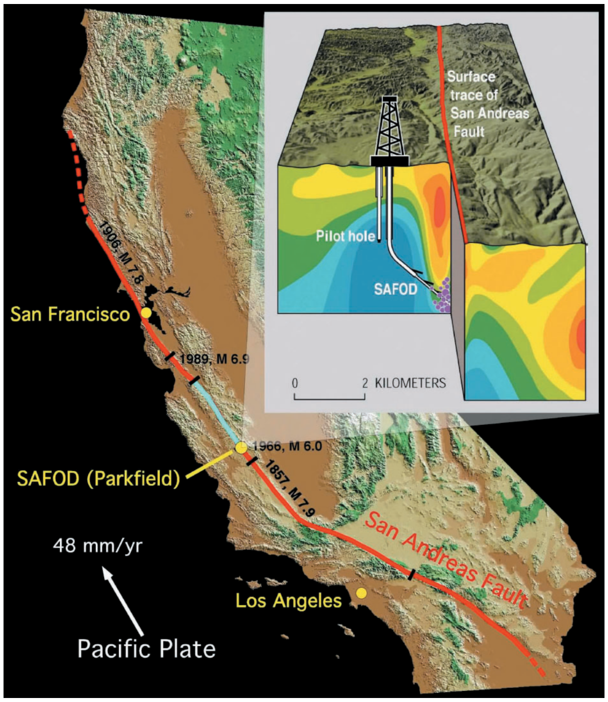
3. SAFOD: The San Andreas Fault Observatory at Depth


Surface
trace of
San Andreas
Fault
Pilot hole
SAFOD
0
2 KILOMETERS
1906, M 7.8
San Francisco
1989, M 6.9
1966, M 6.0
SAFOD (Parkfield)
1857, M 7.9
San Andreas Fault
48 mm/yr
Los Angeles
Pacific Plate

3.1. Field Systems: Technical Description

Scientific Motivation for SAFOD

While the last several decades have seen a greatly improved understanding of the kinematics of the San Andreas and other plate-bounding fault systems around the world, the physical and chemical processes that control earthquake nucleation and rupture propagation remain a mystery. Not surprisingly then, myriad untested and unconstrained hypotheses fill the geophysical literature based on inferences from laboratory and theoretical studies. Today, we know virtually nothing about the composition of the fault at depth, its constitutive properties, the state of *in-situ* stress or pore pressure within the fault zone, the origin of fault zone pore fluids, or the nature and significance of time-dependent fault zone processes.

The central scientific objective of the San Andreas Fault Observatory at Depth (SAFOD) is to study directly the physical and chemical processes that control deformation and earthquake generation within an active plate-bounding fault zone. A detailed scientific rationale and experimental plan for SAFOD can be found in a proposal that was submitted to NSF in August 1998 (available at the SAFOD web site: http://www.icdp-online.de/html/sites/sanandreas/news/). The 1998 proposal also includes synopses of an integrated suite of allied scientific investigations proposed by 33 researchers from 19 U.S. universities, about 15 scientists from the U.S. Geological Survey (USGS) and other national labs, and scientists from 12 institutions in 4 foreign countries. These proposals —and doubtless many more—will be resubmitted to NSF and other U.S. and international funding agencies under EarthScope.

SAFOD will enable a broad spectrum of the Earth science community to address multiple scientific objectives:

- Through long-term fault zone monitoring and *in-situ* observations of the earthquake source, we will be able to test and improve models for earthquake rupture dynamics, including such effects as transient changes in fluid pressure, fault-normal opening modes and variations in slip pulse duration. These observations can be used directly in attempts to generate improved predictions of near-field strong ground motion (amplitude, frequency content and temporal characteristics) and more reliable models for dynamic stress transfer and rupture propagation. These latter processes are believed to control earthquake size (i.e., whether or not a small earthquake will grow into a large one) and, hence, are crucial to long-term probabilistic assessments of earthquake hazard.

- By directly evaluating the roles of fluid pressure, intrinsic rock friction, chemical reactions and the physical state of active fault zones in controlling fault strength we will provide earthquake researchers the opportunity to simulate earthquakes in the laboratory and on the computer using representative fault zone properties and physical conditions. These studies will also allow for improved models of static stress transfer and earthquake triggering at a regional scale and between specific faults, as needed for intermediate-term seismic hazard forecasting following large earthquakes.

- The results of the proposed experiment are critical to development of more realistic models for the seismic cycle and assessment of the practicality of short-term earthquake prediction in two ways. First, in the fault zone monitoring phase of the proposed experiments, we will be able to determine if earthquakes are preceded by accelerating fault slip (e.g., a nucleation phase) and/or transient changes in fluid pressure. Second, we will be able to determine whether or not factors that might dramatically lower fault strength (high pore pressure and/or chemical fluid-rock interactions, for example) are closely related to the processes controlling earthquake nucleation. Our current knowledge of fault zone processes is so poor that not only are we unable to make reliable short-term earthquake predictions, but we cannot scientifically assess whether or not such predictions are even possible.

- As the weakness of plate boundaries (relative to plate interiors) is a fundamental aspect of plate tectonics, how and why plate boundary faults lose their strength is of first-order importance for understanding where plate boundaries form, how they evolve with time and how deformation is partitioned along them.

While the idea of drilling into the San Andreas Fault has arisen many times over the past several decades, this project had its origin in December of 1992 when a workshop was convened on scientific drilling into the San Andreas Fault zone at the Asilomar Conference Center in Pacific Grove, California. The purpose of this workshop, which was attended by 113 scientists and engineers from seven countries, was to initiate a broad-based scientific discussion of the issues that could be addressed by drilling and direct experimentation in the San Andreas fault, to identify potential drilling sites and to identify technological developments required to make this drilling possible. As discussed at Asilomar and numerous workshops since then, there are a number of critical scientific questions about the mechanics of faulting and earthquake generation that can only be addressed by drilling (see SAFOD web site). In the context of the present proposal—to conduct drilling, sampling, *in-situ* measurements, and long-term monitoring to depths of 4 km with SAFOD—these questions include:

- What are the mineralogy, deformation mechanisms, and constitutive properties of the fault gouge? Why does the fault creep? What are the strength and frictional properties of recovered fault rocks at realistic *in-situ* conditions of stress, fluid pressure, temperature, strain rate, and pore fluid chemistry? What determines the depth of the shallow seismic-to-aseismic transition? What is the nature and extent of chemical water-rock interaction and how does this effect fault zone rheology?

- What is the fluid pressure and permeability within and adjacent to the fault zone? Are there superhydrostatic fluid pressures within the fault zone and through what mechanisms are these pressures generated and/or maintained? How does fluid pressure vary during deformation and episodic fault slip (creep and earthquakes)? Do fluid pressure seals exist within or adjacent to the fault zone and at what scales?

- What are the composition and origin of fault-zone fluids and gasses? Are these fluids of meteoric, metamorphic or mantle origin (or combinations of the three)? Is fluid chemistry relatively homogeneous, indicating pervasive fluid flow and mixing, or heterogeneous, indicating channelized flow and/or fluid compartmentalization?

- How do stress orientations and magnitudes vary across the fault zone? Are the principal stress magnitudes higher within the fault zone than in the country rock, as predicted by some theoretical models? What is the strength of the shallow (creeping) fault and how does this compare with depth-averaged strengths inferred from heat flow and far-field stress directions?

- How do earthquakes nucleate? Does seismic slip begin suddenly or do earthquakes begin slowly with accelerating fault slip? Do the size and duration of this precursory slip episode, if it occurs, scale with the magnitude of the eventual earthquake? Are there other precursors to an impending earthquake, such as changes in pore pressure, fluid flow, crustal strain, or electromagnetic field?

- How do earthquake ruptures propagate? Do earthquake ruptures propagate as a uniformly expanding crack or as a “slip pulse”? What is the effective (dynamic) stress during seismic faulting? How important are processes such as shear heating, transient increases in fluid pressure, and fault-normal opening modes in lowering the dynamic frictional resistance to rupture propagation?

- How do earthquake source parameters scale with magnitude and depth? What is the minimum size earthquake that occurs on the fault? How is the long-term energy release rate at shallow depths partitioned between creep dissipation, seismic radiation, dynamic frictional resistance, and grain size reduction (i.e., by integrating fault zone monitoring with laboratory observations on core)?

- What are the physical properties of fault-zone materials and country rock (seismic velocities, electrical resistivity, density, porosity)? How do physical properties from core samples and downhole measurements compare with properties inferred from surface geophysical observations? What are the dilational, thermoelastic, and fluid-transport properties of fault and country rocks and how might they interact to promote either slip stabilization or transient over-pressurization during faulting?

- What processes control the localization of slip and strain? Are the fault surfaces defined by background microearthquakes and creep the same? Would the active slip surface(s) be recognizable (through core analysis and downhole measurements) in the absence of seismicity and/or creep?

