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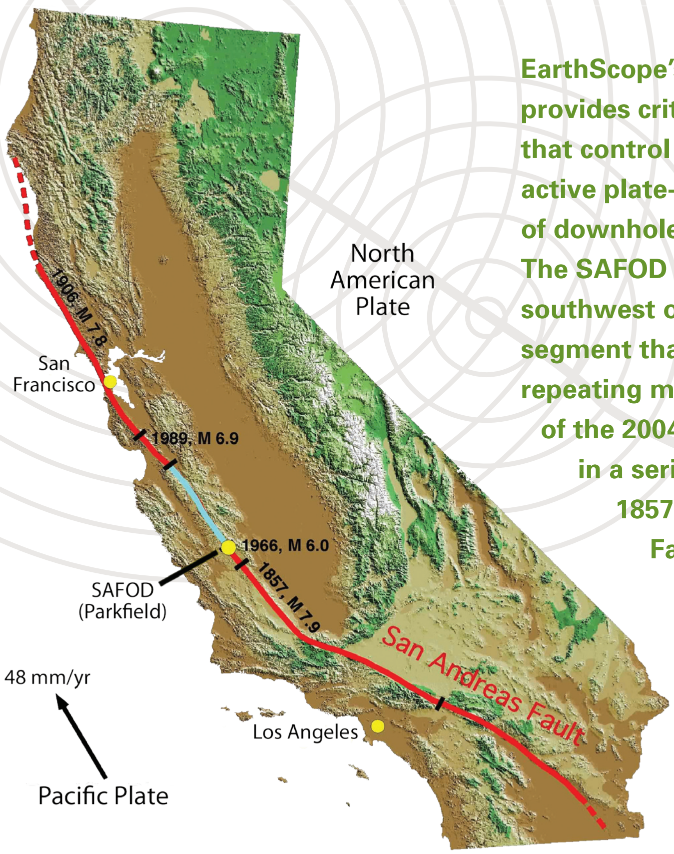
San Andreas Fault Observatory at Depth

the first five years

San Andreas Fault Observatory

SAFOD



EarthScope's San Andreas Fault Observatory at Depth (SAFOD) provides critical information on the physical and chemical processes that control deformation and earthquake generation within an active plate-bounding fault zone through an integrated program of downhole sampling, measurements, and long-term monitoring. The SAFOD main hole is located in central California ~ 1.8 km southwest of the San Andreas Fault near Parkfield, California, on a segment that moves through a combination of aseismic creep and repeating microearthquakes. It lies just north of the rupture zone of the 2004 magnitude ~ 6 Parkfield earthquake, the most recent in a series of events that ruptured the fault seven times since 1857. The SAFOD main hole penetrates the San Andreas Fault where earthquake activity has been identified, and a long-term borehole observatory installed in fall 2008 monitors ongoing activity.

June 6, 2002
Pilot hole drilling begins

July 24, 2002
Pilot hole drilling ends

June 11, 2004
PHASE 1
Main hole drilling begins

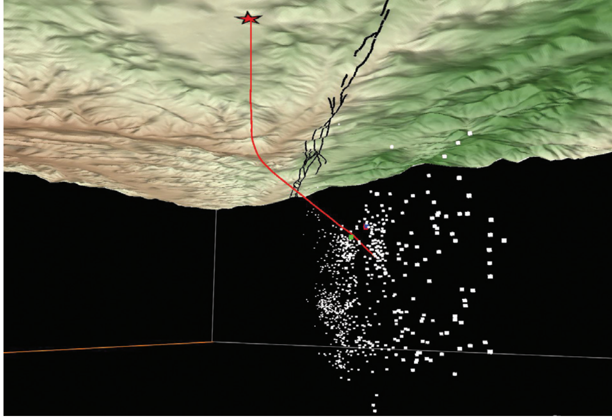
October 6, 2004
PHASE 1
Main hole drilling ends

June 8, 2005
PHASE 2
Main hole drilling begins

August 28, 2005
PHASE 2
Main hole drilling ends

2002 | 2003 | 2004 | 2005 | 2006 | 2007

at Depth



SAFOD Phases

Pilot Hole

In preparation for SAFOD, a 2.2-km-deep vertical pilot hole was drilled and instrumented at the SAFOD site during summer 2002. The pilot hole was a collaborative effort among the International Continental Scientific Drilling Program, the National Science Foundation, and the US Geological Survey. The rotary-drilled pilot hole is available to investigators for fault zone monitoring, instrument testing, cross-borehole experiments, and related scientific activities.

