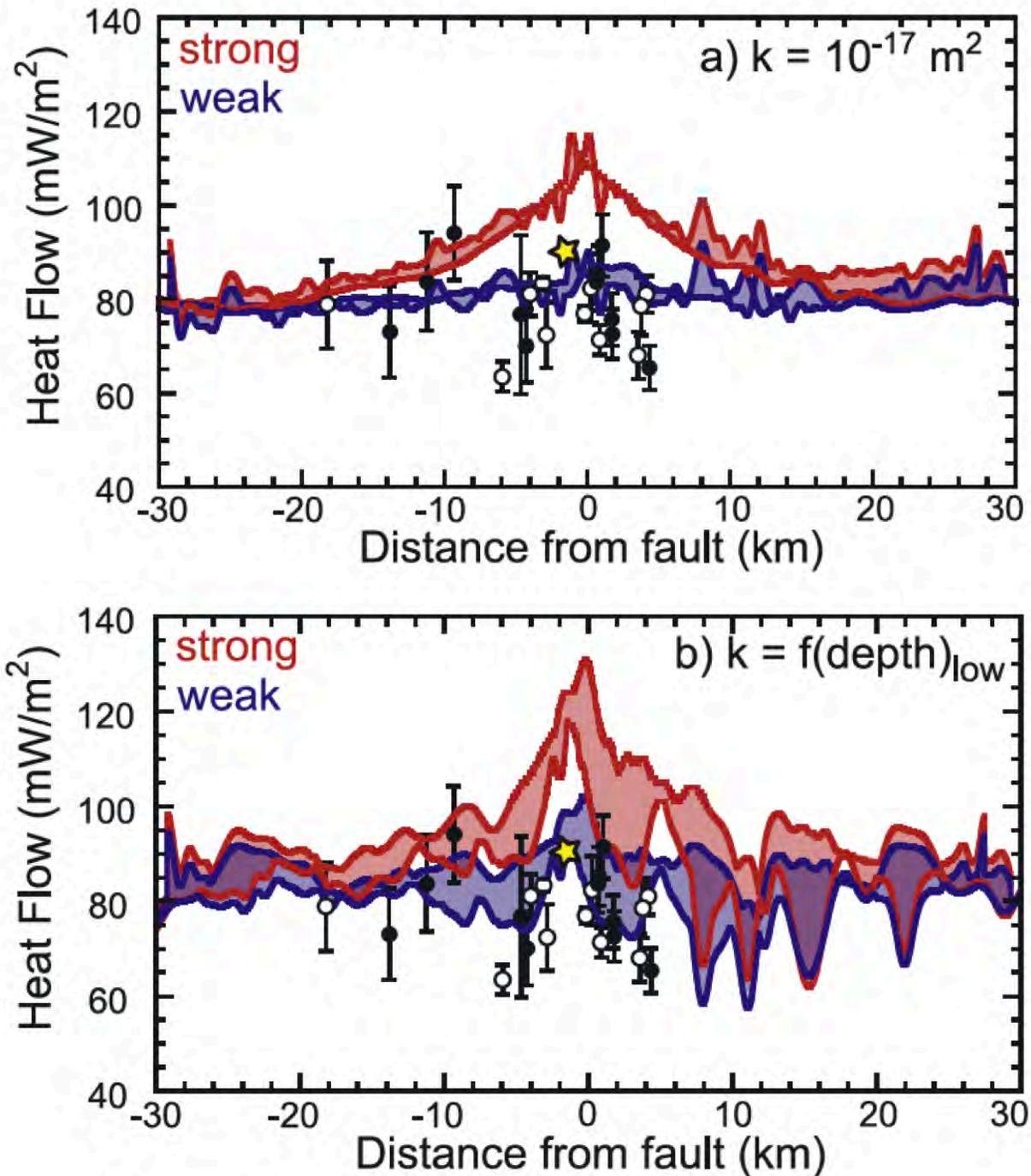


FIGURE 1: Results of numerical model evaluating the effects of long-term topographically driven groundwater flow on heat anomalies for either long-term friction of .6 (strong) or .2 (weak) illustrate how advection by groundwater flow can not explain the lack of an anomaly. More permeable (greater advection) scenarios also create variability in heat flow beyond what is observed and require large recharge rates. Adapted after Fulton et al., GRL, 2004.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

This synthesis figure from Fulton and Saffer, JGR 2009b summarizes hydrologic and geomechanical observations from the SAFOD borehole and surroundings as described above.

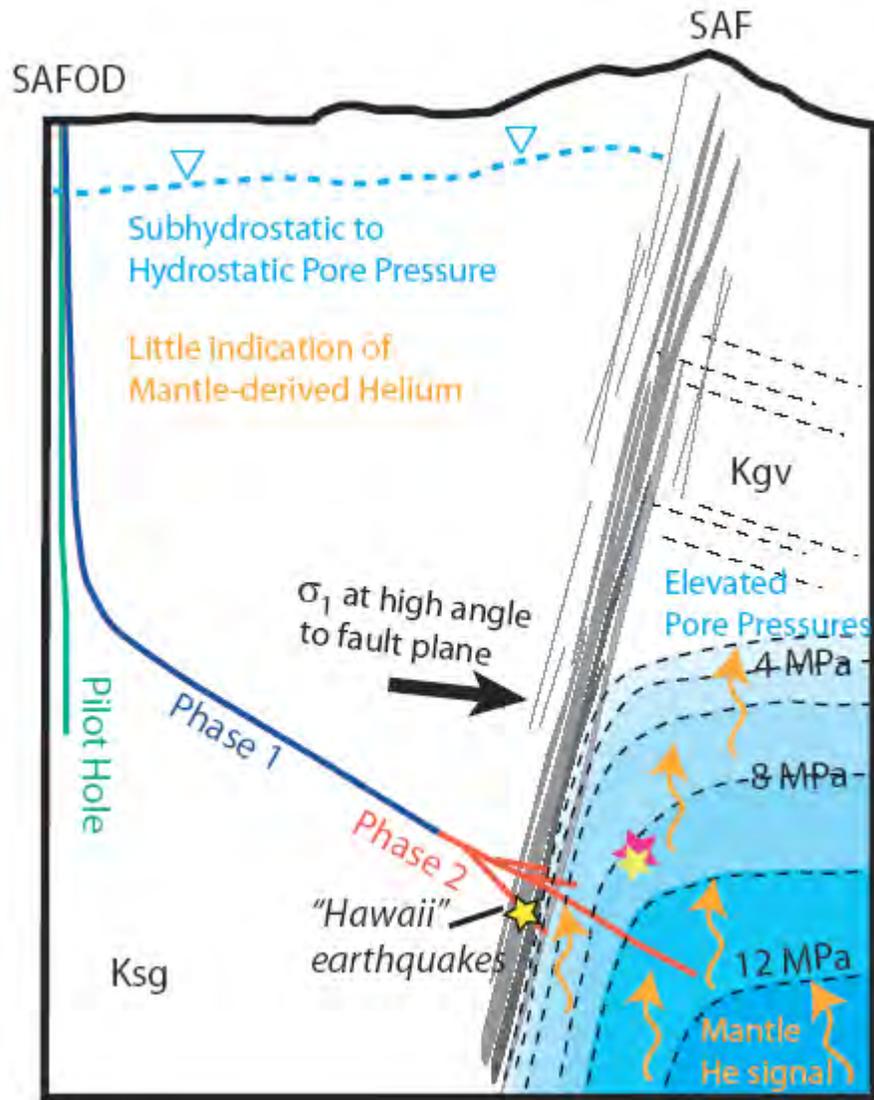


FIGURE 2: This synthesis figure from Fulton and Saffer, JGR 2009b summarizes hydrologic and geomechanical observations from the SAFOD borehole and surroundings as described within the text above.

Petrophysical properties of SAFOD cores

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Open-hole geophysical logs from the SAFOD borehole indicate there is a significant decrease in the P- and S-wave velocity and electrical resistivity from 3190 to 3414 m measured depth (MD) in the phase II SAFOD borehole due to the presence of the San Andreas fault and associated damage zone. Within this 200 m wide zone there are two narrower (2 m wide) zones where velocity and resistivity are reduced, relative to the host rock, by up to 46 % and 87%, respectively, and porosity increases from 6% to 22%. Repeated multifinger caliper logs through the borehole showed that these zones, located at 3192 m MD and 3302 m MD, are actively deforming. These zones, referred to as the southwest deforming zone (SDZ) and central deforming zone (CDZ), respectively, are interpreted to be active traces of the San Andreas fault.

Laboratory measurements of the petrophysical properties of the SAFOD phase III cores have further elucidated the properties of the San Andreas fault zone. Porosity measured on the core samples ranges from 1% to 9% in the damage zone rocks and from 6% to 15% in gouges from the actively deforming zones (Jeppson and Tobin, 2015; Morrow et al., 2015; Janssen et al., 2011). These porosity values are consistent with the porosity range recorded in the borehole porosity log but laboratory porosities tend to be lower than the log at comparable depths due to the presence of macroscale fractures in the wall rock.

Permeability in the damage zone material ranges from 10^{-18} m^2 to 10^{-21} m^2 ; it decreases to $10^{-21} \text{ m}^2 - 10^{-23} \text{ m}^2$ in the deforming zone gouges, despite the higher porosity (Morrow et al., 2015, 2014; Janssen et al., 2011). A high percentage of fine-grained clay in the gouges is the cause of the low permeability. The actively deforming segments of the San Andreas fault will act as a barrier to flow across the fault and fluid flow outside of these zones is probably fracture-dominated.

Lab-based electrical resistivity in the gouges is about 10 Ω -m and is 1 to 2 orders magnitude lower than the measurements made on the surrounding damage zone core samples (Morrow et al., 2015). This decrease in the resistivity is due to the increase in porosity observed in the gouge samples. Ultrasonic P- and S-wave velocity measurements on the gouge samples yielded average velocities of 3.1 km/s and 1.5 km/s, respectively (Jeppson and Tobin, 2015). As with the resistivity measurements, the gouge velocities are significantly lower than velocities measured in the surrounding damage zone material. This low velocity is due to alteration and mechanical deformation of host rock material leading to an increase in porosity and clay content in the gouges. Laboratory-measured velocity and resistivity in the deforming zone gouges are comparable to the log data. However, measurements on the surrounding damage zone rocks are systematically higher than the corresponding borehole log data. This difference is most probably due to the presence of open fractures in situ that are purposely avoided when collected samples for laboratory measurement. The ability to reproduce petrophysical signals observed in the SDZ and CDZ at different scales of measurements, without requiring elevated pore fluid pressures,

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

supports the hypothesis that the San Andreas fault core is intrinsically weak. However, the possibility of an elevated pore fluid pressure in the fault zone cannot be eliminated at this point.