An important scientific benefit of conducting this project at Parkfield comes from the fact that by working at Parkfield we will be drilling in an area of active creep and microseismicity. By drilling in an actively slipping portion of the fault, we will be able to study the nucleation and rupture processes of microearthquakes with near-field seismic recordings, investigate whether temporal variations in pore pressure occur during fault slip (creep and earthquakes) and study the processes responsible for shear localization.

The Need for SAFOD

In spite of the enormous amount of field, laboratory, and theoretical work that has been directed toward the mechanical and hydrological behavior of faults over the past several decades, it is currently impossible to differentiate between—or even adequately constrain—the broad range of conceptual models currently extant in the geological and geophysical literature. For this reason, the Earth science community is left in the untenable position of having no generally accepted paradigm for the mechanical behavior of faults at depth. One of the primary causes for this dilemma is the difficulty of either directly observing or inferring (with some degree of confidence) physical properties and deformation mechanisms along faults at depth.

Most of what we now know about the structure, composition and deformation mechanisms of crustal faults has been learned from geological investigations of exhumed faults, particularly in normal and reverse faulting environments were erosion has exposed previously deeply buried foot- and hanging-wall rocks. These field observations have proven particularly useful for several reasons. First, field observations of exhumed faults allow broad coverage with respect to variations in faulting style (e.g., comparing strike slip, normal and reverse faults), fault movement history and local geology. Secondly, where sufficient surface outcrops exist, field observations can readily address issues related to geometrical complexity and spatial heterogeneity in physical properties and fluid composition.

However, as valuable as these investigations have been, they suffer from several severe limitations when one attempts to draw inferences about active processes operating during faulting at depth. Foremost among these limitations is the fact that constraints on the mechanical state and physical properties of active fault zones (e.g., fluid pressure, stress and permeability) from surface observations are, of necessity, indirect and subject to alternate interpretations. For example, as noted by numerous participants in the USGS Conference on the Mechanical Involvement of Fluids in Faulting (see *J. Geophys. Res.*, **100**, 12,831-12,840), stress heterogeneities induced by fault slip can lead to considerable uncertainties in inferring past fluid pressures from observations of vein geometry in outcrop. In all of these investigations, a complex history of uplift and denudation may have severely altered, or even destroyed, evidence for deformation mechanisms, fault zone mineralogy and fluid composition operative during fault slip. This problem is especially acute for solution-transport-deformation mechanisms (e.g., pressure solution and crack healing/sealing) and other low-activation-energy processes, as the deformation microstructures formed at great depth are easily overprinted by ongoing deformation as the fault rocks are brought to the surface. Finally, with the rare exception of localized melts generated by rapid seismic slip (i.e., the pseudotachylytes occasionally found in exhumed fault zones), there are currently no reliable microstructural indicators that can be used to differentiate between seismic slip and creep. Thus, the importance of fluids in earthquake generation and rupture is impossible to assess with any degree of certainty based solely on studies of exhumed fault rocks.

Drilling and downhole measurements in active fault zones would provide critical tests of interpretations and hypotheses arising from laboratory rock mechanics experiments and geological observations on exhumed faults. Drilling provides the only direct means of measuring pore pressure, stress, permeability, and other important parameters within and near an active fault zone at depth. It is also the only way to collect fluid and rock samples from the fault zone and wall rocks at seismogenic depths and to monitor time-dependent changes in fluid pressure, fluid chemistry, deformation, temperature, and electromagnetic properties at depth during the earthquake cycle. In the context of the key scientific questions presented above, *in situ* observations and sampling through drilling would perform two critical, and unique, functions. First, sampling of fault rocks and fluids and downhole measurements would provide essential constraints on mineralogy, grain size, fluid chemistry, temperature, stress, pore geometry, and other parameters that would allow laboratory investigations of fault zone rheology and frictional behavior to be conducted under realistic *in-situ* conditions. Second, by *in situ* sampling, downhole measurement and long-term monitoring in active fault zones we would be able to test and refine the broad range of current theoretical models for faulting and seismogenesis by providing realistic constraints on fault zone physical properties, loading conditions and mechanical behavior at depth. In particular, by comparing results of microstructural observations and rheological investigations on core with measurements of microseismicity, fluid pressure, and deformation during the fault zone monitoring phase of this experiment, we would be able to differentiate among fault zone processes (e.g., fluid pressure fluctuations) associated with fault creep versus earthquakes.

Overview of SAFOD

The SAFOD drill site is located on a segment of the San Andreas Fault that moves through a combination of aseismic creep and repeating microearthquakes (Figure II-3.1). It lies at the northern end of the rupture zone of the 1966, Magnitude 6 Parkfield earthquake, the most recent in a series of events that have ruptured the fault five times since 1857. The Parkfield region is the most comprehensively instrumented section of a fault anywhere in the world, and has been the focus of intensive study for the past two decades as part of the USGS Parkfield Earthquake Experiment (see http://quake.usgs.gov/research/parkfield/index.html).

A key aspect of the implementation plan for SAFOD is to rely on conventional rotary drilling to penetrate through the entire fault zone (Figure II-3.2). The trajectory shown was designed to satisfy the following geological and geophysical constraints: (1) to move the surface position of the hole far enough to the west so that it will avoid a fault trending subparallel to—and southwest of—the San Andreas fault zone and be well outside of the low-resistivity anomaly coincident with the fault zone, (2) to get as close as possible to the microearthquake hypocenters, (3) to pass all the way through the "geophysically anomalous" fault zone as well as through the vertical projection of the surface trace, terminating drilling in Franciscan rocks on the northeast side of the fault, and (4) to make it possible to measure the relevant geophysical parameters (stress, fluid pressure, permeability, etc.) and obtain rock and fluid samples in a continuous profile across the entire San Andreas Fault Zone.

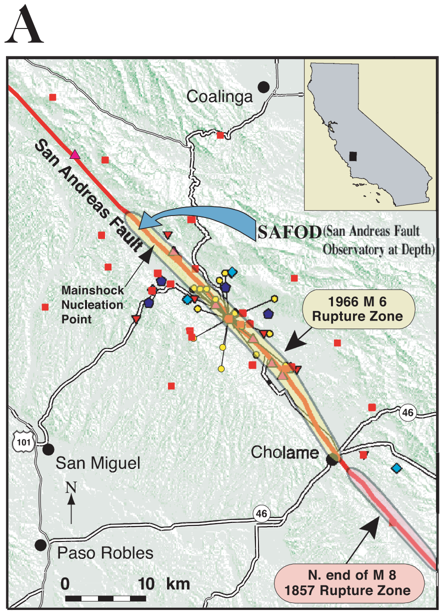
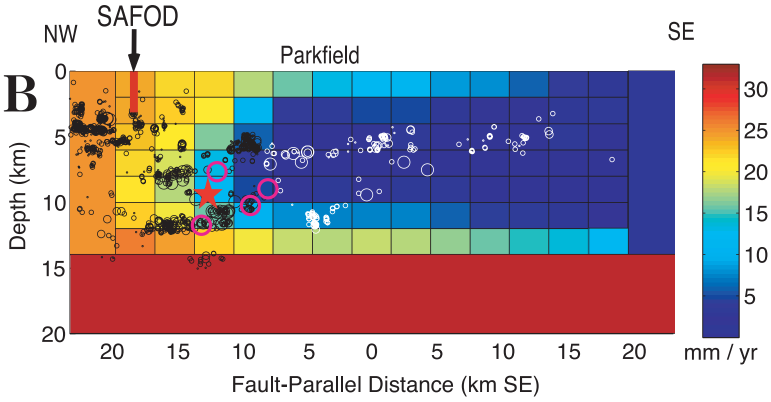


Figure II-3.1. A) Map showing the location of SAFOD together with seismometers, creepmeters, strainmeters, laser rangefinders, GPS receivers and other monitoring instruments associated with the USGS Parkfield Earthquake Experiment (colored symbols; only some of these instruments are shown). B): Cross section along the San Andreas Fault at Parkfield showing time-averaged slip rates inferred from surface geodetic measurements during the time period 1966-1991. Circles denote locations and magnitudes (up to M 5) of microearthquakes located using the double-difference technique for the time period 1984-1999. The hypocenter for the 1966 M 6 Parkfield earthquake is shown as a red star. Note that the SAFOD borehole (red line) is designed to penetrate into or very close to a repeating cluster of M 2 earthquakes at about 3.5 km depth.



Rotary drilling, geophysical logging, casing, and cementing of such deviated holes are routine in the petroleum industry, even in poorly consolidated and overpressured formations. Thus, by using a rotary drilling strategy to penetrate the entire fault zone, it should be possible to drill through the fault zone even if the rock is seriously disaggregated and pore pressures are quite high. After casing the rotary-drilled hole and monitoring this fault crossing for two years, four continuously cored “multi-laterals” will be drilled off of the main hole at carefully selected locations. Once this is complete the borehole will be used to deploy an array of seismometers, strainmeters, and other geophysical instruments to make direct, continuous near-field observations of faulting processes and earthquake generation at depth.

