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Introduction to special section: Preparing for the San Andreas Fault Observatory at Depth

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Introduction to special section: Preparing for the San Andreas Fault Observatory at Depth

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1. Introduction

[1] The San Andreas Fault Observatory at Depth (SAFOD) is a comprehensive project to drill into the hypocentral zone of repeating M $\sim$ 2 earthquakes on the San Andreas Fault at a depth of about 3 km. The goals of SAFOD are to establish a multi-stage geophysical observatory in close proximity to these repeating earthquakes, to carry out a comprehensive suite of downhole measurements in order to study the physical and chemical conditions under which earthquakes occur and to exhume rock and fluid samples for extensive laboratory studies. In the vicinity of SAFOD, the San Andreas is moving through a combination of aseismic creep and repeating microearthquakes (Figure 1). SAFOD is one element of the National Science Foundation's (NSF) new EarthScope initiative (see www.earthscope.org). Drilling, testing and instrumentation of SAFOD is beginning in the summer of 2004 and will be completed in 2007, with fault-zone monitoring activities scheduled to continue for at least 20 years. An overview of the generalized drilling, sampling, testing and monitoring plan for SAFOD can downloaded at http://www.earthscope.org/assets/es_parts_I-IV_lo_1.25.pdf.

[2] SAFOD will provide new insights into the composition and physical properties of fault zone materials at depth and the constitutive laws governing fault behavior. Even after decades of intensive research, numerous fundamental questions about the physical and chemical processes acting within the San Andreas and other major plate-bounding faults remain unanswered. SAFOD also will provide direct knowledge of the stress conditions under which earthquakes initiate and propagate. Although it is often proposed that high pore fluid pressure exists within the San Andreas Fault Zone at depth and that variations in pore pressure strongly affect fault behavior, these hypotheses are unproven and the origin of overpressured fluids, if they exist, is unknown. As a result, myriad untested laboratory and theoretical models related to the physics of faulting and earthquake generation fill the scientific literature. Drilling, sampling and downhole measurements directly within the San Andreas Fault Zone will substantially advance our understanding of earthquakes by providing direct observations of the composition, physical state and mechanical behavior of a major active fault zone at hypocentral depths. In addition to retrieval of fault zone rocks and fluids for laboratory analyses, intensive downhole geophysical measurements and long-term monitoring are planned within and adjacent to the active fault zone. Observatory-mode monitoring activities will include near-field, wide-dynamic-range seismological observations of earthquake nucleation and rupture as well as continuous monitoring of pore pressure, temperature and strain during the earthquake cycle. Directly evaluating the roles of fluid pressure, intrinsic rock friction, chemical reactions, in situ stress and other parameters in the earthquake process will provide the information needed to simulate earthquakes in the laboratory and on the computer using representative fault zone properties and physical conditions.

[3] In preparation for SAFOD, an extensive suite of geophysical site investigations has been conducted around the drill site and across the San Andreas Fault. In addition, a 2.2-km-deep vertical pilot hole was drilled at the SAFOD site in the summer of 2002. This special section of Geophysical Research Letters, which is split into two separate issues of the printed journal, presents results from these site investigations together with geological and geophysical studies conducted in the SAFOD pilot hole. The first of these print issues presents nine papers discussing surface-based and downhole investigations of earthquakes and large-scale crustal structure. The second print issue presents ten papers on the thermomechanical setting of the San Andreas Fault together with laboratory and in situ investigations of physical properties and mineralogy from the SAFOD pilot hole. In this introductory article, we present background material that will help place these papers in the broader perspective of the overall SAFOD project. (For the sake of brevity, no references are cited in this article, aside from a citation to the geophysical model shown in Figure 2. Instead, the relevant references are cited in papers contained within this special section).

2. Overview of SAFOD

[4] The SAFOD site is located 1.8 km southwest of the San Andreas Fault near Parkfield, CA (Figure 1). The San Andreas Fault at this location is creeping at the surface at about 2 cm/year, with most of the fault displacement localized to a zone no more than 10 m wide. Numerous microearthquakes occur along the San Andreas Fault near SAFOD at depths of 2.5 to 12 km. SAFOD lies just north of the rupture zone of the 1966, magnitude 6 Parkfield

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Figure 1. Shaded relief map of California showing the location of SAFOD. Portions of the San Andreas Fault that ruptured in major historical earthquakes are shown in red, with the creeping and microseismically active segment of the fault in blue.

earthquake, the most recent in a series of events that have ruptured the fault five times since 1857.