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Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

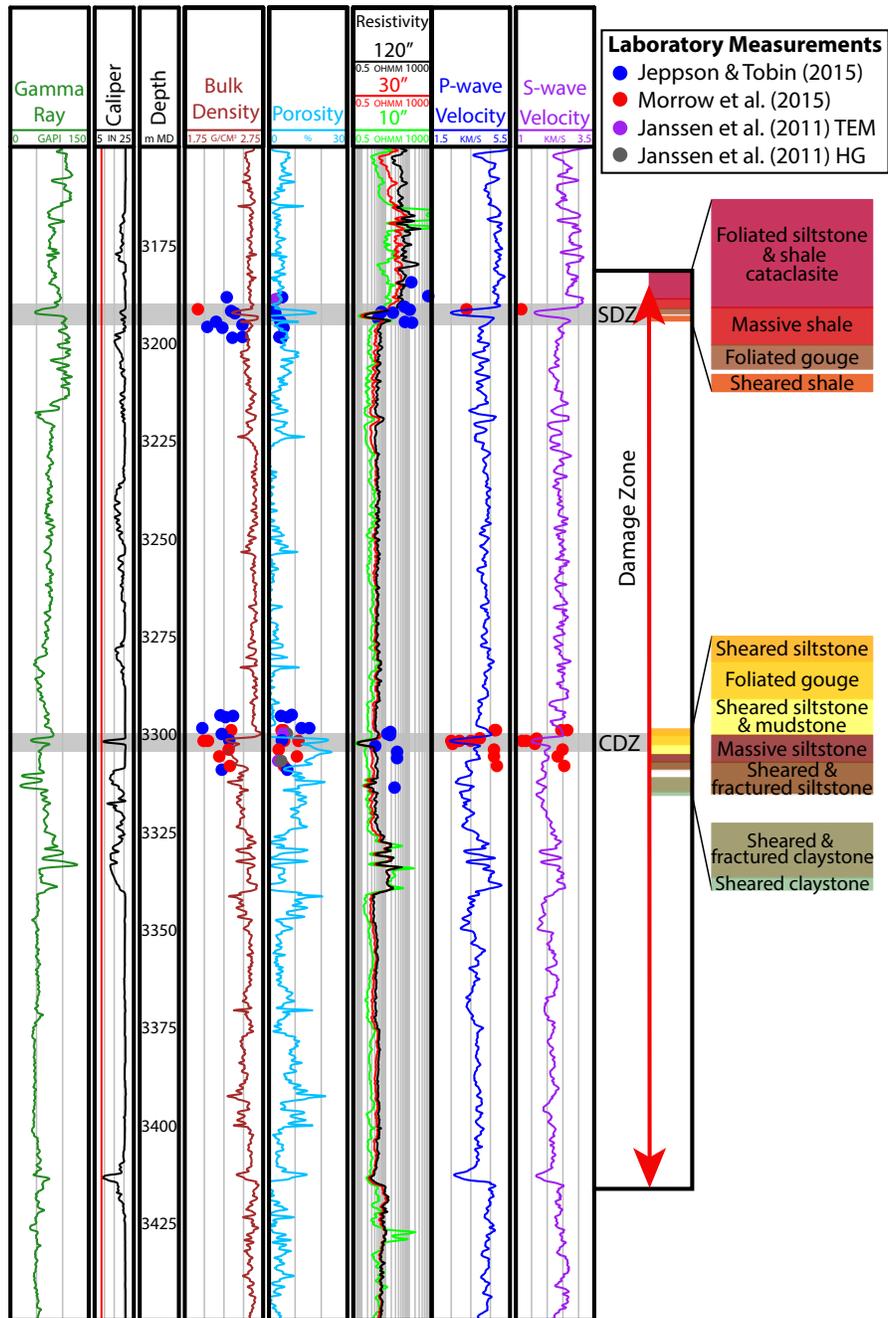


Figure 1. Composite wireline figure summarizing petrophysical measurements from borehole logs and laboratory data (circles) in the fault damage zone, as a function of measured depth in the phase II SAFOD borehole. From left to right: gamma ray, caliper, measured depth, bulk density, porosity, electrical resistivity, P-wave velocity, and S-wave velocity. Locations and lithologies of phase III core are also show. Gray shaded regions show the locations of the southwest and central deforming zones (SDZ and CDZ, respectively). Laboratory data from Jeppson and Tobin (2015), Morrow et al. (2015), and Janssen et al. (2011).

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predications, Key Results, and Future Directions

Mechanical Properties of SAFOD Core

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Recovery of deep core from the actively deforming zones of the San Andreas Fault (SAF) and adjacent rock at a depth of nearly 2.7 km represents a key accomplishment of the SAFOD drilling project. Measurement of frictional strength and other physical properties (e.g., permeability, resistivity, acoustic velocity, and composition) has provided unique constraints on deformation mechanics at this complex transition zone between creeping and locked portions of the SAF. While laboratory measurements of the core are useful by themselves, the unique contextual data available at SAFOD have been important in allowing more precise interpretations. Of particular significance is the observation in the nearby Phase 2 borehole of localized creep, identified from casing deformation, that corresponds to the two weak smectite-rich shear zones in Phase 3 core. Laboratory tests demonstrate that these deforming zones are indeed weak; coefficient of friction $\mu < 0.2$, and are significantly weaker than adjacent host rock and damage zone material ($0.3 < \mu < 0.65$). ($\mu = \tau / (\sigma_n - p)$, where τ is shear stress, σ_n is normal stress and p is pore pressure.) Thus, from direct observation of localized creep, the 1.6 m-wide southwest deforming zone (SDZ) and 2.6 m-wide central deforming zone were identified with confidence. Examination of the core shows that the SDZ occurs at the boundary between the host rock and the broad (~200 m) damage zone associated with the active trace of the SAF. The SDZ also is in apparent alignment with the nearby repeating earthquake cluster (designated 'Hawaii') that is a potential target for future drilling. While core was not recovered from the northeast boundary of the damage zone (NBF) and no casing deformation was detected, it is possible that a third deforming zone (similar to SDZ) is present along this boundary of the damage zone that would align with two other nearby repeating earthquake clusters.

Measurement of frictional strength of the SDZ and CDZ core material as a function of shear rate shows a pronounced increase in μ that is proportional to $\log(\text{velocity})$. At shear rates ranging from 0.001 microns/s (about the SAF plate rate) to 1 micron/s, $d\mu/d\log_{10}(V)$ is in the range 0.004 to 0.009. This strong rate strengthening is consistent with stable creep, a characteristic of this southern extent of the creeping zone of the SAF. However, high speed friction tests of this core material show velocity weakening at shearing rates above about 1 cm/s. This presents the possibility that a large magnitude earthquake propagating north along the SAF could potentially penetrate into the creeping zone in the SAFOD region.

Wireline logging data of velocity, electrical resistivity and density have also been important in providing context for interpretation of the physical properties of the core. Variations in these properties were essential in determining the location and extent of the damage zone following Phase 2 drilling. Then, direct measurements of velocity and resistivity on core samples showed close agreement with logging data. In particular, high fluid content and high surface conductivity of the clay component of the CDZ and SDZ resulted in prominent low resistivity signatures. These localized minima in wireline log resistivity, along with corresponding drops in wave speed, were the best indicators for identifying the narrow, clay-rich deforming zones that appear to dominate the mechanical strength of the fault zone at SAFOD.

In addition to controlling frictional strength, the high concentration of saponite clay in the CDZ and SDZ also results in extremely low permeability (10^{-21} to 10^{-22} m²) and hydraulic

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predications, Key Results, and Future Directions

diffusivity. As a result, the fault zone at SAFOD is a barrier to cross-fault fluid flow. In terms of mechanical strength, it may result in localized pore fluid over-pressure and therefore reduced effective normal stress. This property of the CDZ and SDZ has the potential to further reduce shear strength of the fault zone. Knowing the importance of trapped fluids in the fault zone and the corresponding influence on fault strength will require direct measurement of fault zone pore pressure at SAFOD.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predications, Key Results, and Future Directions

Earthquake Nucleation and Propagation at SAFOD

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One of the main reasons that the Parkfield site was chosen for SAFOD was the opportunity to sample both creeping and seismogenic fault properties from a single borehole. In this regard, initiating Phase 4 drilling into the ‘Hawaii’ repeating earthquake source is a high and obvious priority. Analysis of Phase 3 core from the active southwest deforming zone (SDZ) and central deforming zone (CDZ), as well as the host rock and damage zone rock, have provided important insights into the hydro-mechanical properties of the creeping portion of the San Andreas Fault (SAF). The CDZ and SDZ are strongly velocity strengthening and are weak. These material properties are consistent with a repeating earthquake model in which a brittle locked patch is loaded by creep of the surrounding weak fault material. Observations of shortened interevent times of repeating earthquakes following stressing of the creeping zone by the 2004 Parkfield earthquake are also consistent with this model. Outstanding questions that can be addressed by drilling into the Hawaii repeating earthquake include determination of fault zone material and hydraulic properties, presence or absence of low strength fault gouge, stress state, pore pressure and temperature before (and after!) the next earthquake. If successful, making these observations should help answer a host of long-standing questions about earthquake nucleation processes. These include

- Rupture nucleation process – stress transfer from surroundings to locked patch
- Premonitory signals (or not) – accelerating slip, pore pressure, nano?seismicity
- Rupture propagation parameters
 - fracture energy
 - heat production (measure temperature rise across fault)
 - Stress drop
 - Rupture complexity
 - Slip history and moment release
 - Seismic efficiency
 - Off-fault damage
 - Pore pressure (again)
 - Directionality
- Stopping phase
 - Arrest and post-earthquake stress field
 - Afterslip
 - Permeability structure (before and after earthquake)

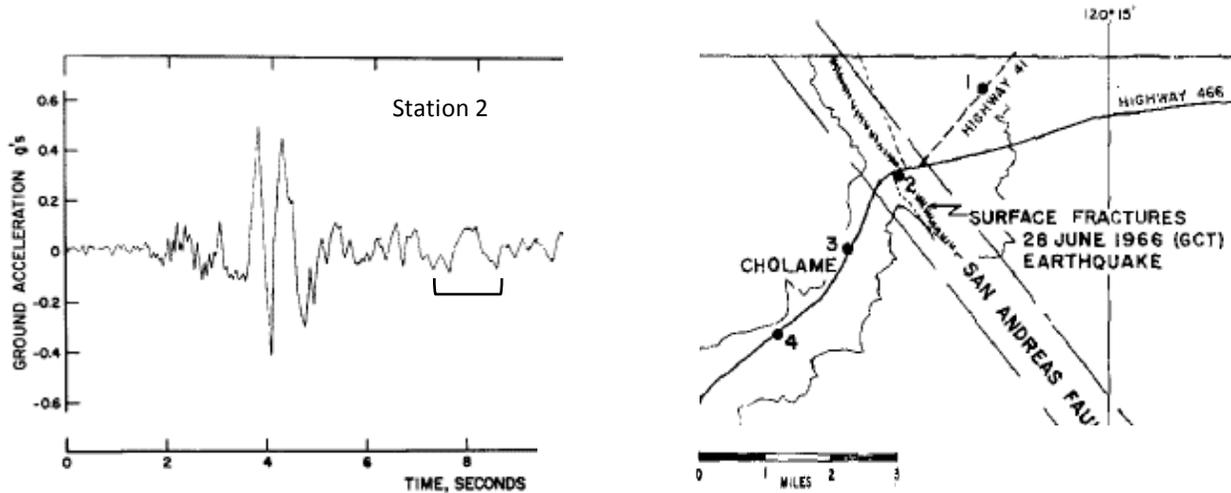
A down hole observatory adjacent to the fault should include a cross-fault creep meter, high frequency accelerometers, pore pressure sensor(s), temperature sensors and other instrumentation capable of detecting transient precursory signals. Retrieved core samples should be tested for fault frictional properties that include strength, rate-state parameters, and viscoelastic properties. Rate-state parameters can provide estimates of the critical patch size, h^* , for dynamic rupture nucleation. In this way, it may be possible to determine if rupture is best represented by a slip weakening model, a cascade-up rupture model or some other earthquake nucleation process.