The overall experiment is explained in more detail in Section 3.3; the key operational elements of the project we propose are as follows (Figure II-3.2):

1. Rotary drilling a hole to 4 km depth through the entire San Andreas Fault zone in an area characterized by creep and microearthquakes. A site near Parkfield, CA was chosen for drilling because of the occurrence of shallow seismicity and particularly good knowledge of fault structure at depth (e.g., Figures II-3.1B and II-3.2). During drilling we will use advanced logging-while-drilling (LWD) techniques, collect spot cores and cuttings, and continuously sample fluids and gases in the drilling mud.

2. After conducting side-wall coring and open-hole geophysical logs (as permitted by hole conditions), the hole will then be completely cased and cemented. A suite of fluid sampling, permeability, and hydraulic fracturing stress measurements will be made through perforations in the casing. The perforations will be sealed after each test, except for a single interval that will be left open for fluid pressure monitoring

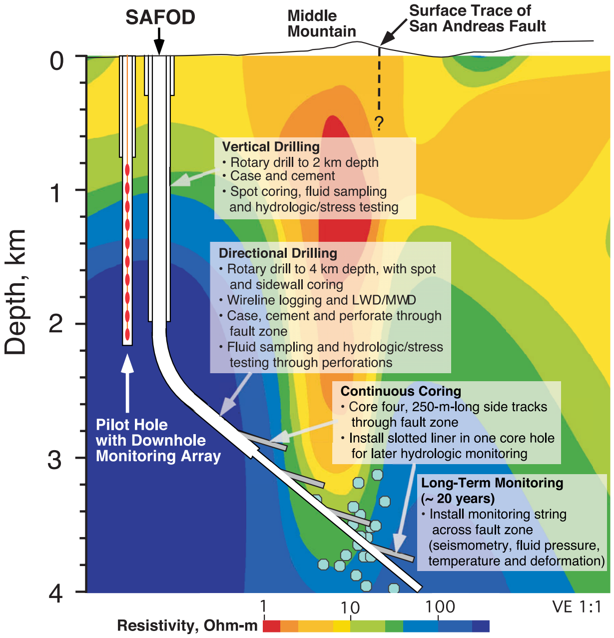


Figure II-3.2. Schematic representation of the SAFOD borehole and pilot hole. The background colors show the resistivity structure of the upper crust determined from surface magnetotelluric profiling, with blue dots representing and the approximate locations of microearthquakes located by the USGS and UC Berkeley seismology laboratories. The drill site will be located sufficiently far from the San Andreas Fault (as determined by surface fault creep, magnetotelluric imaging and microearthquake locations) to allow for rotary drilling and coring through the entire fault zone starting at a depth of about 3 km and continuing until relatively undisturbed country rock is reached on the far side of the fault. The main SAFOD hole will be drilled at the same surface location as the pilot hole, but offset from the pilot hole by about 20 m.

3. An array of seismometers will be deployed in the hole to make near-field observations of earthquakes and to help determine the exact position(s) of the active trace(s) of the fault. Fluid pressure will be continuously monitored at a carefully chosen depth and the hole will be logged repeatedly to identify zones undergoing casing deformation and, hence, the location of active shear zones.

4. While the monitoring “string” of seismometers is in place, a number of surface-based and surface-to-borehole geophysical measurements will be made to characterize the physical properties of the fault zone and the surrounding crust.

5. After identifying the active fault trace(s), using results from drilling and downhole measurements and fault-zone monitoring, 250-m-long continuous core holes will be drilled off of the main hole at four different locations where windows will be cut through the casing. In this manner, we plan to obtain a total of ~1000 m of core material from multiple sites directly within and adjacent to the active fault zone

6. Following coring, we will re-deploy an instrumentation array to permanently monitor earthquakes, deformation, fluid pressure, and ephemeral properties of the fault zone at depth.

Rock and fluid samples recovered from the fault zone and country rock will be extensively tested in the laboratory to determine their composition, origins, deformation mechanisms, frictional behavior, and physical properties (permeability, seismic properties, etc.).

The project we propose will provide the kinds of data needed to constrain the many theories currently being debated about fault zone processes. By obtaining direct information on the composition and mechanical properties of fault zone rocks, the nature of the stresses responsible for earthquakes, the role of fluids in controlling faulting and earthquake recurrence, and the physics of rupture propagation, this project could revolutionize our understanding of earthquake physics. Moreover, although it has been hypothesized that a wide range of deformation processes may precede seismic rupture, they have not been unequivocally detected by surface measurements. By making continuous observations directly within the San Andreas fault zone at seismogenic depths, we will be able to directly test and extend current theories about phenomena that might precede an impending earthquake.

Scientific Components of SAFOD

The three main scientific components of the SAFOD project are: i) continuous monitoring of fault zone processes and microseismicity, ii) sampling of fault zone materials and fluids, iii) direct measurements of the physical properties and mechanical state of the fault zone at depth.

Fault Zone Monitoring

Once constructed, the SAFOD facility will provide the opportunity to continuously monitor an active fault at seismogenic depths and will answer many questions about transient, and possibly precursory, fault zone processes related to earthquake rupture nucleation and propagation, and fault creep. These measurements are intended to continue for a period of at least 20 years after the observatory has been constructed. Prior to this, there will be two preliminary stages of fault zone monitoring (see Section 3.3 for details). The first of these stages already occurred in the summer of 2002, with instrumentation of the SAFOD pilot hole to a depth of 2.2 km using a continuous string of seismometers (see Figure II-3.2). The purpose of the pilot hole array is to accurately locate microearthquakes to be targeted by the main SAFOD borehole and to facilitate imaging of the crust adjacent to the San Andreas Fault during active-source seismic experiments conducted in October 2002 and planned for 2003. The second stage of monitoring will consist of emplacing a strainmeter and seismometer in the main SAFOD hole after reaching a vertical depth of 3 km, to record near-field strain and seismic activity during the approximately 8-month hiatus in rotary drilling prior to crossing through the active fault zone. The third, and final, stage of SAFOD monitoring will begin during the two-year period between the rotary drilling and continuous coring phases of the project. During this stage, a removable seismic monitoring string will be installed across the fault zone and removed periodically to log the hole for casing deformation. The purpose of this two-year monitoring effort is to locate, with extreme precision, the position of the fault patches generating repeating microearthquakes as well as location of actively creeping strands within the overall San Andreas fault zone. This information will be critical in deciding where to conduct the continuous coring operations off of the main SAFOD hole. This monitoring string, augmented by additional strainmeters and other instruments, will then be redeployed in the borehole at the conclusion of coring to commence the 20 years of continuous fault-zone monitoring.

Rock and Fluid Sampling

Rock and fluid samples recovered from the fault zone and country rock will be extensively tested in the laboratory to determine their composition, origins, deformation mechanisms, frictional behavior, and physical properties (permeability, seismic properties, etc.). The sampling strategy has been designed to maximize the scientific return from this experiment, regardless of any operational difficulties that may be encountered, and to allow for continual improvement in our knowledge of the composition and structure of the fault zone during the experiment so that subsequent sampling operations can be carried out with a maximum of efficiency.

Rock samples will be obtained from the fault zone and adjacent crust in four ways:

1. During the initial rotary drilling phase, cuttings will be continuously collected, described, and logged. The drilling budget includes additional geologists to work in the mud logging unit 24 hours a day to assure that appreciable cuttings are collected, accurately described, and properly archived. These geologists will be trained and supervised by the principal investigators responsible for core analysis. The procedure for conducting this cuttings logging, preparation and archiving was already developed and tested during drilling of the SAFOD pilot hole and worked extremely well (see SAFOD web site).

2. Three 20-m-long spot cores will be collected during rotary drilling of the SAFOD hole after setting casing at vertical depths of 2, 3, and 4 km (see Figure II-3.2); these spot core holes will also be used for fluid sampling and measurements of permeability and stress, as described below. The first core will be obtained in the Salinian granite basement at a depth of 2 km, the second just outside the fault zone at a depth of 3 km, and the last core at the bottom of the hole after crossing through the entire fault zone (presumably in rocks from the Franciscan Complex).

3. Assuming that hole conditions permit, side-wall cores will be collected prior to casing the hole, principally from within the fault zone. We have budgeted for a side-wall coring technology—using a wireline tool to core multiple diamond core holes out the side of the hole—that will work in “hard” rocks. The use of more conventional (percussive) side-wall coring is contingent on “soft” formation conditions, as the side-wall sampling tool explosively shoots the core barrel into the formation. We have both technologies available and hole conditions will determine which technology, if either, can be used for side-wall core recovery.