Phase 1 and Phase 2: The Main Hole

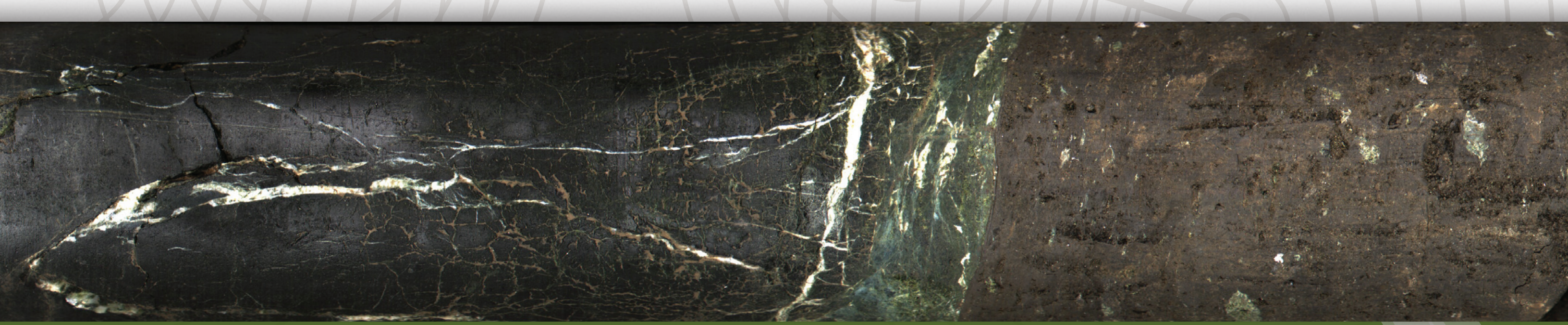
The SAFOD main hole was rotary drilled during the summers of 2004 (Phase 1) and 2005 (Phase 2). The main hole starts vertically, but at ~ 1.5-km depth, directional drilling techniques were used to deviate the borehole at an angle ~ 60° from vertical to drill through the entire width of the San Andreas Fault near two clusters of repeating microearthquakes at a vertical depth of ~ 2.7 km. These events (magnitude ~ 2) rupture the same sections of the fault every few years in nearly identical earthquakes. By drilling through the fault zone, scientists were able to make the first geophysical measurements of the structure and properties of the San Andreas Fault at seismogenic depth, identify active strands of the fault (for subsequent coring operations), and place instruments very close to future rupture zones to study processes associated with earthquake nucleation that cannot be seen at the surface.

Phase 3

During Phase 3, several sidetracks were drilled laterally off the Phase 2 main hole to obtain core samples from two actively deforming traces of the San Andreas Fault. These core samples provide the scientific community with the first samples ever obtained from an active major fault zone at depth. To hundreds of earthquake scientists, access to these samples ends decades of speculation about the actual fault's composition and the need to use proxies in laboratory studies. Studies of these unique samples are getting underway in research laboratories around the world.

Permanent Observatory

Installation of the long-term observatory was completed on September 28, 2008. The instrument package deployed at depth consists of borehole seismometers, accelerometers, and tiltmeters. These instruments permit observation of variations in deformation, fluid pressure, microseismicity, and radiated seismic energy within and adjacent to recurring earthquake rupture patches over multiple earthquake cycles. Acting in concert with studies on recovered samples, SAFOD monitoring makes it possible to observe directly a number of time-dependant processes related to earthquake nucleation, propagation, and arrest.