Fault-zone Guided Waves and Their Implications

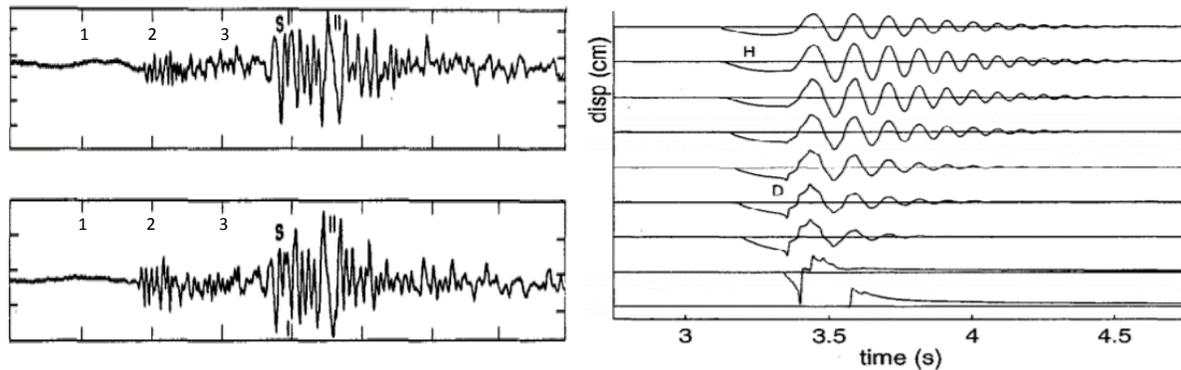
Peter Malin

SAFOD & ΣF_g @ PKF

Two years after the Parkfield 1966 Earthquake, Keitti Aki published a planar dislocation model of the strong motions observed 80 m from the surface rupture in Cholame Valley. The fit was good – for the first 5s. Twenty years later, on a visit to my home in Santa Barbara, I asked him about the signal at about 8s. He knew about it, said he tried to fit it, but to no avail.



I told him that I thought it was a seismic wave snaking along the SAF. I then showed him some seismograms from the 250m deep borehole seismic station our lab had just installed at Middle Mt. The one on the left has a late, dispersed, arrival that appears only at near fault stations. The one on the right has an early-refracted wave that appears only on the slow side of the fault.

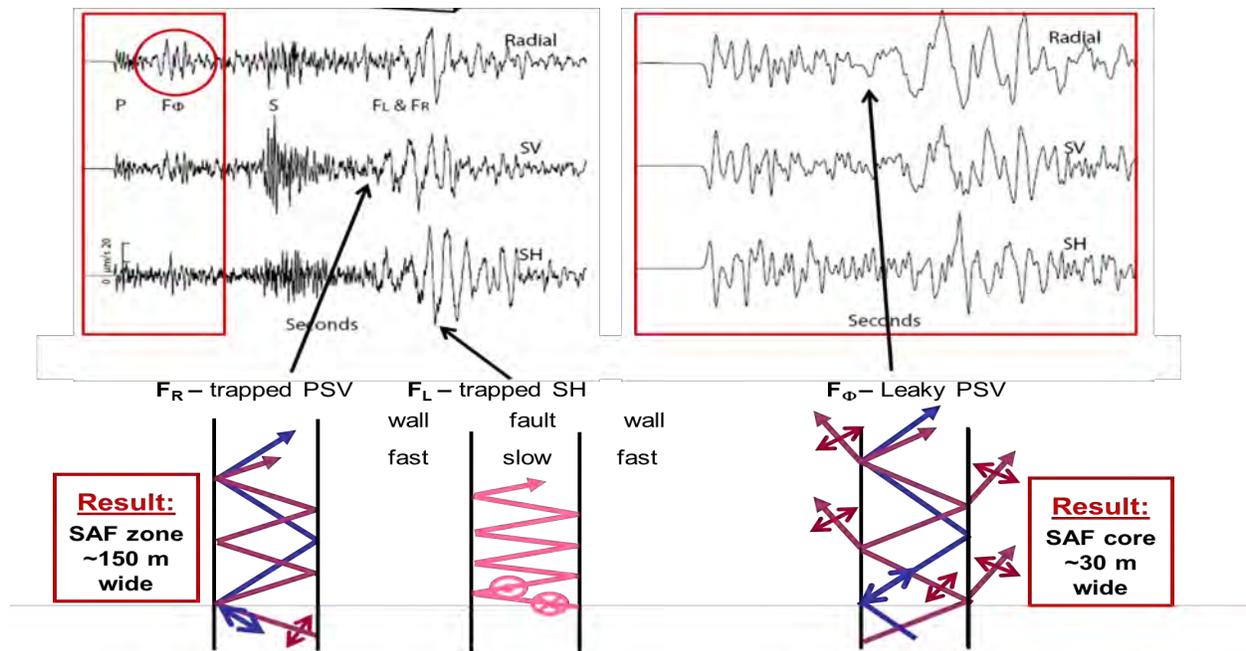


A few weeks later Kei brought up 2 USC students (Y-G Li and Y. Ben Zion) and a research staff (P. Leary), and the race was on. Using the Middle Mt borehole and surface array data, Li et al fit the late arrivals with seismic waves trapped in a order of ~ 100 m wide low velocity zone. Ben Zion et al modeled the 1st break waves as a result of refraction between slow and fast sides of a vertical fault. When these results were published, I received a phone call from Karen McNally, who told of having seen both types of signals in 1966 Parkfield main and aftershock while working on her PhD thesis with Tom McEvelly at UCB. So, while never formally reported in the literature, pre-SAFOD Parkfield SAF was known to have Fault Guided and Refracted Waves.

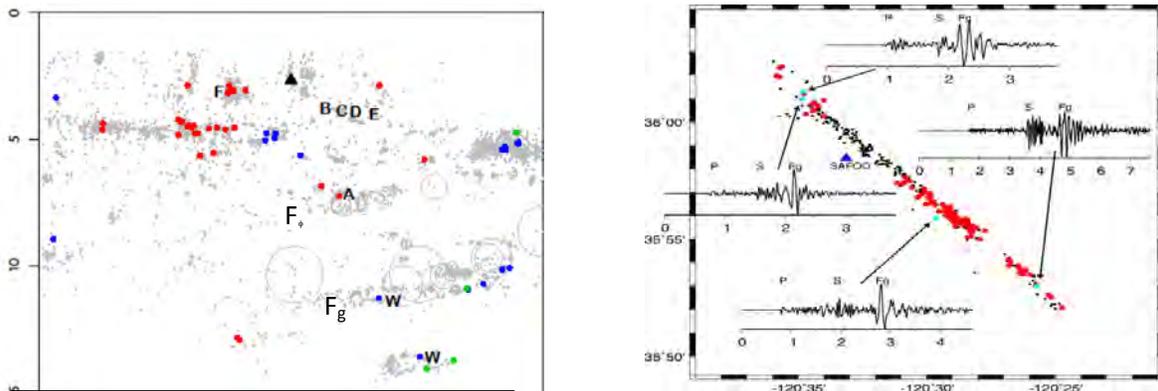
Earthscope Synthesis Workshop
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Like P and S, these waves have their own distinctive labels: F_g and F_H . In the former case, the F_g phases were found to be Love waves, now marked as F_L . As observations of F_g began to be recognized at different locations, fault trapped Rayleigh waves, F_R , were also identified. At the same time, a controversy over the depths these dispersive waves originated and propagated from arose: Li et al., connected them with fault zones extending down to 11 or more km, Ben Zion et al limiting their wave guide to less than half that depth.

A seismometer placed 10's m away from the SAF in SAFOD Main Hole both confirmed the occurrence of F_L and F_R in the immediate vicinity of the fault and revealed a 3 type of F_g : a leaky mode phase F_f . These signals revealed a narrow fault core, roughly 1/5 that of F_L and F_R , and which extends to at least 6 km depth. The locations along the fault that both generate F_g waves and allow their propagation also reveal how the fault is segmented and connected only at depth.



Upper: the 3 types of F_g waves observed at SAFOD. Lower: red dots show the depths and epicenters of F_g sources in cross section and map view.



Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

Geologic Setting and Fault Zone Structure

Diane E. Moore^a, Representing Everyone Involved in the SAFOD Program

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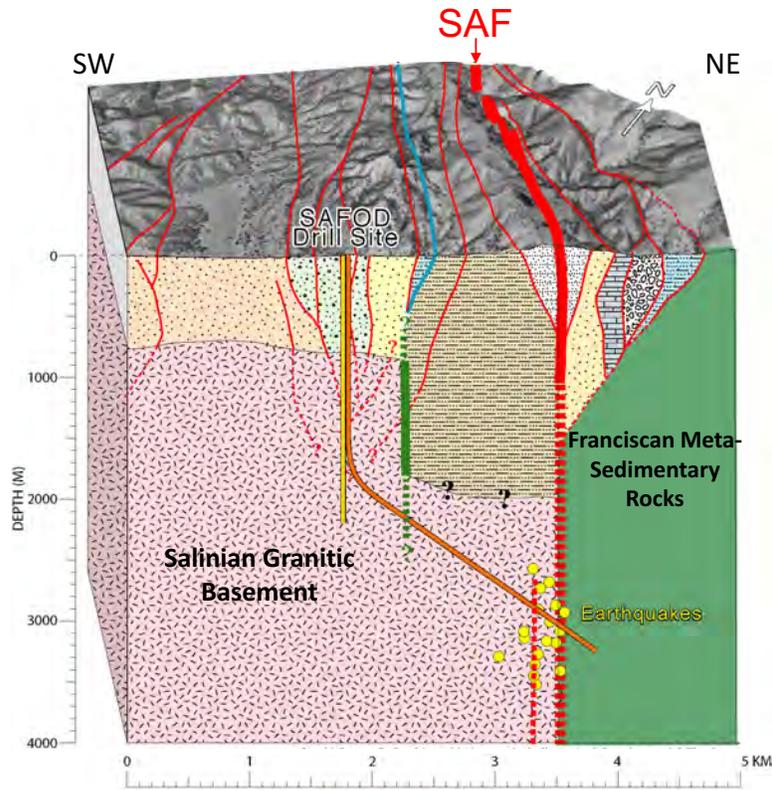


Figure 1. Pre-drilling geologic model.