4. As mentioned above (and described in more detail in Section 3.3), a separate continuous coring phase will be conducted two years after the end of the rotary drilling phase. We propose to drill four continuous core holes, each ~250 m in length, as “laterals” from the main borehole (Figure II-3.2). The locations of these coreholes will be carefully selected on the basis of the results obtained in the initial rotary drilling phase and the subsequent two-year period of fault zone monitoring.

Sampling of fluids for geochemical measurements will be obtained in four ways:

1. During both the initial drilling phase and the final continuous coring phase of operations, gases dissolved in the drilling mud will be analyzed on a continuous basis utilizing extraction and analysis techniques developed during drilling of the German KTB borehole by Joerg Erzinger (Univ. of Potsdam) and used in numerous scientific drilling projects since then. Importantly, this system was used successfully during drilling of the SAFOD pilot hole, where it identified several transient gas anomalies (mostly methane and radon) associated with secondary fractures and faults.

2. Large-volume fluid samples will be extracted from each of the three 20-m-long spot core holes discussed above, in association with industry-standard Drill Stem Tests (DSTs). These DSTs, which will be conducted immediately prior to hydraulic fracturing stress measurements planned for each core hole, will provide relatively large volumes of formation fluid for subsequent geochemical and isotopic analyses along with measurements of the in-situ formation permeability and fluid pressure. Several different tracers (such as fluorescene) are being considered for use in the drilling mud during SAFOD drilling to make it easier to differentiate between drilling and formation fluids.

3. After drilling and casing of the rotary-drilled hole to total depth (TD) of 4 km, a profile of 10 DSTs will be conducted across the San Andreas fault zone through perforations in the cemented casing (i.e., at vertical depths of 2.5 to 4 km). As with testing planned for the spot core holes, these tests will provide large-volume fluid samples together with measurements of formation permeability and fluid pressure, to be immediately followed by hydraulic fracturing stress tests. The procedure for conducting these tests is described in more detail below.

4. Finally, small-volume fluid samples will be extracted from core samples in the laboratory, in particular those obtained from the 250-m-long continuous core holes within and immediately adjacent to the fault zone. Again, “tagging” of the drilling mud used during coring will be used to differentiate between drilling and formation fluids.

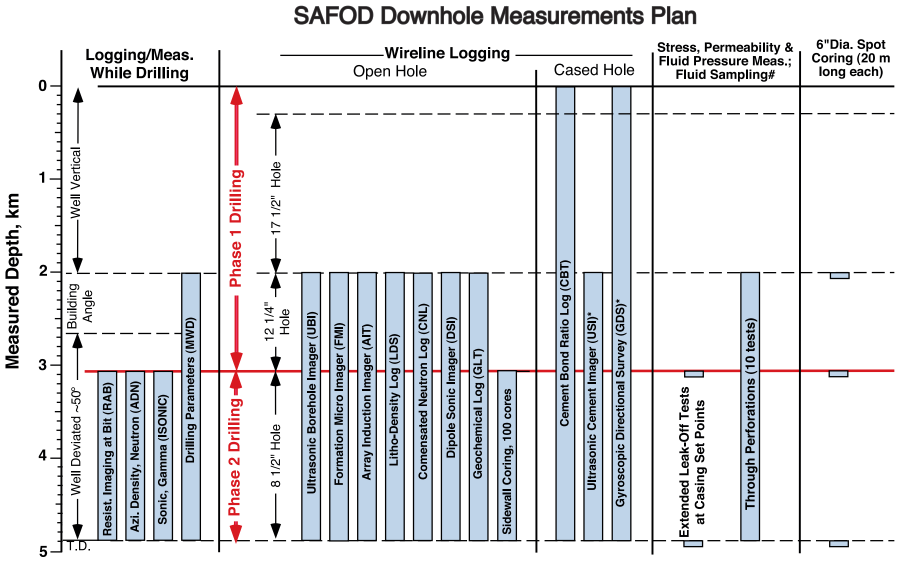
Taken together, these multiple sampling strategies should provide ample rock and fluid samples for the principal investigators to use in their studies.

Downhole Measurements

Downhole measurements of physical properties and mechanical state are critical to understanding overall fault-zone properties and behavior. Accordingly, a multiple measurement strategy is planned to assure their success (Figure II-3.3).

1. First, hole conditions permitting, a comprehensive suite of wireline geophysical logs will be run prior to casing each section of the borehole. The only exception to this being the upper 2-km section of SAFOD, as this depth range was already extensively logged during drilling of the pilot hole, which is located at the same surface location as SAFOD. These logs will be acquired commercially using state-of-the-art technology currently used in the petroleum industry. *In situ* temperature measurements will be made by USGS personnel at various times after the hole is cased, to determine variations in heat flow with depth and proximity to the San Andreas Fault.

2. Since it is possible that unstable hole conditions within the fault zone might seriously curtail the geophysical logging program, a state-of-the-art



*Note: The USI and GDS logs will be repeated twice (once per year) during the two years of fault zone monitoring following completion of Phase 2 Drilling to help identify the active fault trace(s)

Figure II-3.3. Overview of the downhole measurement program proposed for the SAFOD hole as a function of measured depth. Note that while the total vertical depth to be reached with the hole is 4 km, the total measured depth of the hole will be almost 5 km. The vertical, angle building and deviated sections of the hole as shown in Figure II-3.2 are also indicated.

commercial Logging While Drilling (LWD) and Measurements While Drilling (MWD) system will be used during rotary drilling of the inclined portion of the SAFOD hole. This system, which is described in more detail in Section 3.3, will ensure that the most important in-situ physical property measurements are made in real time as we drill across the fault zone. Results from the LWD suite and the wireline geophysical logs will be compared to a detailed Vertical Seismic Profile (VSP) and other surface-to-borehole seismic imaging experiments already planned for the pilot hole and main SAFOD hole. This will allow the physical property measurements made in the borehole (and on the core) to be "scaled up" and extrapolated away from the borehole.

3. To assess pore pressure, permeability and stress, a comprehensive suite of packer tests will be made after the casing is cemented and perforated. The packer tests will be made by Zoback and Hickman, who have extensive experience with such tests. The techniques that we will use employ relatively standard well-test and hydraulic fracturing stress measurement methodologies that are well-established for determination of the least principal stress. These measurements of least principal stress will be integrated with quantitative analyses of borehole wall failure from wireline and LWD image logs to fully constrain the 3-D state of stress within and adjacent to the fault zone.

The series of pore pressure and least principal stress measurements that we propose to make at various positions with respect to the active trace of the San Andreas Fault will test directly several of the hypotheses proposed to explain the weakness of the fault (see SAFOD web site for a discussion of the "stress/heat flow paradox" and the broad range of deformation mechanisms proposed to control fault strength at depth). While performing these measurements at 3-4 km might not show whether such weakening processes are operating at much greater depth, these measurements will represent an important first step towards testing these and other hypotheses pertaining to the mechanical behavior of the San Andreas Fault.

SAFOD Pilot Hole

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 (see Figure II-

3.2). 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. The scientific rationale for the pilot hole as well as daily reports on the drilling and field operation can be found on the SAFOD web site. (This web site, which was created and maintained in close collaboration with the ICDP using their Drilling Information System, is a prototype for the real-time drilling and data tracking system to be employed during SAFOD drilling.)

As presented in several talks and posters from the 2002 annual meeting of the American Geophysical Union, significant progress has already been made in achieving the scientific and technical goals for the SAFOD pilot hole. These goals include:

1. Seismic monitoring instrumentation deployed in the pilot hole are facilitating precise earthquake hypocenter determinations that will guide subsequent SAFOD scientific investigations as well as drilling and coring activities in the fault zone. While precise relative hypocentral locations have been obtained from the permanent surface seismic stations, there remained several hundred meters of uncertainty in the absolute locations of these events. Funded by NSF, Peter Malin (Duke University) successfully installed a 38-level seismic string in the pilot hole in the summer of 2002. An example of recordings from this downhole array for a local, small-magnitude earthquake is presented in Figure II-3.4. Note the clear arrival of P, S, and other phases in these recordings as well as the high signal-to-noise ratio.

2. As discussed below, subsurface instrumentation deployed in the pilot hole recorded surface seismic sources (and provided near-surface velocity control) for seismic imaging experiments already conducted in October 2002 and planned during 2003.