June 14, 2007
PHASE 3
Main hole drilling begins

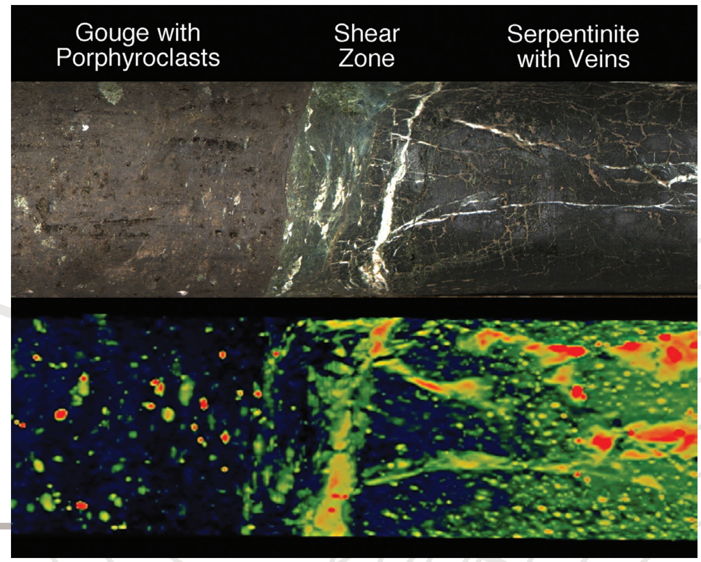
September 15, 2007
PHASE 3
Main hole drilling ends

September 28, 2008
Installation of long-term observatory completed

2008 | 2009 | 2010 | 2011 | 2012

The Science and Discoveries of SAFOD

Core Samples Constrain Composition and Structure of the San Andreas Fault Zone



Altogether, approximately 135 ft of 4-in diameter rock cores weighing roughly 1 ton were extracted from SAFOD during Phase 3. These core samples captured actively deforming traces of the fault at depth and provide a remarkable view of the structure of the entire San Andreas Fault zone at seismogenic depth. Geophysical measurements define a broad zone of damaged rock that is cut by localized zones with large cumulative displacement and a history of seismic and aseismic deformation. Active creep has been documented along two zones that contain meters-thick layers of incohesive, foliated gouge displaying fabrics consistent with distributed shear in the layers. The photograph and 3-D maximum intensity projection of X-ray computed tomography image (right) for a portion of one of the gouge layers shows a sheared zone of serpentinite at the contact with the gouge layer. Scientists have speculated about the presence of serpentinite within the San Andreas Fault zone for over 40 years.

Chester, J., et al. 2008. Structure of the San Andreas fault zone at SAFOD. Geological Society of America Abstracts with Programs, Paper 147-5, 40(6):150.