Extensive geological and geophysical site investigations were combined to produce a geologic and structural cross section prior to the commencement of drilling at SAFOD (Fig. 1). In particular, relatively intact granitic basement was inferred to be present on the Pacific Plate side at the crossing depth, with Franciscan metasedimentary rocks in the adjoining North American Plate. Drilling of the main hole resulted in some modifications to the geologic model (Fig. 2), a few of which are described below.

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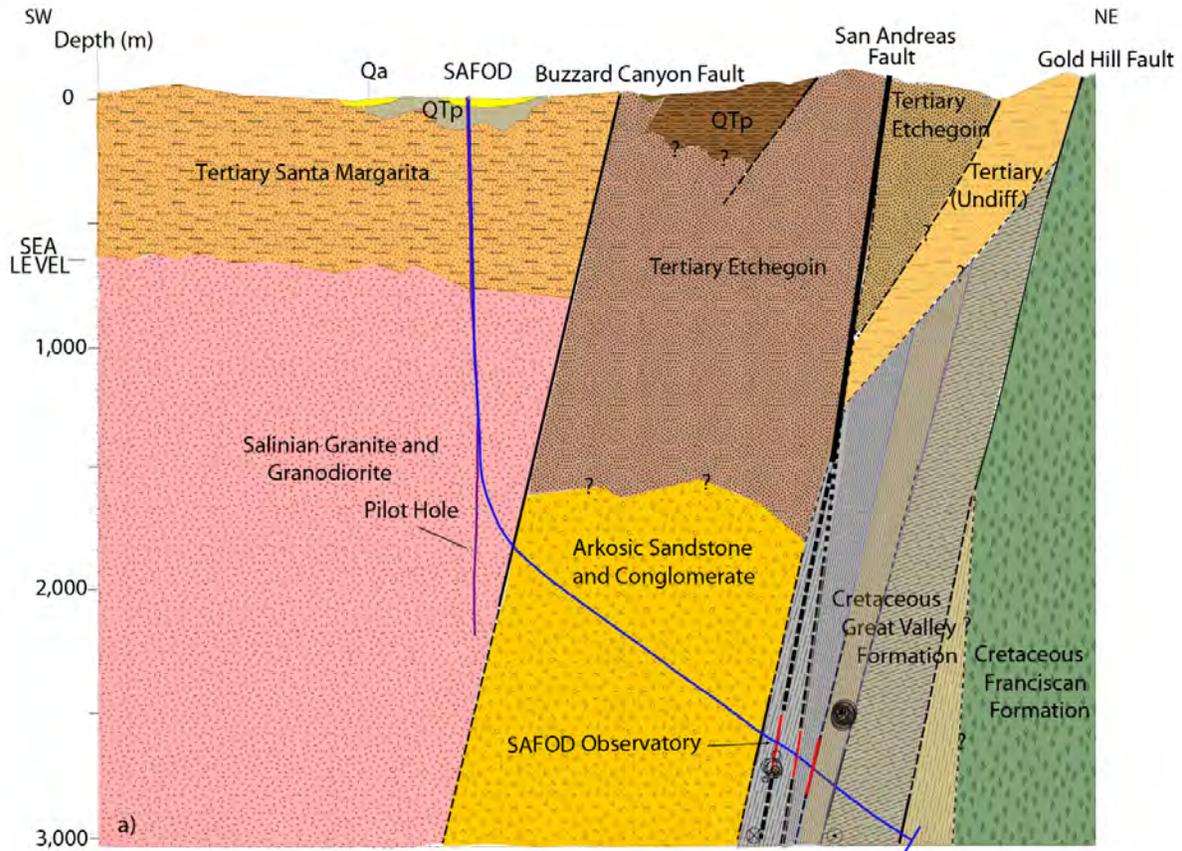


Figure 2. Post-drilling geologic model (Fig. 1a of Zoback et al., 2010, Eos, 91(22), 197-199).

The sedimentary basin adjacent to the San Andreas Fault on the southwest side extends to a substantially greater depth than predicted. These deeper basin-fill deposits consist largely of arkosic sandstones and conglomerates derived from weathering of the Salinian granites. The main hole terminated in Late Cretaceous sedimentary rocks of the Great Valley Group, based on fossil identifications made by K. McDougall (USGS). The damage zone of the presently active trace of the San Andreas Fault is located completely within the North American Plate, displaced ~40 m to the northeast of the "geologic" plate boundary.

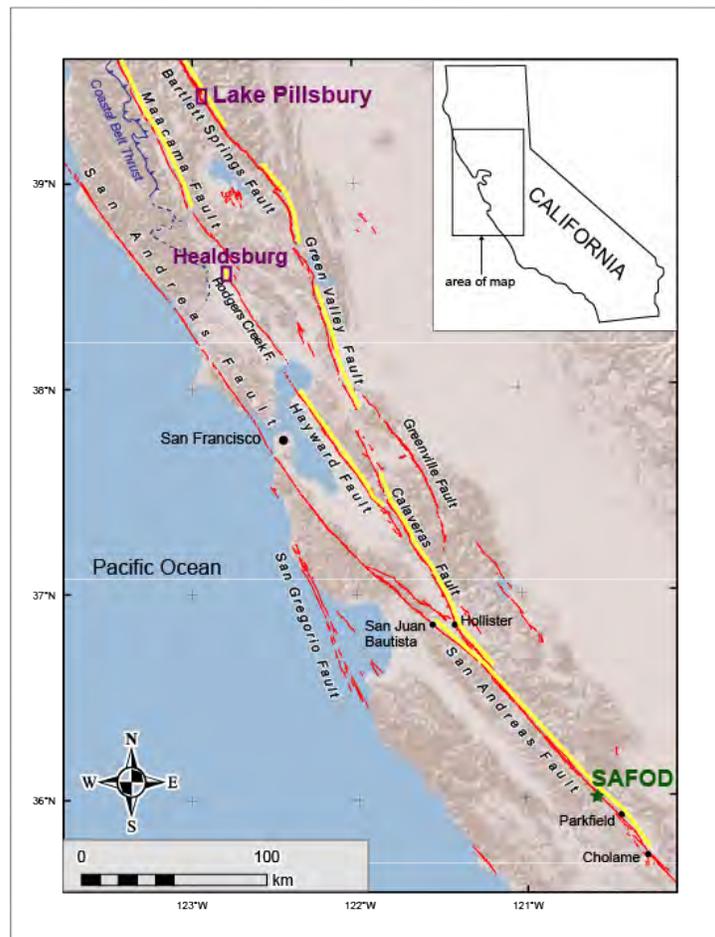
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SAFOD Structure: Application to Other Creeping Faults of the San Andreas System in Central and Northern California

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The core recovered as part of the SAFOD drilling program confirmed the long-held idea that serpentinite is involved in promoting fault creep, at least along the San Andreas creeping section. Creep has also been documented on portions of several faults of the San Andreas System in northern California — with the notable exception of the San Andreas Fault itself (Fig. 1). The basement geology of the northern California Coast Ranges corresponds to that at SAFOD, characterized by accreted terranes associated with Franciscan subduction, including the Coast Range ophiolite. The similar geologic framework suggests the possibility that creep on these other faults may have the same origin as that at SAFOD.



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Figure 1. Faults of the central and northern San Andreas system, with yellow lines highlighting fault segments considered to be >20% creeping (Lienkaemper et al., 2014, BSSA, 106, 3094-3114). Purple boxes mark the locations of serpentinite-bearing exposures of the Bartlett Springs Fault at Lake Pillsbury and the Rodgers Creek Fault near Healdsburg that are the focus of current and future studies, respectively.

A creeping segment of the Bartlett Springs Fault (BSF) at Lake Pillsbury (Fig. 1) has been the focus of recent petrographic, geochemical, and laboratory investigations. An exposure of the fault along a stream-cut terrace (Fig. 2) is a 1.5-m wide gouge zone sandwiched between Late Pleistocene gravel deposits. The gouge consists of antigorite, the high-temperature serpentine mineral, plus talc, chlorite, and tremolite, all of which are stable at temperatures above 250–300°C.



Figure 2. An exposure of the Bartlett Springs Fault north of Lake Pillsbury is a 1.5 m-wide zone of bluish-colored, serpentinite-bearing fault gouge emplaced between gravel-rich wall rocks. The fault trace crosses the stream bed.

The bulk composition, frictional strength, and sliding behavior of the BSF gouge are all closely similar to those of the CDZ and SDZ from the SAFOD core. The BSF gouge is thus considered to be the higher-temperature equivalent of the CDZ and SDZ gouges and to have been tectonically entrained into the fault from a depth at or near the base of the seismogenic zone.

Work is now commencing on a serpentinite-bearing outcrop of the Rodgers Creek Fault near Healdsburg (Fig. 2), where a recently installed alignment array has already recorded a small amount of creep. In addition, a tectonic model is being developed that may explain the distribution of creep north of San Francisco Bay, including the lack of creep on the northern San Andreas Fault.

Continuous cross-well traveltime measurements at SAFOD

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Earthquakes are caused by the sudden release of stresses along faults. Thus the time-varying stress field at seismogenic depths is perhaps the most crucial parameter for understanding fault zone processes. While recent studies suggest that stress release can manifest as a small or large earthquake (e.g., Lay and Kanamori, 2011), as aseismic slip (e.g., Niu et al., 2003; Murray and Segall, 2005), or as non-volcanic tremor (e.g., Nadeau and Dolenc, 2005), it is also found that many processes, such as fault interactions, can significantly affect the long-term stress build up described by plate tectonics (e.g., Freed and Lin, 2001). In-situ measurement of the stress changes at seismogenic depths thus plays a critical role in deciphering fault zone processes, although the measurement itself is notoriously difficult.

It is well known from laboratory experiments that when crustal rocks are subjected to different levels of stress, their seismic velocity changes with the applied stress (e.g., Birch, 1960; Scholz, 1968; Nur and Simmons, 1969; Jones, 1983). Such a stress dependence of seismic velocity is attributed to the presence of microcracks within those rocks, and to the fact that the number of open microcracks and their stiffness can vary with the confining stress. The stress sensitivity, defined as $\eta = d\ln V/dP$, is found to be around 10^{-7} Pa^{-1} right below Earth's surface and decays rapidly to 10^{-9} Pa^{-1} at ~ 1 km depth (e.g., Birch, 1960; Nur and Simmons, 1969). Meanwhile, many field experiments also have been conducted to detect known stress variations, such as those related to the tidal stress, by measuring their induced seismic velocity changes, which is accomplished through shooting seismic waves repeatedly and measuring the delay times among different shots (e.g., De Fazio et al., 1973; Reasenber and Aki, 1974; Leary et al., 1979). These early studies were generally inconclusive due to insufficient precision in the delay time measurements, probably caused by low source repeatability.