3. Downhole measurements of physical properties, stress, fluid pressure, and heat flow in the pilot hole are characterizing the shallow crust adjacent to the fault zone. These measurements are

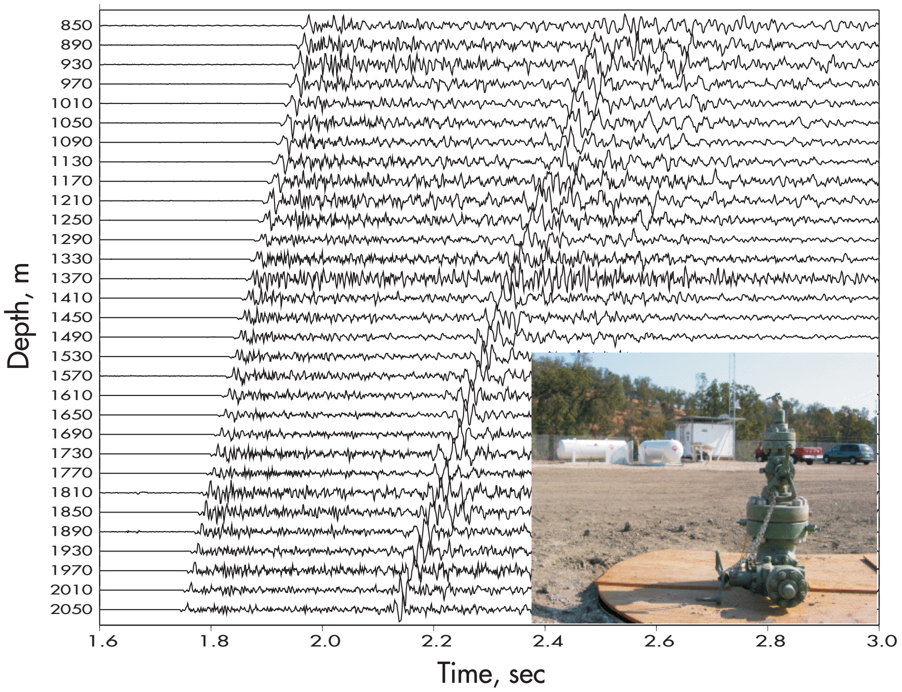


Figure II-3.4. Sample seismograms recorded on the pilot hole seismic array from a M 0 earthquake on October 2, 2002, located about 1 km southwest of the pilot hole and at a depth of 4 km. Only the output from the vertical component of these 3-component, high-frequency (15 Hz) geophones is shown. INSET: photograph of the multichannel pilot hole seismic recording and radio/satellite telemetry building, with pilot hole wellhead in the foreground.

being used to help calibrate physical properties inferred from surface-based geophysical surveys (e.g., seismic velocities, anisotropy, resistivity and density) and better constrain the strength of the San Andreas Fault Zone and adjacent crust prior to SAFOD drilling.

4. Long-term seismic, pore fluid pressure, strain, and temperature 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, as discussed in Section 3.3, the pilot hole will provide a critical facility for developing and testing long-term monitoring instrumentation to be used in the main SAFOD hole.

5. 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 rock samples will determine the nature and extent of fluid-rock interaction along the San Andreas Fault and the sources and transport paths for fault-zone fluids.

6. 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 high-resolution, real-time imaging of the San Andreas fault zone using the drill bit as a seismic source.

7. From a strictly technological point of view, the pilot hole provided detailed information about subsurface geologic conditions and optimal drilling techniques/parameters that have proven invaluable in designing the drilling plan (presented below) for the main SAFOD hole.

Recent Geophysical Studies at the SAFOD Site

Over the past several years, a wide variety of geophysical investigations have been carried out at and around the SAFOD pilot hole site. These studies include deep electromagnetic soundings, gravity and magnetic profiles, geologic mapping, and high-resolution seismic reflection and refraction profiles. In addition, as part of continuing education and outreach efforts, a number of shallow exploration techniques were employed at the drill site during Duke University's NSF-sponsored Parkfield field camp. Information about the Parkfield field camp is available at http://www.eos.duke.edu/Research/seismo/parkfield.htm.

Of course, monitoring of the Parkfield region by the USGS and U.C. Berkeley continues as part of the Parkfield Earthquake Experiment, with networks of borehole strainmeters, global positioning system (GPS) receivers, water wells, creepmeters, magnetometers, high-gain seismometers, and strong motion accelerometers. Work is presently underway to expand the continuous GPS network. Information about deformation monitoring at Parkfield is available at http://quake.usgs.gov/research/deformation/parkfield/index.html.

As mentioned above, a major, NSF-funded microearthquake experiment—the Parkfield Area Seismic Observatory (PASO)—was just completed around the SAFOD site using portable seismic instruments. These stations are augmented by permanent stations of the USGS Northern California Seismic Network and the Parkfield High Resolution Seismic Network, run by U.C. Berkeley (see http://quake.geo.berkeley.edu/hrsn.overview.html). In October 2002, PASO scientists set off a series of calibration shots at the sites of their stations that were recorded by the seismic receivers within the pilot hole in order to test and calibrate their 3-D seismic velocity model. Joint seismic imaging and earthquake relocations conducted using the pilot hole downhole array, together with analysis of data from PASO and the other local networks, are currently underway and are already providing more accurate earthquake locations and a more refined image of the sub-surface velocity structure at the SAFOD site. A description of the PASO instrumentation network and preliminary scientific results can be found at http://gretchen.geo.rpi.edu/roecker/paso_home.html. The instrumentation used in the PASO deployment is identical to that proposed to be made available through EarthScope's USArray component.

Through these investigations, a fairly good picture of subsurface conditions is emerging in the area chosen for drilling. Figure II-3.5 is a cross-section through the proposed SAFOD and pilot hole site along a high-resolution seismic refraction/reflection line conducted in 1998. This figure is a composite of two independent studies. The colored geologic "base" results from an interpretation of aeromagnetic profiling, ground magnetic and ground gravity data. West of the San Andreas, Tertiary and Quaternary sedimentary rocks (TQs) overlie fractured Salinian granite (Kgr). East of the San Andreas, Franciscan rocks (KJf; including serpentinite at ~2 km depth) underlie Tertiary sediments (Te). Note that the location of the drill site was chosen to be on the west side of the fault to avoid serpentinite at depth and to be "outboard" of the abrupt step in the depth of basement about 1.4 km west of the fault. As this abrupt step in the top of basement is likely fault controlled, it is desirable to start drilling "outside" this structure. The contour lines indicate P-wave velocities that were determined through tomographic inversion of first arrivals from this high-resolution seismic line. The velocity contours end at the depth where seismic ray coverage no longer constrains velocity. Note that the potential field model and the velocity model are in very good agreement, in that the low velocity zone centered about 500 m SW of the surface trace of the San

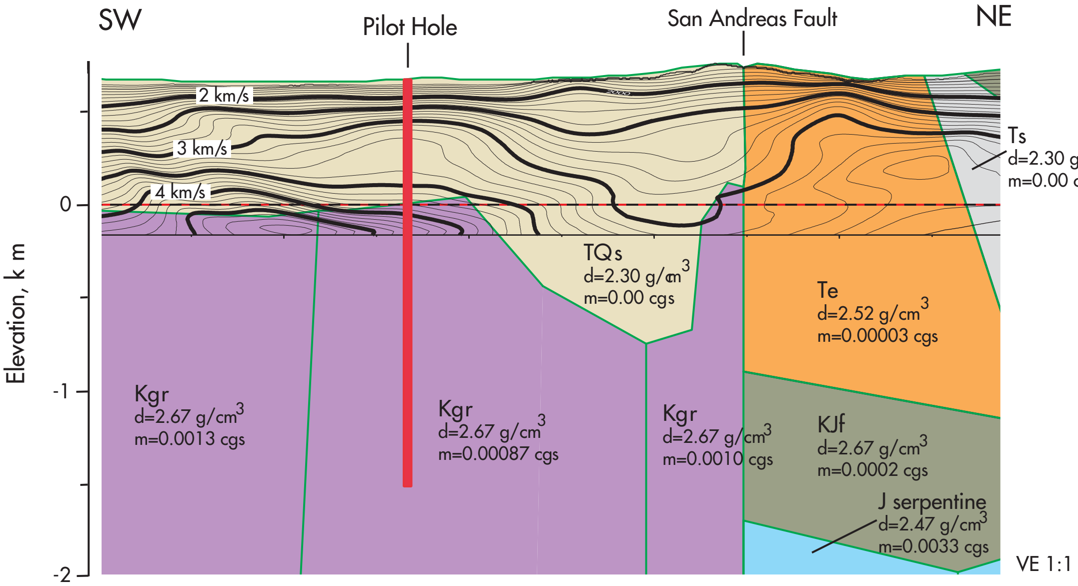


Figure II-3.5. Cross-section through the SAFOD site along the high-resolution seismic profile conducted in 1998, with the pilot hole shown as a red line. West of the San Andreas Fault, Tertiary and Quaternary sedimentary rocks (TQs) overlie fractured Salinian granite (Kgr). East of the San Andreas, Franciscan rocks (KJf, including serpentinite at ~2 km depth) underlie Tertiary sediments (Te). Note that the location of the drillsite is "outboard" of the abrupt step in the depth of basement located about 1.4 km SW of the surface trace of the San Andreas fault. The contour lines indicate P-wave velocities determined through tomographic inversion of first arrivals from this seismic profile.