Talc Found in Fault Zone Samples

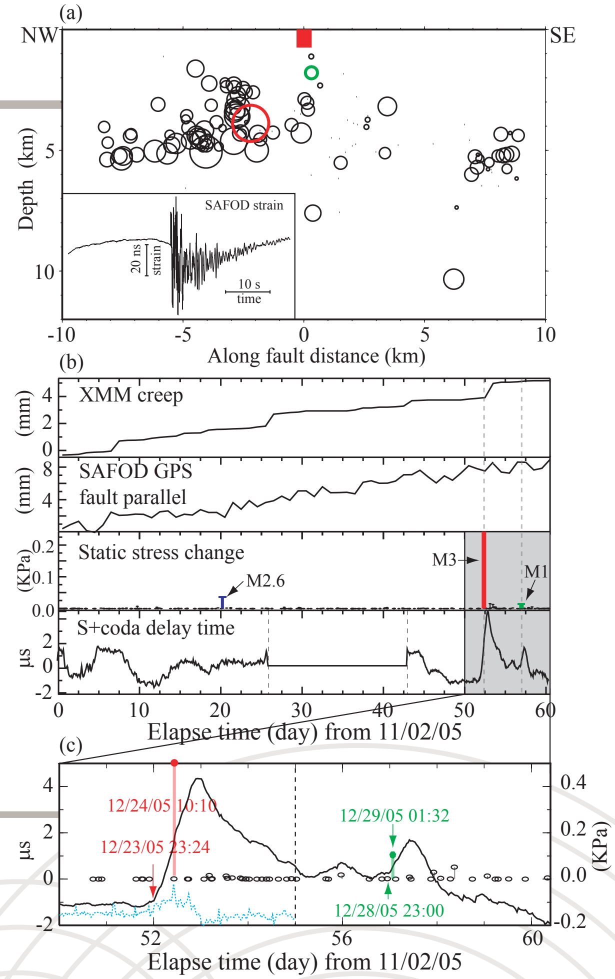
The soft, slippery mineral talc was discovered in cuttings of serpentinite collected from the active trace of the San Andreas Fault that was intersected during drilling of the main SAFOD hole in 2005. The talc was produced by the reaction of serpentine with silica-bearing groundwater that migrated up the fault; the talc in the photo formed along the foliation in a grain of sheared serpentinite. Serpentinite is commonly invoked as the cause of the observed fault creep and the low strength of this section of the San Andreas Fault; however, the frictional strengths of serpentine minerals are too high to give rise to the observed fault behavior. At elevated temperatures, the frictional strength of talc is sufficiently low to meet constraints on the shear strength of the fault, and its inherently stable sliding behavior is consistent with fault creep. Talc may therefore provide the connection between serpentinite and creep in the San Andreas Fault, if shear at depth can become localized along a talc-rich principal-slip surface within serpentinite entrained in the fault zone.

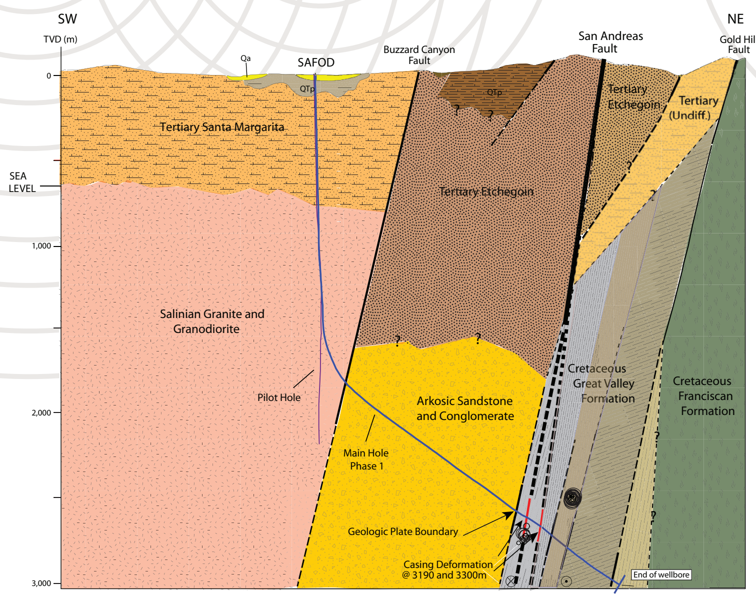
Moore, D.E., and M.J. Rymer. 2007. Talc-bearing serpentinite and the creeping section of the San Andreas Fault. Nature 448:795–797, doi:10.1038/nature06064.

Velocity Changes Observed

A long-sought goal of seismology is to measure stress changes within seismically active fault zones. One approach is to exploit the stress dependence of seismic wave velocity. An active source, cross-well experiment at the SAFOD drill site showed that stress changes are indeed measurable using this technique. Over a two-month period, scientists observed an excellent anti-correlation between changes in the time required for a shear wave to travel through the rock along a fixed pathway (a few microseconds) and variations in barometric pressure. They also observed two large excursions in the travel-time data that coincide with two earthquakes that are among those predicted to produce the largest coseismic stress changes at SAFOD. The two excursions started approximately 10 and 2 hours before the events, respectively, suggesting that they may be related to pre-rupture stress-induced changes in crack properties, as observed in early laboratory studies.