Recent advances in control source and data acquisition techniques have triggered new efforts to develop a seismic stress-meter by utilizing the stress sensitivity of seismic velocity. Yamamura et al. (2003) conducted a field experiment in a vault near the coast of Miura Bay, Japan, using a highly repeatable piezoelectric source and found that the measured P-wave velocity responds regularly to the tidal stress changes. They obtained a stress sensitivity of $5 \times 10^{-7} \text{ Pa}^{-1}$. Silver et al. (2007) also conducted a series of cross-well experiments to continuously measure in situ seismic velocity at two test sites: building 64 (B64) and Richmond Field Station (RFS) of the Lawrence Berkeley National Laboratory in California, from which they demonstrated that changes in seismic velocity induced by variations of barometric pressure are indeed observable at very shallow depth. The stress sensitivity is estimated to be $\sim 10^{-6} \text{ Pa}^{-1}$ and 10^{-7} Pa^{-1} at the B64 and RFS sites, respectively. These in-situ estimates of the stress sensitivity are in good agreement with the laboratory results. However, all these controlled source experiments were conducted at surface, and it is very challenging to separate medium changes occurring at shallow and seismogenic depths associated with environmental and earthquake processes, respectively.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

The SAFOD pilot and main holes provided an unprecedented opportunity for continuous active-source cross-well observation to monitor velocity changes at seismogenic depth. Here we summarize results from two cross-well experiments that we conducted in 2005-2006 and 2010. We went back to the SAFOD site in May of 2017 and conducted the third cross-well experiment that has been continuously recording data since the June of 2017.

In the 2005-2006 experiment, we installed a specially designed 18-element piezoelectric source and a three-component accelerometer inside the pilot and main holes, respectively, at ~1 km depth. The experiment was conducted for ~2 months: the first period was 29 October to 28 November 2005, and the second was 11 December 2005 to 10 January 2006. We fired a pulse with a width of 1 ms four times per second and recorded 200-ms-long data with a sampling rate of 48,000 Hz. The waveforms were automatically stacked in groups of 100 shots, resulting in one record acquired every 27 s. In the first-month data, we found a 0.03% change in the average S-wave velocity, which shows a good negative correlation with barometric pressure, corresponding to a stress sensitivity of $2.4 \times 10^{-7} \text{Pa}^{-1}$. In the second-month data, we observed two large excursions in the delay time measurement, corresponding to 0.055% and 0.015% decreases of seismic velocity, that are coincident with two earthquakes, a magnitude 3 and a magnitude 1 earthquake, which occurred sufficiently close to produce large coseismic stress changes at the SAFOD site. Interestingly, the two excursions started approximately 10 and 2 hours before the events (Figure 1), respectively, suggesting that they may be related to pre-rupture dilatancy observed in the early laboratory studies.

In the 2010 experiment, we employed the 2005-2006 experimental configuration and deployed a piezoelectric source and a three-component accelerometer at 1 km deep inside the pilot and main holes,

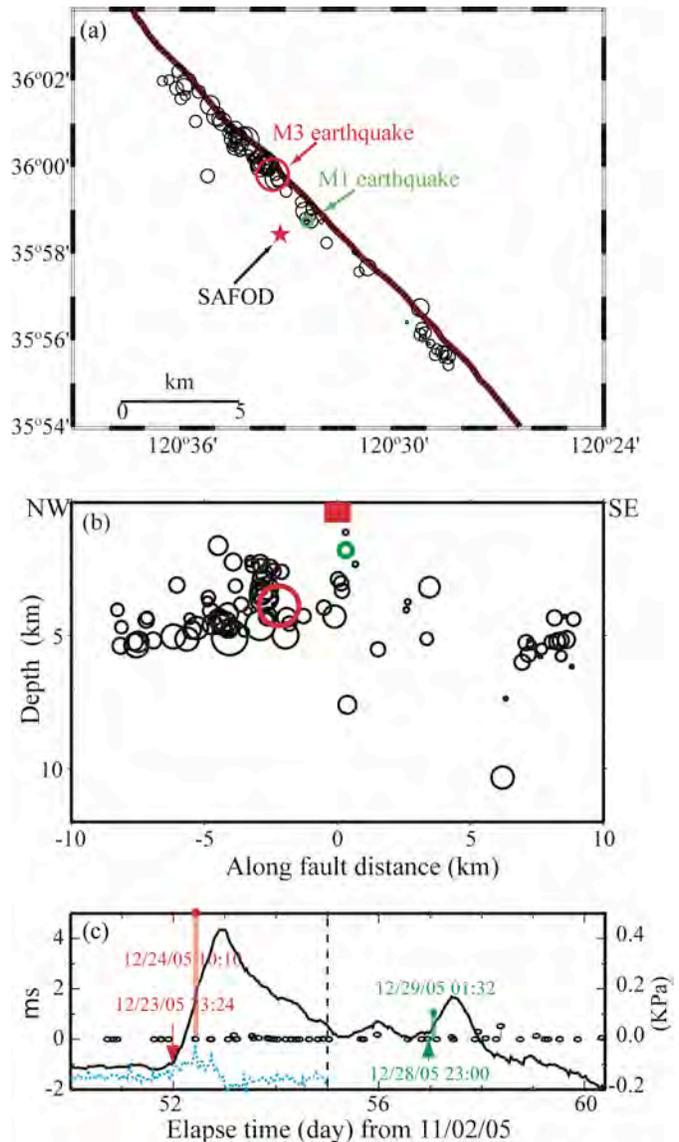


Figure 1. (a) Map of the experiment site showing the SAFOD drill site and the seismicity (circles). (b) Depth distribution of earthquakes that occurred in the experimental period. Red square, red and green circles indicate the SAFOD experiment site, the M3 and M1 earthquake, respectively. (c) Predicted coseismic stress changes at SAFOD for earthquakes occurring between December 22 of 2005 (day 50) and January 1 of 2006 (day 60). Note velocity changes (arrows) started a few hours before the two earthquakes (solid lines).

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

respectively. We also added a hydrophone, which is attached to the source, to monitor the repeatability of the source waveforms. Because of a sensor failure, we were only able to obtain ~40 days of recording. Over the 40-day recording period, we confirmed a ~0.04% travel time variation in S-wave and coda that roughly follows the fluctuation of barometric pressure. We attributed this correlation to stress sensitivity of seismic velocity and the stress sensitivity is estimated to be $2.0 \times 10^{-7} \text{ Pa}^{-1}$ (Figure 2). The results confirm the hypothesis that substantial cracks and/or pore spaces exist at seismogenic depths and thus may be used to monitor the subsurface stress field with active-source crosswell seismic.

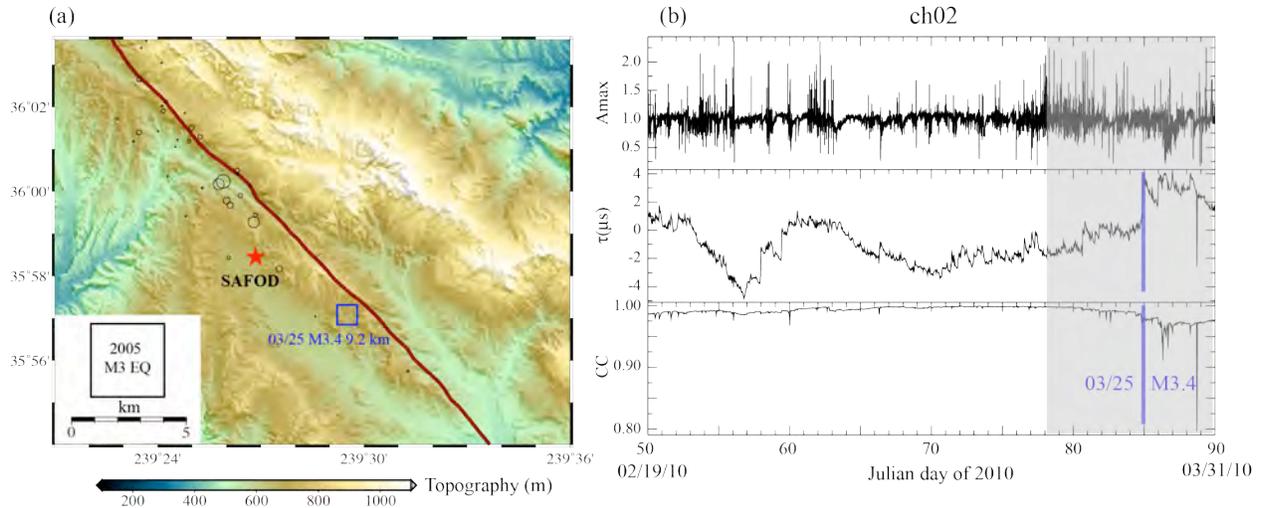


Figure 2. (a) Topography map showing the surface trace of the San Andreas Fault (thick line) and the SAFOD drill site (star). Earthquakes occurred during the experiment period are shown by circles. The open square indicate the M3.4 earthquake that occurred on March 25, 2010. The size of the square is scaled by the calculated coseismic stress change with respect to the stress drop of the 2005 M3 earthquake (open square in the legend) discussed in Niu et al. (2008). (b) The maximum amplitude of individual records, the measured delay time, and the cross-correlation between the 43-minutes records and the reference trace of channel 2 are shown from the top to the bottom. The thick vertical lines indicate the time when the M3.4 earthquake occurred. The shaded area represents the final stage of the recording that is featured by large amplitude perturbations and low correlation coefficients, which may suggests that the 3C accelerometer is deteriorating before its final collapse on April 2.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

Seismic and Resistivity Structure

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The seismic and resistivity structure of the region in and around the SAFOD drill site has been studied by numerous investigators over at least the past four decades. Indeed, the intense geophysical scrutiny of this region in the 1980s, largely a result of the anticipated repeat of the 1966 Parkfield earthquake, was a key consideration in the selection of the Parkfield area as the SAFOD drill site. Efforts devoted to resolving seismic and resistivity structure the early 2000s were driven mostly by the practical goal of defining the drilling targets, and as the wavespeed models improved the objectives of the drilling project evolved from simply being able to intersect the seismogenic part of the SAF to close-up monitoring of repeating “target” microearthquakes. Resistivity models that focused specifically on the upper few kilometers of the drill side provided an unambiguous image of the general position of the fault zone as a region of highly conductive region, a possible indicator of fluid infiltration. This resistivity image was later corroborated by images from a variety of seismic and gravity (density) images generated by inversion for medium properties or migration of converted phases. To first order, seismic models show that wavespeeds decrease sharply from SW to NE across the SAF, which is consistent with the geologic transition from Salinian granite to Franciscan mélangé with a narrow region (on the order of 100 m) of localized low wavespeed corresponding to the fault zone itself. Resistivity models show identical trends with the Salinian granite as a resistive body, the Franciscan as moderately conductive, and the fault zone itself as highly conductive. The close correspondence between wavespeeds determined from drill cores and those obtained from seismic modeling, as well as the success of the Phase II drilling between the “Hawaii” and “SF/LA” target events attest to the accuracy of these models, or at least that the stated goal of resolving seismic structure at a sufficient level to obtain location accuracies in the 10’s of meters range had been achieved. A number of other investigations of both seismic and resistivity structure allowed for mapping of additional properties such as attenuation and anisotropy. In general, regions of high and low attenuation correlate with low and high wavespeeds, respectively, and anisotropy from shear wave splitting, while complicated, is consistent with strain one would anticipate from a right lateral strike slip fault. Other studies at a more regional scale (10’s to 100’s of km) and not specifically centered on the drill site have provided context for the interpretation of observations from SAFOD. Results from these investigations provide some insight into the role of fluids in the fault zone and the potential importance of lithological contrasts across the fault in the generation and propagation of large earthquakes. For example, large scale resistivity studies, combined with crustal scale investigations that use teleseismically recorded events, suggest a deep source for fluids in the fault zone, and that these fluids may result from the dehydration of serpentinite left over from the subduction of the Farallon plate. A particularly intriguing aspect of recent studies of seismic properties is the potential for monitoring the time dependence of both bulk properties and minor scatterers using interferometric approaches. Monitoring the time evolution of medium properties benefits from the availability of the frequent repeater events that provide a virtually invariant, high-energy source of seismic waves.