Andreas fault occurs at the same location where the potential field data indicates locally greater depth to basement.

Analysis of the steep gradients in P-wave velocities (Figure II-3.5) and the loss of coherent reflections in the high-resolution seismic reflection image, presumably at the base of the sedimentary section, were used to predict a depth to granite basement of about 700-750 m at this site. This basement depth was used to design the drilling and casing program for the SAFOD pilot hole.

One of the most gratifying aspects of the SAFOD pilot hole project was confirmation of our preliminary geologic model for the SAFOD site by drilling. In particular, the predicted depth to basement (700-750 m) 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 the velocity and potential field models presented in Figure II-3.5. Finally, the electrical resistivity measured in the pilot hole by wireline logs increased with depth from about 50 Ohm-m at 0.8 km to about 800 Ohm-m at 2.2 km, which agrees quite well with the resistivities inferred using surface-based magnetotelluric measurements (Figure II-3.2).

The next phase of the geophysical exploration of the fault zone and surrounding crust is planned for the spring and summer of 2003, through projects already funded by NSF and international sources. This phase will be conducted by a joint U.S./German scientific team and will include a 50-km-long seismic reflection/wide-angle refraction profile across the San Andreas Fault Zone through the SAFOD site. This long-baseline survey will be supplemented by a high-resolution profile between the SAFOD site and the San Andreas, as well as along two shorter high-resolution lines perpendicular to this main line and crossing through the SAFOD site and along the San Andreas Fault. The long-baseline seismic line will constrain the deep structure of the San Andreas Fault system at Parkfield and help place SAFOD in a regional geophysical context, whereas the high-resolution add-on studies will be used to determine the velocity structure in the immediate vicinity of the pilot hole (by recording at the surface and on the pilot hole array) and the distribution and geometry of secondary faults between the drill site and the San Andreas. Additionally, observations of fault-zone guided waves using the high-resolution arrays deployed along and perpendicular to the San Andreas Fault will help determine the magnitude and width of velocity anomalies associated with the San Andreas Fault where it will be crossed by the SAFOD drill hole.

In many ways, the coalescence of these studies at Parkfield, together with the seismic and deformation monitoring carried out at Parkfield by the USGS, U.C. Berkeley, and other institutions over the past 15-20 years, represents an excellent example of the type of synergy that will result from utilization of the various EarthScope components over the coming years. This comprehensive suite of geophysical investigations in and around the drill site are achieving a number of critical milestones. These include better defining the absolute locations of repeating microearthquakes to be targeted with the main SAFOD hole, the structure and geophysical setting of the San Andreas fault zone at Parkfield, and the deformation field associated with aseismic and seismic slip on the San Andreas and other nearby faults.

3.2. Site Selection and Permitting

Why Parkfield?

When considering potential sites along the San Andreas fault system for the SAFOD observatory and related experiments, 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 was key for two reasons. First, we would like to be able to conduct experiments within (and adjacent to) seismically active parts of the fault. Second, we intend to use ongoing seismicity to tell us the precise location of the active trace of the fault. In a sense we will use the background seismic activity as "guide stars" to direct the fault zone crossing.

To identify potential sites a systematic search was conducted of the strike-slip faults in California, identifying all faults that met the shallow seismicity criteria. To our surprise, these criteria eliminated all candidate faults in southern California. In central and northern California only three fault segments met the criteria 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 convened a workshop on the scientific goals, experimental design, and site selection for SAFOD at the USGS in Menlo Park 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 the proposed experiment because:

- Surface creep and abundant shallow seismicity allow us to accurately target the subsurface position of the fault (Figure II-3.1B).
- There is a clear geologic contrast across the fault, with shallow granitic rocks on the west side of the fault and Franciscan melange on the east (Figure II-3.5). The granitic rocks provide for good drilling conditions.
- This segment of the fault has been the subject of an extensive suite of investigations establishing its geological and geophysical framework and is centered within the most intensively instrumented part of a major plate-bounding fault anywhere in the world.

An important new discovery about Parkfield that strongly supports its selection as the drilling target and adds a new scientific dimension to the experiment is the observation that the majority of the earthquakes there repeat in a characteristic manner. The upshot is that we will be targeting specific earthquake source zones with the drill hole, and have a very high expectation that the target earthquakes will repeat numerous times over the lifetime of the experiment.

At the surface near the SAFOD site, the San Andreas is creeping at a rate of about 2 cm/year (Figure II-3.1B), with most of the fault displacement localized to a zone no more than 10 m wide. Numerous earthquakes occur directly on the San Andreas Fault in the depth interval from about 3 to 12 km. The shallow seismicity at Parkfield occurs in tight clusters of activity that have remained spatially stationary for at least the past 20 years.

Although uncertainties exist in the exact location of the earthquakes, the integration of improved velocity models resulting from the PASO array and recordings from the pilot hole array are yielding greatly improved hypocentral locations. Figure II-3.6 shows the locations of some of the microearthquakes recorded on pilot hole array (as viewed from depth looking up at the surface and drillsite). While efforts to improve the locations of these events are still underway, the cluster of events shown by the green dot are the shallowest earthquakes in the area to be intersected by the SAFOD hole.

An important feature of the microearthquakes beneath Middle Mountain is that they occur in families of repeating events. Individual earthquakes have been observed to recur numerous times using the U.C. Berkeley High Resolution Seismic Network (HRSN), at precisely the same location and with the same magnitude. Repeating sources of up to M=2 are located at drillable depths beneath the proposed drill site. Thus, a major goal of this experiment will be to drill as close as possible to one or more of these sources and to follow the build-up of strain and its release through multiple earthquake cycles during the monitoring phase of the experiment.

Almost all events along this fault segment have right-lateral strike-slip focal mechanisms, corresponding to the geologic sense of movement on the fault. Non-San Andreas type earthquakes close to the San Andreas include strike-slip, normal, and reverse faulting mechanisms, the vast majority of which have P- or T-axis orientations in agreement with a north-south shortening and east-west extension within the fault zone. The few events that locate more than about 5 km from the San Andreas Fault, however, commonly have P axes oriented at a high angle to the fault, which is consistent with the regional framework of fault normal compression and a weak fault. Also, recent heat-flow determinations in 17 wells located within 10 km of the San Andreas Fault near Parkfield—including a 1.6-km-deep well located 12 km from the proposed drill site—confirm previous conclusions that there is no heat flow anomaly associated with the San Andreas fault in central California, indicating that the fault is sliding under low levels of resolved shear stress.

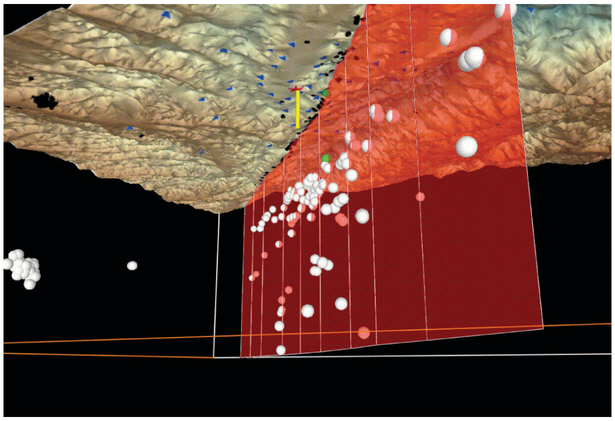


Figure II-3.6. View from depth of the SAFOD pilot hole, San Andreas Fault and microearthquakes recorded on the pilot hole array in the Fall of 2002 (between 2 and 4 events per day on the San Andreas are recorded on the vertical array). The green dot represents the shallowest events on the fault in the area where the SAFOD hole will penetrate it.

The Expected M ~ 6 Earthquake

The site we have selected also lies in close proximity to the 1966 Parkfield earthquake hypocenter (Figure II-3.1). Thus, one final question about the seismicity at Parkfield deserves some discussion: What would happen should the anticipated Parkfield mainshock occur either before or after the drilling experiment is completed? Should the earthquake occur before the hole is either drilled or completed, we can anticipate an enhanced production rate of shallow earthquakes as part of the aftershock sequence, which would add to the return of the fault zone monitoring stage of the experiment.

Should the Parkfield mainshock occur after the hole 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 M=6 earthquake at close range. While this is not an earthquake prediction experiment, the opportunity to make observations of seismicity, pore pressure, deformation, and temperature directly within a fault zone preceding and during a moderate earthquake is a truly unique opportunity. If the

M=6 Parkfield earthquake should occur during the lifetime of the experiment, we would make unique observations not only of preparatory fault zone processes but also of the dynamics of rupture propagation and the energetics of large-scale faulting.