[5] At the surface, the SAFOD drill site is located west of the vertical San Andreas Fault so that the borehole will pass through the entire fault zone and continue into relatively undisturbed country rock on the east side (Figure 2). Rock and fluid samples recovered from the fault zone and country rock will be tested in the laboratory to determine their compositions, deformation mechanisms, frictional behavior and physical properties. Importantly, we will use the locations of microearthquakes and ongoing fault creep (detected through repeat measurements of casing shear) to select intervals in which to obtain continuous core from sidetracks to the main SAFOD borehole. This will allow us to compare and contrast the mineralogy, physical properties and deformational behavior of fault rocks that fail primarily through creep against those that fail during repeating microearthquakes. During drilling SAFOD will undergo an intensive series of downhole measurements to determine how stress, fluid pressure, heat flow and other properties vary across the San Andreas Fault Zone. After this, the borehole will be instrumented as a long-term geophysical observatory to monitor earthquakes, deformation, fluid pressure and temperature within and adjacent to the fault zone.

[6] As mentioned above, NSF is funding SAFOD as part of the EarthScope project. The other funded elements of EarthScope include USArray and the Plate Boundary Observatory (PBO). USArray consists of a large transportable broadband seismic array that will eventually cover the entire continental United States, augmented by a pool of portable seismic instruments for high-resolution, short-term observations. USArray will also help complete the U.S. Geological Survey's (USGS) Advanced National Seismic System backbone network. The PBO is a network of deformation sensors now being deployed throughout the Western United States. The PBO will consist of a backbone network of Global Positioning System (GPS) receivers, together with focused deployments of GPS receivers and borehole strainmeters (plus a limited number of long baseline strainmeters) in tectonically active areas. Scientific studies using SAFOD and the other EarthScope facilities will be supported through programs within the NSF, USGS and other institutions in the U.S. and abroad.

[7] When considering potential sites along the San Andreas Fault system for SAFOD, we focused on sites with shallow seismicity, a clear geologic contrast across the fault and good knowledge of the structure of the fault zone and surrounding crust. The requirement for shallow seismicity

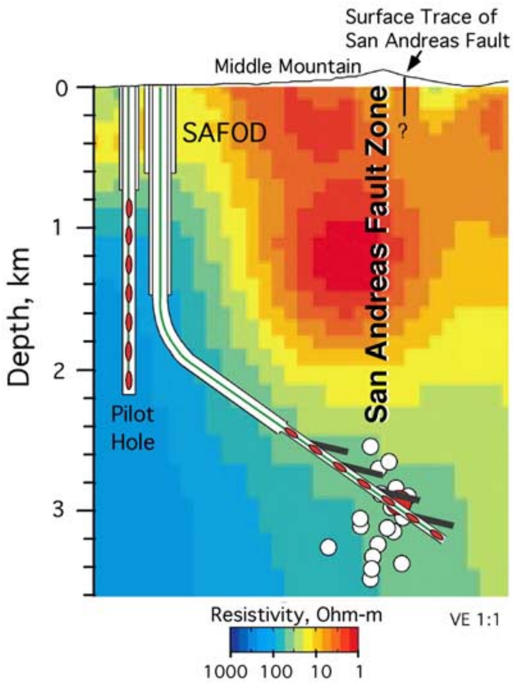

Figure 2. Schematic of SAFOD, superimposed on electrical resistivity structure from surface magnetotelluric recordings [*Unsworth and Bedrosian*, 2004]. Approximate locations of small ($M \leq 2$) earthquakes are shown as white dots, with the location of the SAFOD target earthquakes in red. An extensive program of downhole measurements, spot coring and fluid sampling will be conducted during drilling, both before and after setting casing. Following a two-year period of downhole seismic monitoring and repeat measurements of casing deformation, four 250-m-long core holes (shown in black) will be drilled off the main hole to obtain rock and gouge samples from the most active portions of the fault zone. SAFOD will then be instrumented with downhole sensors (red ovals) for long-term monitoring of seismicity, deformation, fluid pressure and temperature. The surface locations of the pilot hole and SAFOD are within 10 m of each other, and are separated here only for clarity. The geophone array currently installed in the pilot hole is schematically shown in red.

was key for two reasons. First, we intend to conduct experiments within (and adjacent to) seismically active parts of the fault. Second, we are using ongoing seismicity to tell us the precise location of the active trace (or traces) of the fault at depth.

[8] To identify potential drilling sites, a working group was formed in 1993 to systematically examine all of the strike-slip faults in California, identifying all faults that met the shallow seismicity criterion. This criterion eliminated all candidate faults in southern California. In central and northern California only three localities met the criterion for reasonably complete geological and geophysical control. These were the Hayward fault near San Leandro, the San Andreas Fault in the Cienega Road to Melendy Ranch region, and the Middle Mountain region along the Parkfield segment. We then convened a workshop in 1994 on the scientific goals, experimental design and site selection process for SAFOD that was attended by about 45 people. Although all three potential sites had unique advantages, it became clear that the Middle Mountain site at Parkfield was the best place to conduct SAFOD because:

[9] • Surface creep and abundant shallow seismicity allow us to accurately target the subsurface position of the fault (Figure 2).