Off-fault Deformation During the Interseismic Period

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Studies of the kinematic ground movement in California have suggested that a significant fraction (about 1/3) of the Pacific-North America plate motion in California occur as permanent distributed off-fault deformation (Bird, 2009; Johnson, 2013). It is also observed from geodetic studies across various segments of the San Andreas and San Jacinto fault (e.g., Lindsey et al., 2014; Materna and Burgmann, 2016) that the elastic moduli in fault damage zones are significantly lower than the host rock, even lower than inferred from fault zone guided waves (Li et al., 2004) and high-resolution tomographic studies (Allam and Ben-Zion, 2012). These observations are indicative of the fact that considerable fraction of the off-fault deformation could be taking place in damage zones interseismically. We argue that such off-fault plastic deformation significantly influences shear-stress loading on faults, its distribution, and potentially the resulting seismicity as well.

Considering the potential occurrence of significant off-fault deformation and realistic fault zone structures, we set up a 2D finite element model with a viscoelastic fault zone and slight roughness between the fault zone and host rock. We apply a steady far field displacement parallel to the fault to represent tectonic loading and observed the stress evolution within the viscoelastic fault zone. Due to the geometrical irregularity, a stress concentration develops over time where the fault zone is narrowest, which increases not only in magnitude but also in fault-parallel dimension. This growth in stress asperity width, which we refer to as “stress diffusion”, is a characteristic of a rough fault zone that allows plastic yielding, as such phenomenon does not arise if the fault zone is set to be elastic.

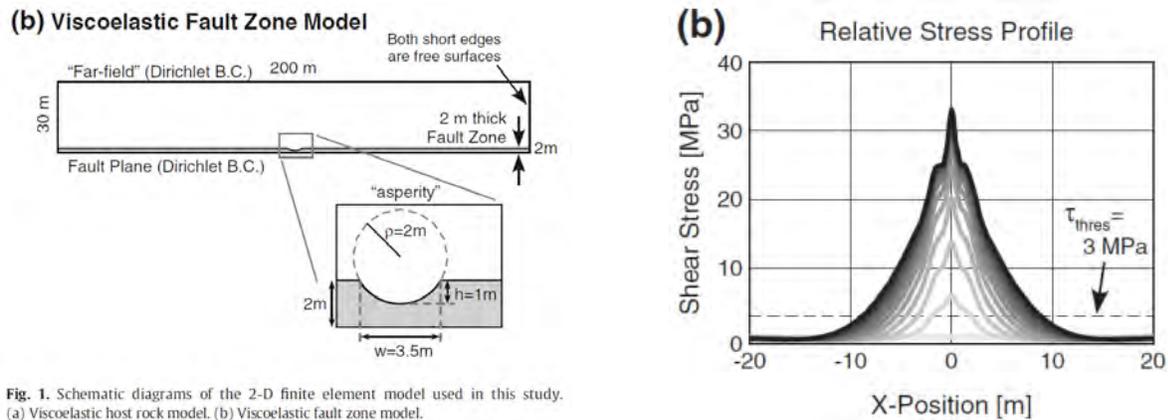


Fig. 1. Schematic diagrams of the 2-D finite element model used in this study. (a) Viscoelastic host rock model. (b) Viscoelastic fault zone model.

[Left] FEM model set up. Gray region represents viscoelastic fault damage zone with relatively low elastic moduli compared to the host rock and Maxwell rheology. [Right] Relative shear stress profiles inside the fault damage zone resulting from constant rate tectonic loading. Note that the stress asperity magnitude and dimension increase with time from the gray profile to the black profile (figures from Sone and Uchide, 2015, 2016).

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

These results may contrast from those models which do not take into account the thickness of fault zones and treat faults as a frictional interface. Comparing different behaviors of stress asperity growth and the associated off-fault elastic/plastic deformation could highlight what strain signals we can look for around fault stress asperities to quantify off-fault plastic deformation and test different fault constitutive laws.

Quantifying and understanding the impact of off-fault interseismic deformation is a fundamental question in fault mechanics as it pertains to our first-order understanding of how plate motion is accommodated by major fault zones. Observing interseismic off-fault deformation and its recovery (or non-recovery) upon earthquake events near a well-characterized repeating earthquake would be a rare opportunity to understand the strain-budget of fault systems and to validate different fault zone models.

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Towards *In Situ* Continuous Measurement of Fault Zone Deformation Process using Crosswell Continuous Active-Source Seismic Monitoring and Passive Seismic Interferometry

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Continuous measuring *in situ* fault-zone deformation process is a key and challenging step to a better understanding of the earthquake nucleation process. Recent works from field and laboratory experiments observe seismic velocity changes preceding microearthquakes and rock failure [Niu *et al.*, 2008; Scuderi *et al.*, 2016]. These results suggest that a continuous monitoring of seismic velocity could provide additional insight into the earthquake nucleation phase. Crosswell Continuous Active-Source Seismic Monitoring (CASSM) with an array of borehole sources and sensors has proven to be a very effective seismological tool to measure *in situ* seismic velocity and to identify its temporal variations at seismogenic depth [Daley *et al.*, 2007; Silver *et al.*, 2007]. In June 2017, we have begun to perform a multi-year-long CASSM field experiment at the San Andreas Fault Observatory at Depth (SAFOD) where the preceding CASSM experiment detected the two sudden velocity drops approximately 10 and 2 hours before microearthquakes [Niu *et al.*, 2008]. Our field experiment installed a piezoelectric source and a three-component accelerometer at the SAFOD pilot and main holes (~1 km depth) respectively. A seismic pulse was recurrently fired from the piezoelectric source four times per second, and waveforms are sampled at 48 kHz.

The system has been operating normally under a very unusual borehole setting (extremely high temperature and very corrosive borehole fluid) for more than 15 months, which has never been achieved before. To explore seismic velocity change at quasi real-time, we have developed an automated system for transferring waveforms collected at the SAFOD site to University of California, Berkeley and for analyzing waveforms to monitor seismic velocity changes. During the 15-month observation period, there was no local earthquake with magnitude (M) > 3.0 occurred within 10 km from the SAFOD site, and expected static stress changes from local microearthquakes were less than 30 Pa. Our 15-month observation period provides an unique data set in which we can address potential stress changes due to environmental effects such as barometric pressure and atmospheric temperature (Fig. 1). It appears that thermal noise (crock drifts) are dominant in the resultant seismic velocity fluctuations for the 15-month observation period. By correcting thermoelastic effects, we will explore subtle responses to stress changes from microearthquakes that are previously undetected in the seasonal velocity perturbations.

Passive seismic interferometry is another approach for continuous seismic velocity monitoring [Campillo and Paul, 2003; Snieder, 2004]. In particular, this seismic interferometry approach may become more important when an array of seismic sensors installed over fault deformation zones because resultant Green's functions inferred from the interferometry extract information on inter-station seismic wave properties that propagates deformation zones [Vasconcelos and Snieder, 2008; Lewis and Gerstoft, 2012]. Chen *et al.* [2017] provides a framework to explore inter-station isotropic seismic velocity and anisotropy properties. Following this work, we

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

analyzed continuous seismic data from seven SAFOD pilot hole sensors (the sensor depths range from ~1850-2010 m). The preliminary result from one-day -long data (collected on October 14, 2004) in a frequency of 10-30 Hz shows that the P-wave and S-wave velocities are about 5.11 km/s and 3.26 km/s, respectively. We find that the strength of S-wave anisotropy is 2.43~3.19 %, and the fast direction of the azimuth anisotropy is 100-110 degrees (Fig. 2). This work demonstrates along with previous works [Vasconcelos and Snieder, 2008; Lewis and Gerstoft, 2012] that seismic interferometry with SAFOD pilot hole data retrieves subsurface properties between seismic sensors. Our plan is to extend this analysis for other SAFOD pilot hole continuous data to explore time-dependent velocity and anisotropic properties related to the 28 September 2004 M 6.0 Parkfield earthquake.