As noted above, the dominant pattern is spatial stationarity of the seismicity (clusters), even through two Parkfield earthquake cycles. The spatial stationarity of seismicity through other mainshock events elsewhere in the San Andreas fault system is the norm, and has been well-documented in many cases. Furthermore, it is now known that repeating earthquake sources can be triggered into rapid repetition as aftershocks, when located near or within a mainshock rupture zone. Thus, should the M~6 Parkfield earthquake occur during the lifetime of the experiment, we might also have an unparalleled opportunity to observe time-dependent loading and frictional behavior in the near field.

Permits and Permissions

One point that should not be overlooked is the difficulty of obtaining permission to drill holes of any kind in California. At Middle Mountain, however, the once off-limits southwestern approach to the fault has become accessible due to the inheritance of the land by a cooperative new landowner. Thus, logistical as well as scientific considerations also favored the Parkfield site. We have a signed agreement with the landowner at Parkfield that will allow us to carry out the proposed drilling and downhole measurements and then access the site for 20 years during the fault zone monitoring phase of the experiment. In addition, all of the necessary environmental approvals and permits have already been obtained for the SAFOD site.

3.3. Site Installation and Detailed Experimental Plan

In this section, we provide an overview of the operational details that must be addressed to make sure that the scientific objectives of SAFOD are met. These operational issues are grouped into the following categories:

- rotary drilling and continuous coring
- testing through perforations
- fault zone monitoring
- downhole measurements
- measurements on core, cuttings and fluids
- on-site technical personnel.

To insure the success of this project, we are requesting all of the funds necessary to carry out these operational aspects of the SAFOD experiment in the present proposal. Detailed work plans and budgets for the scientists seeking funding from NSF to participate in SAFOD will be submitted as separate "stand alone" proposals to NSF. The USGS and DOE scientists (as well as those from other countries) will provide detailed work plans and budgets to their respective funding agencies.

Rotary Drilling and Continuous Coring

As a result of our experience in drilling the pilot hole, the drilling plan for the main hole has been slightly modified (with respect to the plan in the 1998 SAFOD proposal) and will be carried out in three distinct phases. These phases have been designed to: (i) optimize acquisition of key scientific data (*in situ* measurements, core and fluid recovery, etc.), (ii) facilitate deployment of different types of fault zone monitoring instrumentation at various levels (seismic, deformation, pore pressure, etc.), (iii) minimize drilling costs, and (iv) use drilling technologies that are most likely to work effectively in the highly fractured, altered and possibly overpressured rocks comprising the San Andreas fault zone. The drilling plan described below has been developed in consultation with Mr. Louis Capuano, President of ThermaSource, Inc. ThermaSource was the prime contractor of the SAFOD pilot hole and both Mark Zoback and Steve Hickman have worked successfully with Mr. Capuano on other scientific drilling projects. This information is excerpted from a highly detailed report entitled, "San Andreas Fault Zone Drilling Project: Drilling Program and Cost Estimates," that was prepared by Mr. Capuano in 1998 and has been modified taking into account our experiences in drilling the SAFOD pilot hole. Copies of this drilling plan are available on request.

Phase 1: Drilling to 3 km

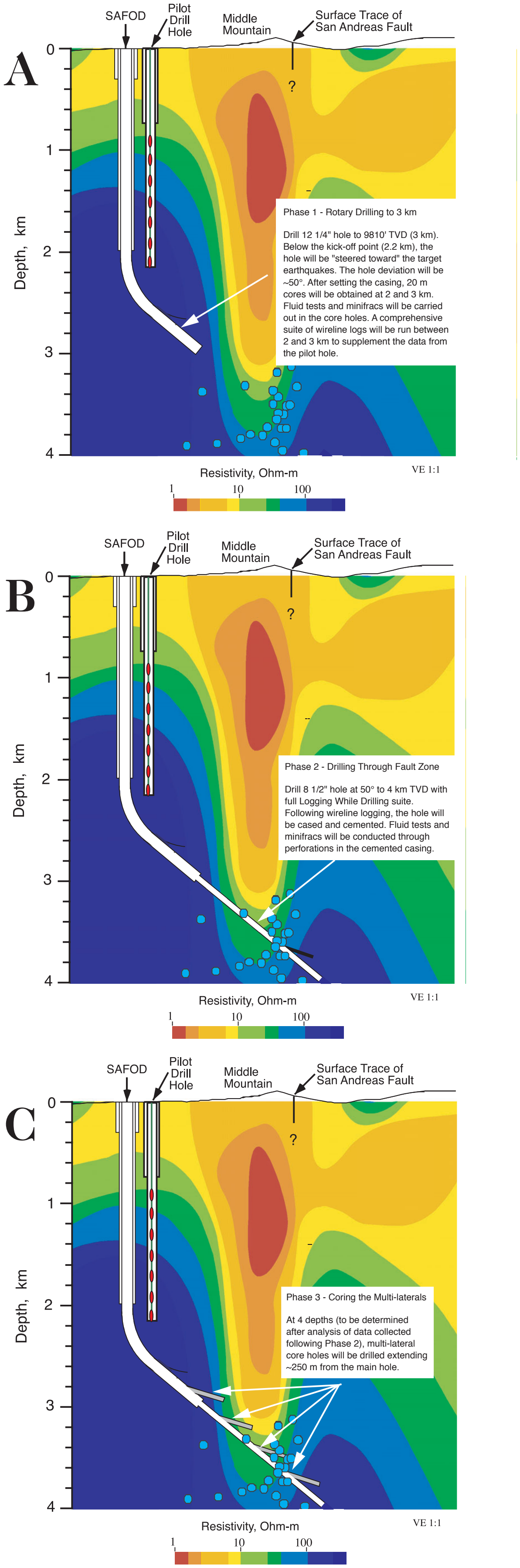
As shown in Figure II-3.7A, except for its much larger diameter, the upper part of the SAFOD main hole will be quite similar to that already drilled in the pilot hole. After setting 13 3/8" casing in a 17" vertical hole at 2.0 km, two 10-m-long cores will be cut from the bottom of the hole (using a 6", or larger, core bit). After the spot cores are obtained, an extended leak off test (a small hydrofrac) will be conducted in the core hole at the bottom of the 13 5/8" casing.

The primary objective of Phase 1 will be to directionally drill a 12 1/4" hole to a total vertical depth (TVD) of 3.0 km (corresponding to a measured depth, MD, along the hole of 3.3 km) and install 9 5/8" cemented casing. Fluid pressures are expected to be normal, but a 10,000 psi blow out preventer (BOP) will be used as a precaution.

As illustrated in Figure II-3.7A, the hole will be drilled vertically to 2.0 km, at which point the well will be kicked-off to the northeast, toward the San Andreas fault. The build angle will be 2.5° per 100'. The end of the build angle will be at a deviation of 50.5° at a MD of 2.6 km. This deviation will be held to the total depth of Phase 1, resulting in a horizontal offset of 750 m from the surface location of the hole. As was done for the pilot hole, extensive cuttings will be collected and drilling fluids and gases will be analyzed in real time during drilling. All of the methodologies to be used were successfully employed in the pilot hole. In addition, the ICDP Drilling Information System (DIS) was successfully used during pilot hole drilling to create a real-time database and synthesis of all of the scientific and operational information collected.

After completing the 12 1/4" hole, a wireline logging program will be conducted in the open hole section (from 3.3 to 2.0 km MD). The logs to be run are shown in Figure II-3.3. The 9 5/8" casing is then to be run to the surface and completely cemented. Two, 10-m-long spot cores will be obtained (again using a 6", or larger, core bit) after setting the 9 5/8" casing. After the spot cores are obtained, an extended leak off test (a small hydrofrac) will be conducted in the core hole at the bottom of the 9 5/8" casing.

The weather window for drilling at the SAFOD site is from May through October. Phase I is expected to take 131 days. We anticipate drilling to begin in May 2004.



Phase 1 - Rotary Drilling to 3 km

Drill 12 1/4" hole to 9810' TVD (3 km). Below the kick-off point (2.2 km), the hole will be "steered toward" the target earthquakes. The hole deviation will be ~50°. After setting the casing, 20 m cores will be obtained at 2 and 3 km. Fluid tests and minifracs will be carried out in the core holes. A comprehensive suite of wireline logs will be run between 2 and 3 km to supplement the data from the pilot hole.

Phase 2 - Drilling Through Fault Zone

Drill 8 1/2" hole at 50° to 4 km TVD with full Logging While Drilling suite. Following wireline logging, the hole will be cased and cemented. Fluid tests and minifracs will be conducted through perforations in the cemented casing.

Phase 3 - Coring the Multi-laterals

At 4 depths (to be determined after analysis of data collected following Phase 2), multi-lateral core holes will be drilled extending ~250 m from the main hole.