[10] • There is a clear geologic contrast across the fault, with granitic rocks on the west side of the fault and Franciscan melange on the east. The granitic rocks provide for good drilling conditions, and the geologic contrast will help us determine when the drill hole has crossed the main fault trace.

[11] • The Parkfield region is the most comprehensively instrumented section of a fault anywhere in the world, and has been the focus of intensive study establishing its geological and geophysical framework over the past two decades as part of the USGS Parkfield Earthquake Experiment (see http://quake.wr.usgs.gov/research/parkfield/).

[12] An important feature of the microearthquakes being targeted by SAFOD is that they occur in families of repeating events; individual earthquakes of magnitude 2 and smaller have been observed to recur numerous times within the SAFOD target region at precisely the same location at intervals of 3 years or less. Thus, a major goal of SAFOD is to drill as close as possible to one or more of these repeating earthquake sources and monitor temporal variations in strain, fluid pressure and other parameters through multiple earthquake cycles. Should the magnitude 6 Parkfield earthquake recur after SAFOD is completed, it is likely that the coseismic displacement of the earthquake would extend to within a few km of the SAFOD fault crossing. This presents the possibility that we might observe the nucleation and initial rupture propagation of a magnitude 6 earthquake at close range, and observe an enhanced production rate of shallow earthquakes as part of the aftershock sequence. This would add greatly to the scientific return from the fault zone monitoring stage of SAFOD.

3. SAFOD Pilot Hole

[13] To lay the scientific and technical groundwork for SAFOD, a 2.2-km-deep pilot hole was drilled in the summer of 2002 at the SAFOD site (Figure 2). Drilling of the pilot hole was funded by the International Continental Drilling Program (ICDP), with considerable scientific and logistical support provided by NSF and USGS.

[14] As presented in several of the papers from this special section, significant progress has already been made in achieving the scientific and technical goals for the SAFOD pilot hole. The goals and accomplishments of the pilot hole include:

[15] • A 32-level array of three-component geophones deployed in the pilot hole by Duke University is facilitating precise earthquake hypocenter determinations that will guide subsequent SAFOD scientific investigations as well as drilling and coring activities in the fault zone.

[16] • As discussed below, this pilot hole geophone array also recorded surface seismic sources (and provided near-surface velocity control) for seismic imaging experiments conducted in October 2002 and October–November 2003.

[17] • Downhole measurements of physical properties, stress, fluid pressure and heat flow in the pilot hole helped characterize the shallow crust adjacent to the fault zone. These data are being used to help calibrate physical properties inferred from surface-based geophysical surveys (e.g., seismic velocities, seismic anisotropy, resistivity and density) and better constrain the strength of the San Andreas Fault and adjacent crust prior to SAFOD drilling.

[18] • Long-term seismic, deformation and fluid pressure monitoring in the pilot hole will make it possible to assess time-dependant changes in the physical properties and mechanical state of the crust adjacent to the fault zone for comparison with similar measurements to be recorded in SAFOD. Also, the pilot hole is providing a critical facility for developing and testing long-term monitoring instrumentation to be used in the main SAFOD hole.

[19] • Although our plan to collect a 60-m-long spot core at the bottom of the pilot hole was not successful due to a logging tool that became stuck in the hole, drill cuttings were continuously collected and described during drilling of the pilot hole. Laboratory studies of these drill cuttings are being used to determine the alteration mineralogy and uplift history of the granitic basement adjacent to the San Andreas Fault.

[20] • Multi-level seismic monitoring in the pilot hole (and at the surface) during SAFOD drilling using the drill bit as a seismic source will allow us to attempt to make high-resolution, near real-time images of the San Andreas Fault Zone at depth.

[21] • From a strictly technological point of view, the pilot hole provided detailed information about subsurface geologic conditions and optimal drilling techniques and parameters that have proven invaluable in designing the drilling and completion plan for the main SAFOD hole.

[22] One of the most gratifying aspects of the SAFOD pilot hole project was confirmation of the preliminary geologic model for the SAFOD site. In particular, the depth to basement of 700–750 m predicted from pre-drilling seismic surveys was very close to the basement depth of 768 m actually encountered during drilling. From this point until reaching total depth, the pilot hole remained in fractured granite, as predicted by members of our science team based upon various geophysical models. Finally, the electrical resistivity measured in the pilot hole by wireline logs increased with depth from about 100 Ohm-m at 0.8 km to about 1000 Ohm-m at 2.2 km, which agrees quite well

with the resistivities inferred using surface-based magnetotelluic measurements (Figure 2).