Niu, F., et al. 2008. Preseismic velocity changes observed from active source monitoring at the Parkfield SAFOD drill site. Nature 454:204–208, doi:10.1038/nature07111.





A Weak Fault in a Strong Crust

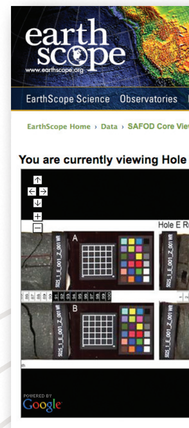
Downhole measurements made during Phases 1 and 2 address fundamental questions about the physics of faulting on the San Andreas Fault. The direction of maximum horizontal stress was found to be at a high angle to the San Andreas Fault at depth, indicating that fault slip occurs in response to low resolved shear stress. These measurements, and other information on the forces acting within the fault zone at depth, are consistent with the strong crust/weak fault model of the San Andreas proposed nearly 40 years ago that had not been confirmed by direct observations. Further support for the strong crust/weak fault model comes from temperature measurements at depth in the SAFOD main hole that show no evidence of frictionally generated heat. In addition, there has been no evidence of elevated pore fluid pressure in the fault zone at depth. It had been widely speculated that elevated fluid pressure in the fault zone was responsible for its low frictional strength. We now know that this is not the case and that other mechanisms (such as the composition and chemical alteration of the fault gouge) are responsible for its low strength.

Zoback, M.D., and S.H. Hickman. 2007. Preliminary results from SAFOD Phase 3: Implications for the state of stress and shear localization in and near the San Andreas Fault at depth in central California, EOS, Transactions of the American Geophysical Union, 88(52).

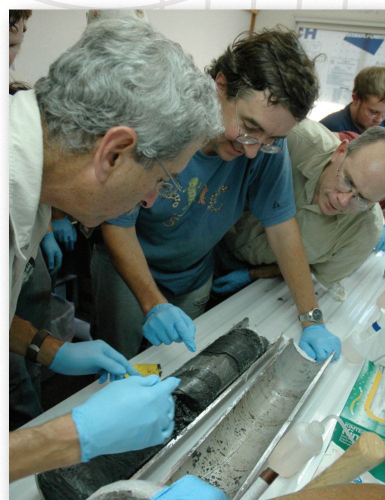
SAFOD
Cooperation,

A Partnership With NSF

EarthScope's San Andreas Fault Observatory at Depth (SAFOD) was funded by the National Science Foundation (NSF) and conducted in full partnership with the US Geological Survey (USGS). The SAFOD pilot hole was drilled in 2002 with financial support from the International Continental Scientific Drilling Program, USGS, and NSF. The successful completion of the SAFOD observatory would not have been possible without the assistance of numerous researchers at US and foreign institutions who participated in pre-drilling surveys, operation of field laboratories, and data collection during drilling operations. SAFOD also received major support from Stanford University, USGS, the Integrated Ocean Drilling Program Gulf Coast Repository, and the German Research Centre for Geosciences. NASA made important contributions to SAFOD downhole instrumentation. A variety of commercial companies provided goods and services to SAFOD at greatly reduced costs, including ThermaSource Inc., which provided drilling engineering and supervisory services, Pinnacle Technologies, Geometrics, Guralp Systems Inc., Oyo Geospace, Paulsson Geophysical Services, and Scientific Drilling, as well as Baker-Hughes, Schlumberger, and Halliburton.