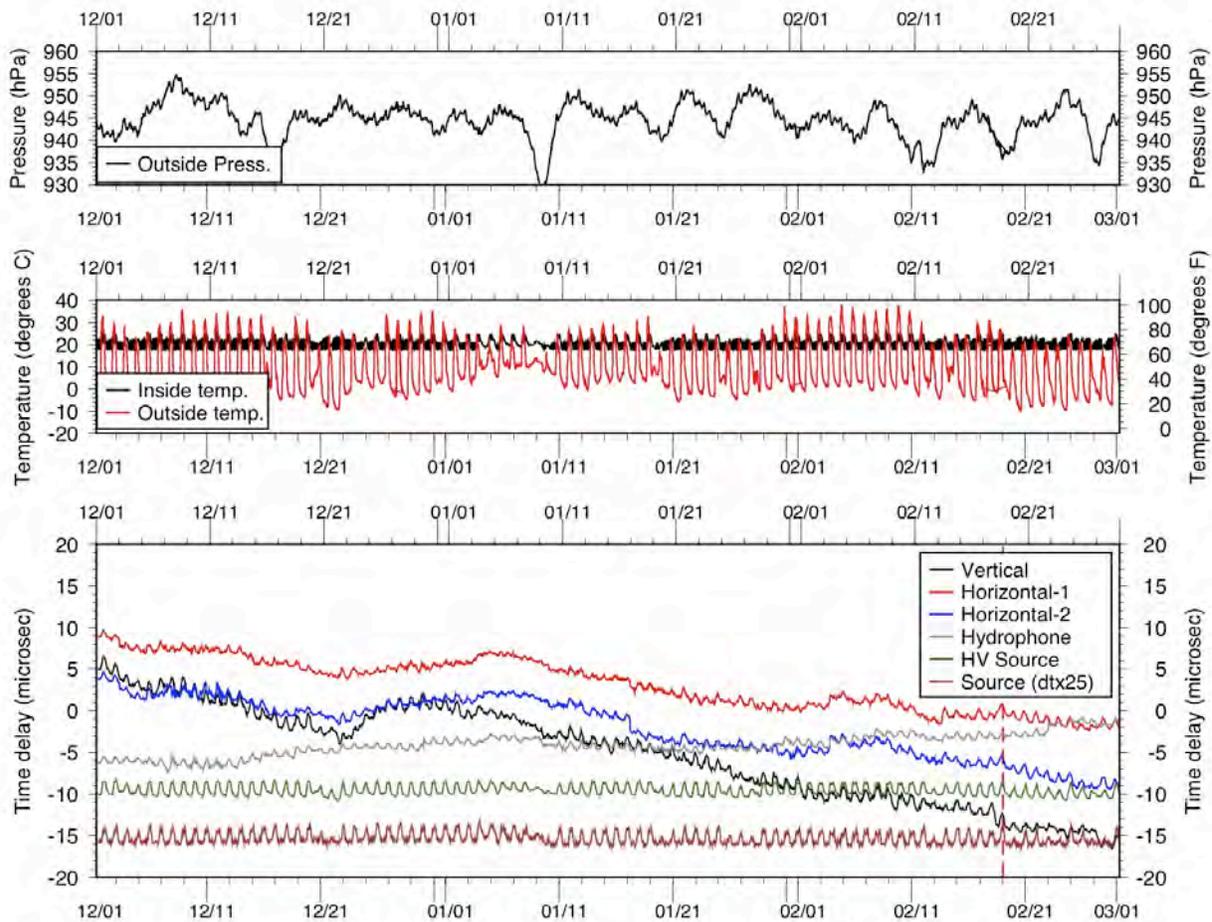


Figure 1: An example of our time delay measurement for the 2017-2018 SAFOD active source experiment for December 2017 through February 2018. The top panel shows outside atmospheric pressure at the SAFOD site. The middle panel shows outside and inside air temperature. The bottom panel shows delay time measurement for the S-wave arrival plus the coda recorded on the three-component accelerometer (vertical, horizontal-1, horizontal-2) installed at the SAFOD main hole. Also shown are time delay estimates for hydrophone (located near the active source installed at the SAFOD pilot hole), source, and amplified high-voltage source.

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

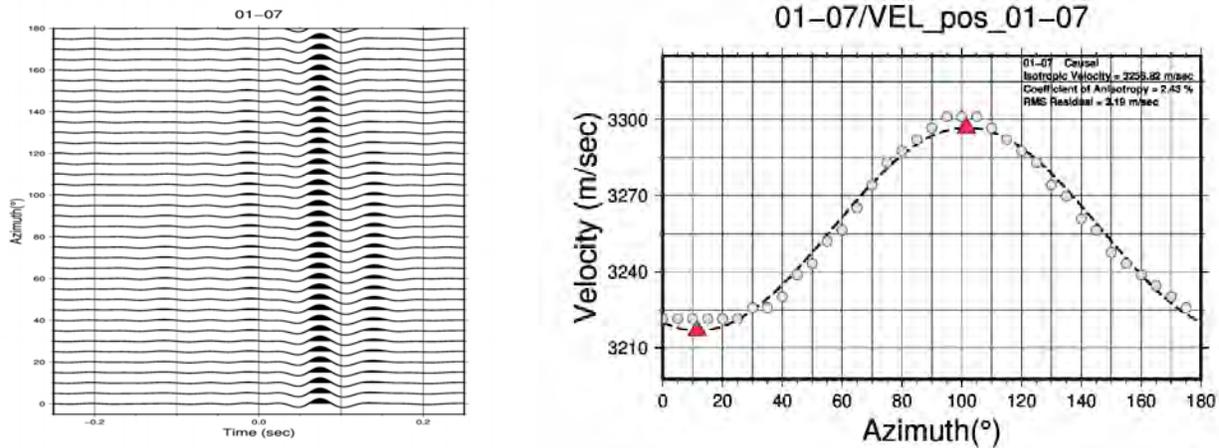


Figure 2: Anisotropy measurement at SAFOD pilot hole sensors 01 (the sensor depth is ~2100 m) and 07 (the sensor depth is ~1850 m). The left panel shows the variations of empirical Green's functions obtained seismic interferometry as a function of polarization direction. The right panel shows measured S-wave velocities as a function polarization direction. The resultant isotropic S-wave velocity, the fast polarization direction, and the strength of anisotropy are 3.26 km/s, 110 degrees, and 2.43 %, respectively.

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EarthScope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

Locating the SAFOD Target Earthquakes

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An overarching goal of SAFOD was to penetrate the San Andreas fault very close to three clusters of repeating magnitude ~ 2 earthquakes, known as SF, LA, and HI, with SF and LA considered as the primary targets for sampling their rupture patches. To that end, from 2000 through 2006, Steve Roecker and I led a major passive and active seismic experiment, nicknamed PASO (Parkfield Area Seismic Observatory), that deployed up to 59 temporary seismic stations surrounding the SAFOD site (Figure 1) in four different phases, and carried out dozens of "calibration" explosions. A refraction-reflection line was run approximately normal to the San Andreas fault in 2003 (Hole et al., 2006), and we reoccupied about 30 PASO sites during that project. Through those years and into 2007, we steadily refined our 3D velocity models and our estimates for the locations of the earthquakes in the three target clusters. Prior work had produced conflicting estimates for the geographic coordinates and depths of these earthquakes, so it was critical to develop well-constrained locations in order to accurately define the drilling trajectory. Intense seismic tomography analysis and further field work in 2003 through 2007 produced increasingly well constrained estimates for the target earthquake locations, which served to guide the first two phases of SAFOD drilling in 2004 and 2005. The Phase 2 drilling passed through the San Andreas fault zone, putting the borehole within an estimated 100 meters of the Hawaii target cluster, and a somewhat greater distance from the SF and LA clusters. Significant deformation of the SAFOD borehole was observed between the HI and SF/LA clusters, so that factor combined with the closer distance to the HI cluster resulted in the plan for HI to be a target for Phase 3 multilateral drilling. Unfortunately, a number of technical problems occurred and drilling costs had skyrocketed, so in the end a conservative multilateral drilling plan was carried out close and subparallel to the SAFOD main borehole, meaning that in the end, there was no attempt to puncture the rupture patch of HI. I note that later work (Zhang et al., 2009) produced locations for the HI and SF/LA clusters that align with two inferred faults observed in the SAFOD borehole (Figure 2).

In my presentation, I will provide a bit of history regarding the effort to locate the target events, and suggest a possible path forward. Specifically, although there still are some uncertainties regarding precisely where to drill to be certain of hitting the HI rupture patch, in my opinion, those uncertainties could very likely be resolved with a combination of a modest multi-element borehole seismic string, a small deployment of seismic stations at the surface, a limited amount of active-source work, and careful tomography and relocation analysis. Successfully sampling the rupture patch of a small earthquake would be a unique and monumental achievement, and would add greatly to the scientific legacy of SAFOD.

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EarthScope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

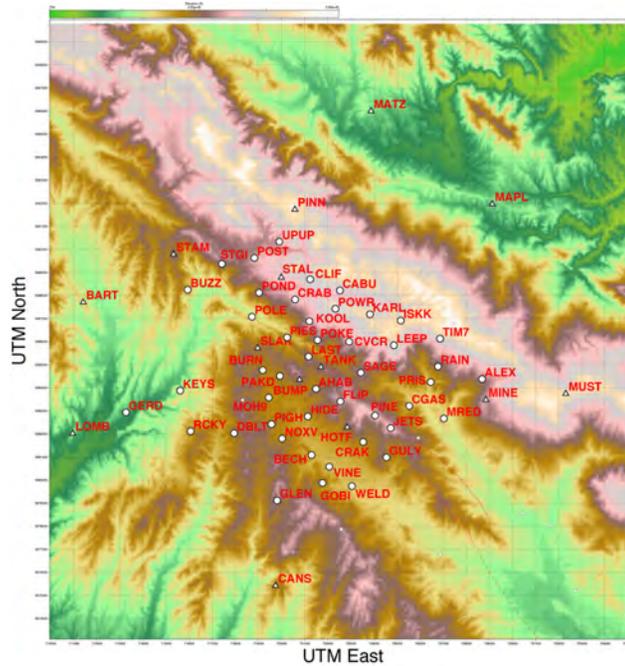


Figure 1. Map showing the 59 stations deployed in the second phase of PASO, known as PASO-DOS. All stations were 3-component, and 30 were broadband. All sites were telemetered to a central recording site in real time, thanks to a telemetry system established by Glen Offield.

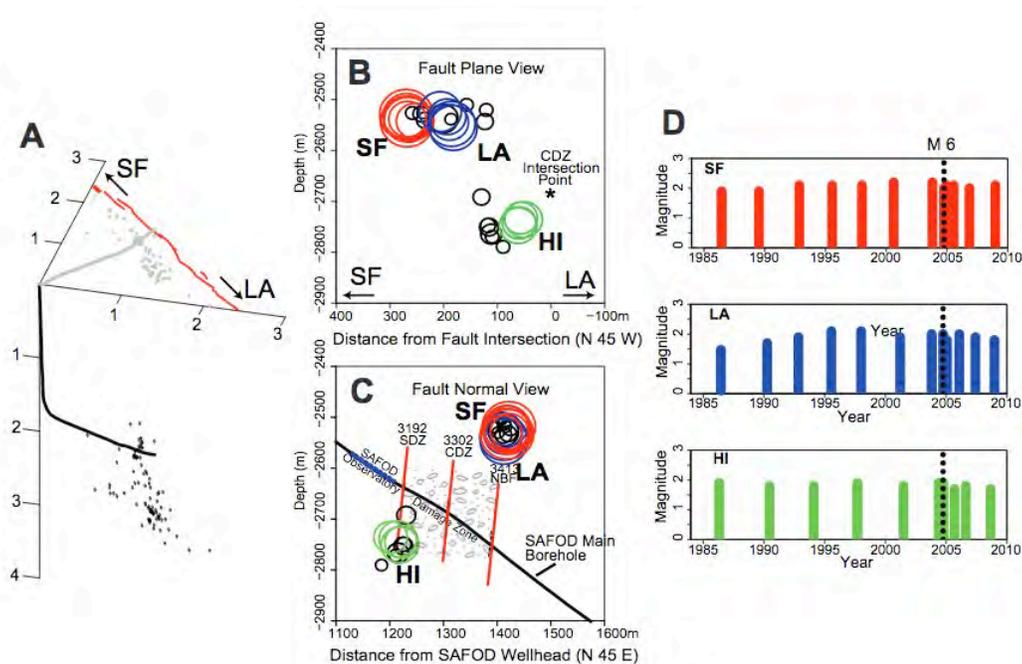
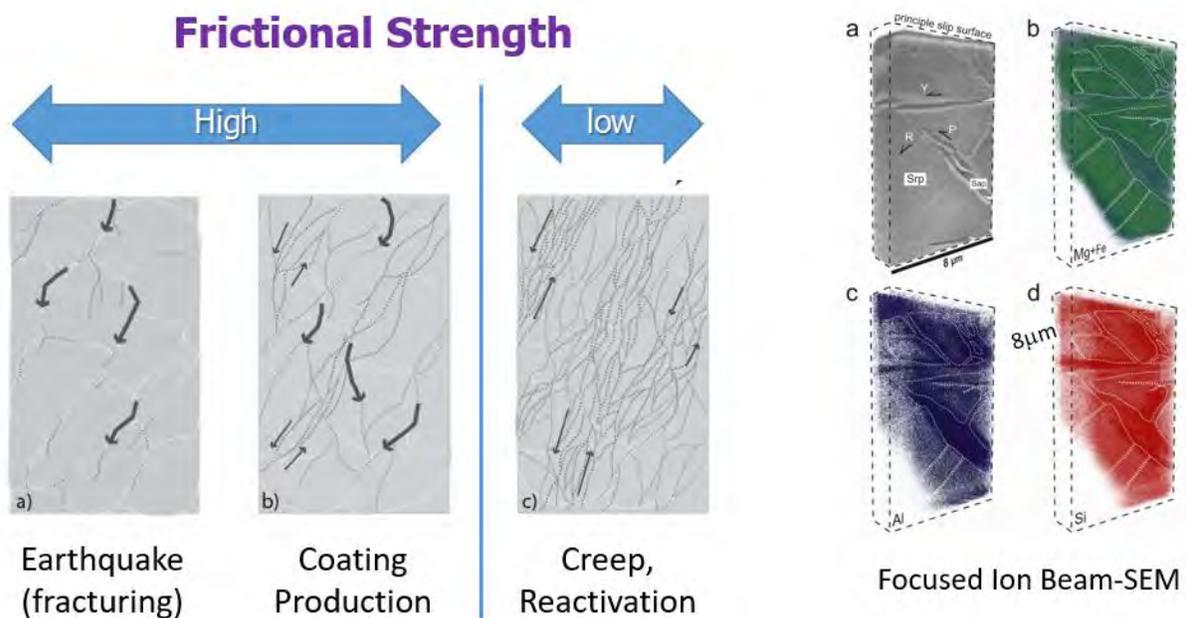


