

Earthscope Synthesis Workshop (Oct. 12-14, 2018)

SAFOD: Reviewing Past Predictions, Key Results, and Future Directions

(http://www.earthscope.org/research/synthesis_workshops/SAFOD)

Brett M. Carpenter, Bill Ellsworth, & Cliff Thurber

Abstract:

The SAFOD project penetrated the San Andreas fault (SAF) at ~3km depth, recovered core samples from the Pacific-North America plate boundary, and placed subsurface instruments within ~100 m of a small repeating earthquake patch. The recovered cores have been distributed to hundreds of investigators around the world. Data gathered on these samples have provided explanations for the weakness and creeping behavior of the fault. Furthermore, these samples have shown the degree that fluid-rock interactions (chemical reactions) play 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 gathered a substantial archive of strain and seismic data for earthquakes and tremor along the San Andreas fault zone. Borehole measurement results have highlighted the structure of the fault zone, that deformation along the SAF in central California is accommodated by a few remarkably narrow (around 2-meter-wide) zones of highly localized active creep embedded within a much broader (200-meter-wide) damage zone. Finally, surface and borehole seismology studies have resulted in the detailed characterization of repeating earthquake clusters and the observation of pre-earthquake seismic velocity changes, a possible observable precursor to earthquake slip. Overall, SAFOD sampling, down-hole measurements, and instrumentation at earthquake depths have significantly advanced our understanding of fault-zone evolution, structure, composition, and behavior. To date, SAFOD-related science has been published in over **118** (*as of the workshop*) peer-reviewed manuscripts, with more on the way. In October, 2018, a workshop was convened with the following goals: (1) Synthesize the key scientific outcomes from SAFOD science, (2) Compare the pre-drilling hypotheses that formed the scientific rationale for the SAFOD project with the outcomes of the project, 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.



Workshop Strategy:

Until the October 2018 workshop, there had not been a comprehensive review of the fundamental science questions that motivated the project or the broad spectrum of scientific results from SAFOD project. The workshop provided a unique opportunity to bring together key scientists in order to share and consolidate knowledge gained from SAFOD research, review pre-drilling site characterization predictions as a tool for future drilling projects, and document the impact of SAFOD research on our understanding of fault zones and earthquakes. The workshop was convened with the main goals to: 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, and 3) develop a plan to apply SAFOD data to key problems in earthquake hazard for creeping faults and the physics of earthquake nucleation.

The workshop addressed several Earthscope 2010-2020 Science Plan goals. Existing work was expanded upon at the workshop as we discussed the application of SAFOD data to other faults and fundamental questions in earthquake physics. In addition to addressing Earthscope goals, the workshop aimed to define how SAFOD data could address the following fundamental questions: How do earthquakes initiate? How do fault geometry, rheology, and history combine to determine the size, location, and propagation characteristics of earthquakes? What is the slip distribution during earthquakes and what can we learn from heterogeneities about fault geometry and fault rheology? How localized is the slipping zone during a single earthquake and how does it evolve to form a mature shear zone? How localized is the shear zone beneath the seismogenic zone? What are the physical properties of fault-zone materials and country rock (seismic velocities, electrical resistivity, density, porosity)? What are the mineralogy, deformation mechanisms, and constitutive properties of fault gouge? We discussed how existing and future SAFOD data provides a path to answer such questions. 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." The SAFOD project was an ambitious undertaking with equally ambitious goals. Significant technical and scientific accomplishments resulted from this campaign.

Key Dates:

1992	Asilomar workshop on San Andreas Fault Zone Drilling
1994	Marconi and Menlo Park workshops on site characterization and selection
1998	Initial project proposal for the Earthscope initiative was submitted to NSF with 68 Principal Investigators from U.S. universities, the United States Geological Survey, Department of Energy, and International Continental Drilling Program (ICDP)
2000	Dense seismic network installed
2002	SAFOD Pilot Hole (ICDP project)
2004	SAFOD Main Hole, Phase 1
2005	SAFOD Main Hole, Phase 2
2007	SAFOD Main Hole, Phase 3
2008	Deployment of USGS seismometers in the damage zone (through 2015)
2010	Experimental measurement of travel time variations between the pilot and main holes
2017	Experimental measurement of travel time variations between the pilot and main holes (continuing as of 2019)
2018	Synthesis workshop

Key SAFOD Technical and Outreach Successes:

- The SAFOD borehole was the first to cross a plate-boundary fault at seismogenic depths, and remains one of the deepest boreholes into a major plate boundary in the world.
- The decision to drill the project in phases allowed for improved locations of the repeating microearthquakes, enough time to digest all the logging data, and the coring targets to be precisely identified.
- The project achieved almost 100% recovery of rock core samples from two fault strands that are actively slipping at seismogenic depths.
- The borehole was the first to directly document the location of fault creep at depth.
- The project drove innovation and technique development for data analyses. For example, double-difference seismic tomography, joint geophysical inversions, “virtual earthquake” method, clay characterization and dating, etc., were some of the techniques developed, utilized, and applied over the course of the project. Some of the methods, such as those related to seismic characterization, were key factors in locating the drill site successfully and guiding the trajectory of the borehole to the target earthquakes.
- An entire generation of students, undergraduate and graduate, were involved in the project. Students, along with early career scientists, participated in the project and gained experience in: field work, scientific drilling, core logging, seismic studies, data analysis, etc.
- The project resulted from the successful integration of different earth science disciplines. In addition, a wide diversity of collaborations (international, inter-university, industry, and extra-USGS) were formed and continue to this day. In all phases of the project, the natural exchange of ideas was promoted.
- The SAFOD project was a great success in terms of outreach and education. A significant number of undergraduate and graduate students owe their theses and careers to science done as part of the overall project. Furthermore, the project hosted the public, media, and visiting scientists at the drill site during various phases of drilling.
- The SAFOD project has been used as a model for drilling in other fault zones (e.g., JFAST, Koyna, DFDP, and other IODP/ICDP projects).