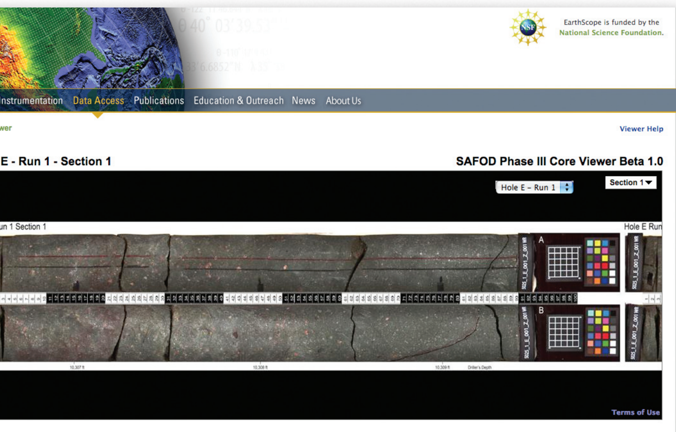


Data For Research and Education



SAFOD data include: (1) physical samples for laboratory studies; (2) time series collected by borehole seismometers, accelerometers, and tilt and strain meters; and (3) fault zone physical property measurements. The Northern California Earthquake Data Center at the University of California, Berkeley, is in charge of metadata, data conversion, and quality assurance/quality control for SAFOD time-series data and is the primary archive for these data, with the IRIS Data Management Center serving as a backup archive. SAFOD data pertaining to drilling operations, downhole measurements, and samples are maintained as part of the International Continental Scientific Drilling Program (ICDP). Raw data files for the variety of geophysical logs collected are available for download via the ICDP Web site and EarthScope Data Portal. All physical samples collected by SAFOD are stored at the Gulf Coast Repository of the Integrated Ocean Drilling Program at Texas A&M, as are petrographic thin sections prepared from selected cuttings and core samples.

Research, and Education



SAFOD Core Viewer

As a result of the very successful recovery of cores from across the active San Andreas Fault, EarthScope has received proposals to work on SAFOD Phase 3 samples from over 100 scientists from around the world with over 800 requests for SAFOD core and cuttings samples. As a mechanism for tracking core sample requests, the SAFOD Core Viewer was developed using the Google Maps Application Programming Interface for display and navigation of the core images, facilitating the zooming and panning controls and core sample selection. The core viewer can be accessed at http://www.earthscope.org/data/safod_core_samples.

Lots More Yet to Come

Now that drilling and coring are complete, a wide range of scientific studies are getting underway. Comprehensive studies of the core are beginning in about 20 research laboratories around the world. These studies will provide, for the first time, a direct view of the wide variety of complex physical and chemical processes occurring within active fault zones at seismogenic depth. Acting in concert with studies on recovered samples, SAFOD downhole monitoring will make it possible to observe directly a number of time-dependant processes related to earthquake nucleation, propagation, and arrest within and adjacent to recurring earthquake rupture patches over multiple earthquake cycles, including: (1) the possible role of temporal variations in fluid pressure within the fault zone in controlling earthquake periodicity and rupture propagation and arrest, (2) the interplay between aseismic and seismic fault slip in the nucleation process for repeating microearthquakes, (3) the time scales and physical processes through which stress and strain interactions occur between nearby earthquakes, and (4) the manner in which earthquake energy is partitioned among seismic radiation, frictional dissipation, grain-size reduction, and chemical reactions.

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About earthscope

EarthScope is a set of integrated and distributed multipurpose geophysical instruments that provide observational data to significantly enhance our knowledge of the structure and evolution of the North American continent and the processes controlling earthquakes and volcanic eruptions. Three components being implemented in parallel define EarthScope:

- The **San Andreas Fault Observatory at Depth** is a three-kilometer-deep hole drilled through the San Andreas Fault in an area between San Francisco and Los Angeles near Parkfield, California, that has ruptured seven times since 1857.

- **USArray** is a dense network of permanent and portable seismographs and magneto-telluric sensors that are being installed across the continental United States to record earthquakes and naturally occurring variations in Earth's electric and magnetic fields.

- The **Plate Boundary Observatory** is a network of geodetic and strain instrumentation that is imaging fast and slow deformation in the lithosphere along the western United States and Alaska.

The EarthScope facilities were constructed under the National Science Foundation's Major Research Equipment and Facilities Construction account.

SAFOD is funded by the National Science Foundation and conducted in partnership with the US Geological Survey. It is a project of the International Continental Scientific Drilling Program.

www.earthscope.org/observatories/safod