Figure 2. Microearthquakes selected for targeting with SAFOD. [A] 3-D perspective view of the seismicity with respect to the path of the SAFOD borehole, with north pointing up, east to the right, and depth down (all axes in km). [B] View of the plane of the San Andreas Fault at about 2.7-km depth looking to the northeast. The red, blue, and green circles represent seismogenic patches of the San Andreas Fault that produce repeating microearthquakes termed the San Francisco (SF), Los Angeles (LA), and Hawaii (HI) clusters, respectively. The point at which the SAFOD borehole passes through the central deforming zone (CDZ) is shown by the asterisk. [C] Cross-sectional view of these earthquakes looking to the northwest, parallel to the San Andreas Fault, including the trajectory of the SAFOD borehole and the principal faults. Note that the HI events occur about 100 m below the fault intersection at 3192 m (measured depth), indicating that the HI microearthquakes occur on the southwest deforming zone (SDZ). The SF and LA sequences occur on the northwest bounding fault (NBF). From Zoback et al. (2011).

SAFOD and Clays

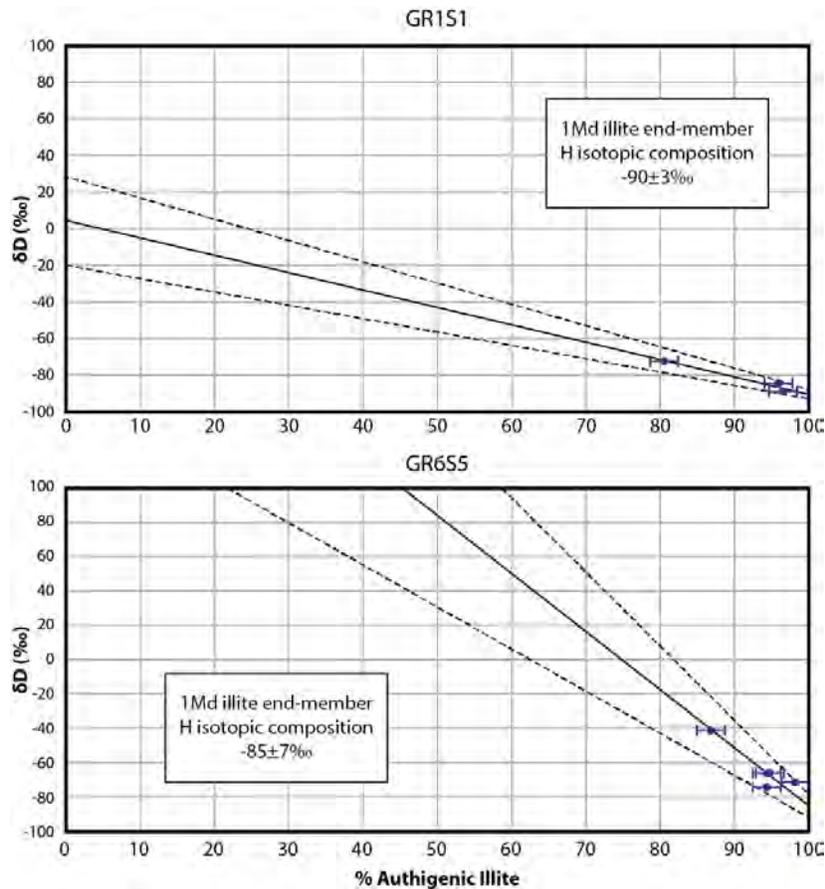
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Cuttings and core from SAFOD sampling (phases 1-3) of currently active and inactive fault rock sections preserve abundant evidence for clay neomineralization in fault segments in the form of coatings on shear surfaces (Schleicher et al., 2006; 2009; 2010). Clay characterization using XRD pattern matching of polytypes distinguishes host rock (detrital) clays from small, newly-formed, low-temperature smectitic illite (authigenic clays) in fault rock. Ar dating of clay mixtures gives ages of 4 and 8 Ma for authigenic clay neomineralization, which falls well within the timing of geologically constrained San Andreas Fault displacement. We propose a scenario where fracturing of host rock creates fluid pathways that precipitate coatings of illitic clays on shear surfaces. With time, a network of connected clay coatings forms that links shorter segments. This connected network results in a change from strong frictional behavior during fracturing to low-frictional behavior controlled by clay, promoting creep (Figure). Rock friction experiments on SAFOD samples (PSU and USGS) confirm the mechanical role these clays (van der Pluijm, 2011), while high-resolution FIB-SEM images the microscopic networks (Warr et al., 2014; Figure). Deeper sections of the fault are similarly governed by chloritic clays where shallow smectitic clays are no longer stable (Schleicher et al., 2012). Given the connection between clay growth and active faulting we call this process fault self-lubrication.



Newly-formed clays precipitated from geofluids, which can be characterized with stable isotope geochemistry of crystal-bound Hydrogen in clays. New (unpublished) stable isotopic measurements of clay grain-size fractions gives highly negative δD values for extrapolated authigenic material (figure). Using solid-fluid fractionation for representative temperatures at borehole sampling depth gives a fluid composition in the range of -56 to -61‰. These values are within the range of modern meteoric fluids in the area (-40 to -70‰). Thus, we propose that mineralizing geofluids are predominantly meteoric (=surface-derived) and not sourced from deeper crustal metamorphic reactions, nor mantle-derived.

Instead, surface-derived fluids along the SAF are able to circulate down to depths >3 km, which also indicates that hydrostatic fluid conditions, instead of fluid overpressure, dominate fault zone properties.



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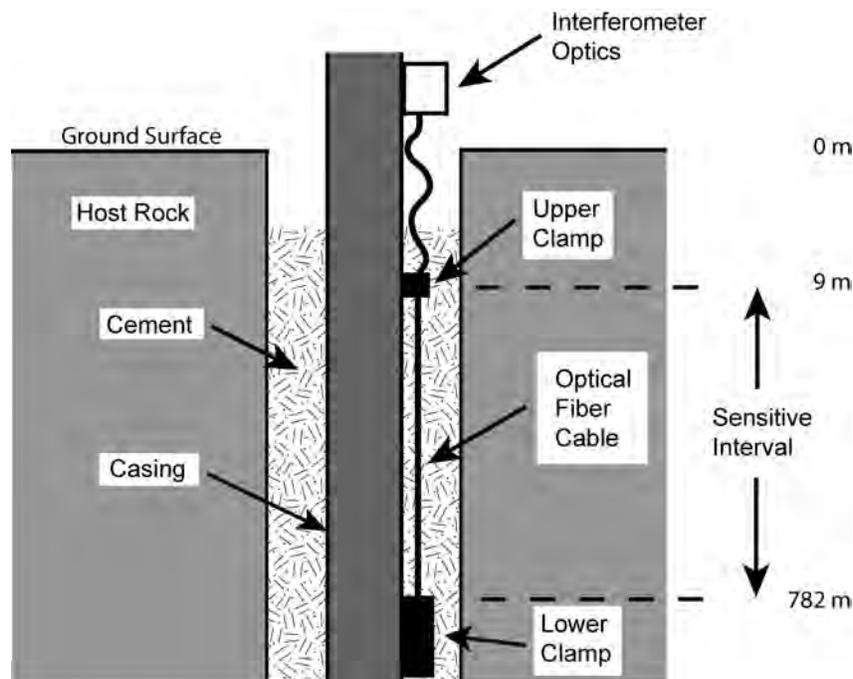
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Strain in the SAFOD Borehole

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Optical fibers are well suited to measure Earth strain because they can be stretched over long distances to average strain over a large interval. This is important to reduce disturbances to the measurement from very local effects. An optical fiber strainmeter consists of a single-mode optical fiber stretched between two fixed positions, either within a borehole or attached to anchors on the seafloor. If the ground within the interval spanned by the sensor undergoes strain, the length of the stretched, elastic fiber changes accordingly. Monitoring the optical length of the fiber provides a measure of strain integrated along the fiber's path, which is equivalent to the displacement of one endpoint with respect to the other.



In October of 2004 we installed several optical fiber strain sensors to varying depths outside the casing in the SAFOD borehole. Since then, two of these cables have been monitored interferometrically. The first, to a depth of 864 m, failed in 2007 during a drilling operation. The second, to a depth of 782 m, is still being monitored today.

The interferometric method of tracking strain in an optical fiber is capable of discerning events smaller than 1 nanostrain ($\Delta L/L = 10^{-9}$). However the temperature coefficient of the index of refraction of the material in the optical fiber is approximately 10^{-5} per °C. In our SAFOD installation, certain exigencies during deployment resulted in segments of the fiber being exposed to atmospheric temperature fluctuations, rendering the instrument incapable of recording

Earthscope Synthesis Workshop
SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

secular strain. However the instrument is highly sensitive to short period signals (less than an hour in duration) and faithfully records coseismic offsets.

Since the development of the SAFOD instrument – our first interferometric optical fiber strainmeter of significant length – we have developed a new method of temperature compensation. Highly sensitive and stable optical fiber strainmeters are currently in use at several sites and have been successfully deployed at 1900 m depth in the Pacific Ocean. Suitable for the detection of slow-slip events, the technology represents a promising new strain sensing method for tectonic studies.