Key SAFOD Science Outcomes

- The project showed that slip between the North American and Pacific tectonic plates in central California takes place along a few remarkably narrow (2- to 3-m-wide) zones of highly localized active creep embedded within a much broader (200-m-wide) damage zone.
- The subsurface geology around the fault in central California is now well constrained, which was impossible to do without drilling.
- Borehole measurements and measurements on the core samples document that the fault slips easily at low stresses—it is “weak”—whereas the crust around it is strong. This may be a characteristic of plate-boundary faults, which differ from other faults.
- The project determined that the fault behavior observed at this location and depth is related to the presence of exceedingly weak minerals. These minerals formed during ongoing chemical reactions within the fault due to association with and juxtaposition of different rock types reflecting the rich tectonic history of the San Andreas fault zone.
- Borehole instruments currently sit 50–100 m from repeating microearthquakes.

- The project determined that the fault is a barrier to horizontal flow. However, it also determined that the role of fluids is significant. Fluids within the fault zone helped facilitate chemical reactions leading to the observed fault behavior.
- Project measurements of trapped and guided seismic waves showed that the damage zone is 200 m wide and extends for kilometers along strike and to depth.
- The target repeating earthquakes near SAFOD responded to the Parkfield earthquake. This indicated that fault movement accelerated in response to the earthquake; the repeat rate increased.
- Earthquakes recorded at the SAFOD site are similar to other earthquakes observed on other segments of the SAF. Down to $M = 0$, the stress drop is magnitude-invariant (meaning: $M = 2$ earthquakes have a range of stress drop values that are similar to the range of values for $M = 6$ earthquakes). In addition, instruments at SAFOD recorded earthquakes as small $M = -3$ and showed that small earthquake ruptures can be complex, just like large earthquakes.
- Borehole instruments showed that the repeating earthquakes start abruptly without seismically observable transition, i.e. within a millisecond of rupture initiation they release most of the accumulated stress.

Biggest Disappointments:

- Due to technical, schedule, and funding challenges, the project was not able to realize one of its goals, coring one of the target microearthquake patches (the Hawaii patch being the most logical and technically feasible). The scientific rationale for realizing this goal is still as critical and appropriate now as it was when the project was designed (see Future Directions).
- The lack of NSF support to establish the observatory and, in consequence, the absence of long-term monitoring beyond the USGS effort. The rationale for near-field monitoring is still as important and as timely now as it was before. Drilling techniques and instrumentation are also better now than they were then (see Future Directions).

Future Directions and Next Steps:

Future (SAFOD Phase IV) SAFOD drilling was discussed. The future project would be guided by the PI Team, science goals, and expected outcomes. The plan outlined below is shared as a potential future direction (road map), as discussed by the workshop participants.

SAFOD PHASE IV: Drilling and Near-Field Instrumentation

- Main Activities
 - Drill out of the current borehole and aim towards the HI nucleation patch, without drilling through it.
 - Install a fiber optic cable behind casing in the new borehole.
 - DAS: Obtain wide-band (0.01 Hz to 4 kHz) seismic data, capture earthquake initiation (nucleation) process.
 - DTS: Capture fluid flow and poroelastic phenomenon near an earthquake.
 - DSS: Measure low frequency deformation and creep within the fault zone.
 - Install a pore pressure sensor at end of hole near the fault plane.
- Pre-drilling Activities

- Instrument the current borehole and observe several “Hawaii” earthquake cycles in order to improve the location of the nucleation patch.
- Collect a 3D seismic survey at the site. The survey, combined with the large, existing detailed geological and borehole datasets would result in an unprecedented model of the geological and seismic structure of the SAFOD site.
- Expected Outcomes
 - Detection of the nucleation process of the repeating earthquakes.
 - Observation of seismic, strain, and pore pressure changes during the seismic cycle as measured in the near field.

Outcomes:

- 1) Discussions and planning are underway for submission of a grant to instrument the current borehole with a fiber optic cable (DAS) and a 3-component geophone. These instruments would serve a strong scientific purpose by observing the repeating earthquakes in the near-field at high rates, would continue to gain valuable information on local and regional seismicity and would be critical for any potential future SAFOD drilling. Such instruments have already shown their utility and ability to survive in the borehole environment. Issues concerning borehole access, management, and potential funding sources (NSF I/F) are ongoing (site lease is being renewed).
- 2) Workshop participants discussed the “core” facility. Core sampling and distribution responsibilities are currently in the process of being transferred to IODP control (it is physically housed at the IODP GCR at TAMU). Core would then be distributed under IODP guidelines (with some potential agreed changes) and be available to a wider array of scientists. Participants agreed that this should be done as soon as possible, but AFTER currently funded NSF projects (n = 2) receive their samples. This would also require the new core viewing system to be rolled out publicly. Discussions between Judi Chester, IODP GCR, NSF, and some workshop participants are ongoing to iron out the final details.
- 3) The identification of science goals that would drive and individuals that would lead a future drilling phase at the SAFOD site. Expected outcomes were also documented.

Public Output:

1. This Report
2. Workshop Abstract Book:
 - a. (http://www.earthscope.org/sites/default/files/2019-03/2018_SAFOD_Synthesis_Workshop.pdf)
3. 2019 AAAS Presentation:
 - a. “*Scientific Accomplishments at The San Andreas Fault Observatory at Depth (SAFOD)*”
4. 2019 Earthscope Newsletter Article
 - a. (http://www.earthscope.org/articles/SAFOD_gold_standard)