4. Recent Geophysical Studies at the SAFOD Site

[23] Since the SAFOD project was first proposed about 12 years ago, a wide variety of focused geophysical and geological investigations have been carried out at and surrounding the SAFOD site. These studies include high-resolution seismic reflection and refraction profiles conducted through the SAFOD site and across the San Andreas Fault in 1998 and 2003, airborne and ground-based gravity and magnetic surveys, thermal and geochemical studies in shallow wells, geologic mapping, magnetotelluric profiling, microearthquake relocations, 3-D seismic tomography and fault-zone guided wave studies. This comprehensive suite of geophysical investigations surrounding the SAFOD site is achieving a number of critical milestones. These include determination of the absolute locations of the repeating microearthquakes to be targeted with the main SAFOD hole and better defining the overall structure and geophysical setting of the San Andreas Fault Zone at Parkfield. These investigations are also providing critical information on the locations of secondary fault zones and velocity discontinuities that are being used to design the SAFOD drilling, sampling and testing program.

[24] A key component of the SAFOD site characterization effort—the Parkfield Area Seismic Observatory (PASO)—was deployed by Univ. Wisconsin and Rensselaer Polytechnic Institute around the SAFOD site in 2000–2002, with partial reoccupation of these stations in Oct.–Nov. 2003. These station deployments were augmented by permanent stations of the USGS Northern California Seismic Network and the Parkfield High Resolution Seismic Network run by Univ. of California, Berkeley. In October 2002, a series of calibration shots were set off and recorded by these surface arrays as well as the pilot hole geophone array. As discussed in several of the papers in this special section, analyses of these data have provided improved earthquake locations and a more refined image of the 3-D velocity structure surrounding the SAFOD site.

[25] The latest phase of the geophysical exploration of the fault zone and surrounding crust was conducted in Oct. and Nov. 2003. This included a 50-km-long seismic reflection/wide-angle refraction profile across the San Andreas Fault Zone and through the SAFOD site, which was conducted by a team of U.S. and German scientists. This long-baseline seismic survey was supplemented by a coincident gravity survey and a number of high-resolution, active-source seismic experiments surrounding the SAFOD site and along the San Andreas Fault. All shots from these seismic surveys were simultaneously recorded on the pilot hole geophone array (for more details on the Oct./Nov. 2003 seismic deployments see http://quake.usgs.gov/research/parkfield/2003site.html).

[26] Intensive efforts (too recent to be discussed in this special section) are now underway to analyze the Oct/Nov 2003 data. These analyses are yielding improved images of the velocity structure immediately surrounding the SAFOD site and the distribution and geometry of secondary faults between the drill site and the San Andreas Fault, as well as more accurate locations for the SAFOD target earthquakes. As a result of these efforts, we now know that the SAFOD target earthquakes occur in two distinct "patches" ~100 m in size. The relative locations of these patches are known extremely well (within several 10's of meters), and our best current estimates of the absolute locations of these target earthquakes place them at depths of 2.9–3.0 km below ground surface at the SAFOD wellhead. This information was used to develop the SAFOD drilling, testing and completion plan shown in Figure 2, which is now being implemented at Parkfield. The locations of the SAFOD target earthquakes will be further refined at the conclusion of SAFOD Phase 1 drilling (i.e., in Oct. 2004), when members of the SAFOD science team will deploy a 3-component geophone at the bottom of the SAFOD drill hole and record surface calibration shots on this geophone, on the pilot hole array and at 12 PASO stations that are being reoccupied for a 2-year period starting in August 2004.

5. Concluding Remarks

[27] The papers in this special section present significant scientific contributions in their own right, while also providing information and experience that has been critical for planning and initiating the SAFOD experiment. In addition to the importance of the scientific and technical results obtained in the pilot hole, the appreciable work on 3-D site characterization has lead to more precise target earthquake locations. As a result, the uncertainty in the locations of the ~100 m "patches" of the fault producing the repeating earthquakes we are attempting to intersect with SAFOD has decreased substantially over the past few years to months. Additionally, this work has greatly improved our knowledge of the overall geological and geophysical setting of the San Andreas Fault Zone at Parkfield, as well as the location and geometry of secondary faults between the drill site and the San Andreas Fault itself. Thus, from both a scientific and technical perspective, the site characterization and pilot hole investigations conducted to date have been an outstanding success, and the stage is now very well set for drilling, testing and instrumentation of SAFOD.

[29] **Acknowledgments.** We must begin by noting the scientific contributions of the many member of the SAFOD science team that are only in part reflected by the papers in this special section. We thank the International Continental Drilling Program (ICDP) for providing financial support for drilling the pilot hole as well as providing important technical support for SAFOD itself. The National Science Foundation and U.S. Geological Survey are thanked for providing financial support for the site characterization and pilot hole scientific studies. We also thank the scores of our colleagues from around the world who have participated in the deliberations, preparations and planning for SAFOD over the past 12 years for their perseverance and dedication to the success of this project.

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