Figure II-3.7. Schematic drilling plan for SAFOD. A) During Phase 1, the SAFOD hole will be drilled as close to the pilot hole as possible, (not taking the risk of intersecting it). The hole will be terminated in the high resistivity, fractured granitic rock, outside the intensely deformed fault-zone rocks. B) Phase 2 of the drilling plan is to directionally drill a deviated well through the fault zone, eventually passing to the northeast side of the active trace of the fault, terminating in the Franciscan formation. C) Phase 3 of drilling involves using multi-lateral drilling technology to create four, directionally-drilled core holes with carefully selected depths and trajectories. The core holes (shown schematically in the figure) will each be approximately 250 m in length.

Phase 2: Drilling Through the San Andreas Fault Zone to 4 km Depth

After a ~9 month hiatus, the objective of Phase 2 is to directionally drill a 8 1/2” hole to a TVD of 4.0 km (MD = 4.9 km) and install 7” cemented casing (Figure II-3.7B). The expected lithology is highly fractured granite and crushed rock (probably largely altered to clay gouge). Fluid pressures are unknown and could range from normal (hydrostatic) to severely overpressured. A 15,000 psi BOP stack will be used during Phase 2 as a precaution. A comprehensive suite of LWD measurements will be acquired (see Figure II-3.3) to assure that as much geophysical data as possible is collected as the well is drilled, in case hole stability problems preclude conventional logging data from being acquired. As in Phase 1, extensive cuttings will be collected and drilling fluids and gases will be analyzed in real time. A contingency drilling plan has been developed in case of severe drilling difficulties crossing the San Andreas fault zone. Using this plan, an extra “string” of 5” casing will be cemented into the hole.

The 50.5° deviation will be held approximately constant to the total depth, resulting in a total horizontal borehole offset of 2.0 km. However, the hole will, in fact, be “steered” so as to intersect the fault zone in the vicinity of seismogenic patches where repeating microearthquakes occur.

After drilling the 8 1/2” hole through the fault zone, a wireline logging program will be carried out in the open hole section. The logs to be run are shown in Figure II-3.3. After logging, the 7” liner is to be run into the 9 5/8” casing, “tied-back,” and cemented. After the hole is cased and cemented, 10 intervals will be perforated between 2.0 and 4.9 km MD for hydraulic tests (fluid sampling, pore pressure, and permeability measurements) and minifrac tests to determine the magnitude of the least principal stress. The procedure used to conduct these tests through perforations are described below.

After the perforations are sealed-off, the cement will be drilled out and two 10-m-long spot cores will be obtained at the bottom of the hole. A prototype instrumentation system will be deployed in the hole during the ~ 2 year interval between Phases 2 and 3 (see below).

Phase 2 is expected to take a total of 108 days for drilling and testing. Drilling is expected to begin in May 2005.

Phase 3 – Coring in the San Andreas Fault Zone

Approximately two years after the completion of Phase 2, a hybrid rig (a conventional rotary rig with top drive) will be used to carry out wireline coring operations through four multi-laterals at depths to be determined after analysis of data obtained during Phases 1 and 2 and the precise locations of microearthquakes (Figure II-3.7C). The prospects of sampling both seismogenic patches and stably sliding sections of the San Andreas Fault, as well as sub-parallel faults that are no longer active are especially exciting. The multi-lateral technology to be used (i.e., drilling holes from a main hole that is cased and cemented) has been developed and used routinely by the petroleum industry over the past 10 years.

Each core hole will be approximately 250 m in length. The current plan is for DOSECC (Drilling, Observation and Sampling of the Earth’s Continental Crust, a nonprofit corporation providing technical assistance on scientific drilling projects in the United States) to carry out this phase of the project. To do so, DOSECC will use the drill rig they recently acquired and the top drive coring system they successfully used in scientific drilling projects in Long Valley, Hawaii, and elsewhere. This type of coring assures the best possible core retrieval, especially in broken-up rock.

After coring, each hole will be used for hydraulic testing and a minifrac. It is likely that three of the four coreholes will then be squeezed with cement to seal off the holes in order to prevent fluid flow between the core holes.

With a slotted steel liner in one corehole to allow for long-term fluid pressure monitoring, a retrievable geophysical instrument package will be lowered into the borehole via small diameter pipe or coil tubing for long-term monitoring.

Phase 3 is expected to take 96 days to complete, starting in May 2007.

Testing Through Perforations

The procedures for fluid sampling and pore pressure, permeability, and least principal stress (i.e., hydrofrac) measurements through perforations were developed to take advantage of equipment and procedures used routinely in the petroleum industry. These measurements require the cemented casing to be perforated at 10 different depths, packers to be used to isolate the test zone from the rest of the hole, and all of the test intervals to be re-cemented prior to the fault zone monitoring phase of the experiment. To minimize the rig time and costs associated with this part of the project, a number of experimental procedures were investigated. The procedure decided upon is termed a "Squeeze Retainer Procedure" and permits the tests to be conducted in sequence (see Drilling Report). This procedure involves the following steps, working from the deepest test interval upward:

1. Perforate the test zone with a wireline casing gun.
2. Run in with a composite packer on the drill string and set it above the perforations.
3. Conduct a drill stem test (DST) to estimate formation permeability and pore pressure from pressure build-up; use a wireline sampler inside the drill pipe to obtain fluid samples (26 hours).
4. Conduct hydraulic fracturing test with multiple pumping cycles to determine the least principal stress (6 hours).
5. Pull drill pipe out of the packer; displace almost all of the fluid out of the pipe with cement.
6. Stab pipe back into packer and squeeze cement below packer into perforations.
7. Pull drill pipe out of packer and wait for cement to cure.
8. Perforate next test zone with wireline casing gun.

There is a prescribed sequence of operational steps to make this possible. It is estimated to take approximately 61 hours to conduct each measurement; the next test interval will then be perforated and the entire procedure repeated.

When all of these tests are complete, the composite packers and residual cement inside casing will be drilled out to leave the borehole with all the perforations plugged. Pressure testing will be done to assure that this is the case. Any leakage from perforations will be re-cemented ("squeezed"). This entire downhole measurement program will take about 3 weeks of rig time to complete and should yield a comprehensive suite of fluid samples and pore pressure, permeability and least principal stress measurements at varied depths and positions within and adjacent to the fault zone. At the end of this sequence of measurements, the spot core will be obtained from the bottom of the hole and a single interval will be perforated in order to monitor fluid pressure during the initial fault zone monitoring phase of the experiment. The drill rig will then be demobilized.

Fault Zone Monitoring

The goal of fault zone monitoring is twofold: (1) to make *in situ* measurements of deformation, pore pressure, seismic wave radiation, and other relevant parameters in the nearfield of earthquakes, and (2) to select the optimal intervals for continuous coring through the fault zone during Phase 3 of drilling, as described above. We expect to observe multiple earthquake cycles for repeating earthquakes (M ~ 2) in the target zone at distances of less than a few hundred meters to about 1.5 km over SAFOD's 20-year lifetime. We may also observe the rupture of the fault in a large-magnitude (M~6) event over this same time period.

A team of scientists and engineers with extensive experience in the design, manufacture, and installation of borehole instruments has been assembled to assist in the construction and deployment of the borehole monitoring systems. The functional design of the removable monitoring array has been set by a combination of scientific and technical considerations, the latter as a consequence of extensive discussions with industry and the substantial experience of members of the design team with similar instrumentation. This monitoring array will consist of multiple, three-component seismic sensors of proven design for long-term deployment in deep boreholes. A number of the sensor packages will contain gimbaled three-component seismometers with natural frequencies around 4.5 Hz. Our recent experience recording earthquakes at 2 km depth in Long Valley at hypocentral distances as short as 1.4 km demonstrates that moving-coil geophones can detect kilohertz energy at close range. Other sensor packages will contain internal fluid-damped, three-component accelerometers with (undamped) frequencies around 30 Hz. Overdamped accelerometers of this design have been in operation in the 1-km-deep Varian well at Parkfield for over a decade, where they provide wideband acceleration response for recording in the nearfield. All data will be digitized at the surface using a dedicated data collection platform with high-sample-rate, high-resolution digitizers. Such a system is currently being employed at the SAFOD site to record data from the downhole pilot hole array, such as that shown in Figure II-3.4.

As illustrated in Figure II-3.8, a multi-stage strategy has been devised to establish a comprehensive borehole observatory at the SAFOD site. There is essentially no instrumentation "off-the-shelf" that is suitable for SAFOD because of the depths (pressures) and temperatures at which it will have to perform. Through this multi-stage strategy, our goal is to have both redundancy and the flexibility to deploy new instrumentation as it is developed.

Stage 1: Monitoring in the Pilot Hole

When pilot hole drilling was completed in July 2002 a 38-level, three-component seismic recording system was deployed in the pilot hole that was manufactured by GERI (GeoSpace Engineering Resources International), a subsidiary of OYO corporation. The data being recorded by this array (shown schematically in Figure II-3.8a) is helping refine the location of earthquake hypocenters to be targeted during drilling and coring in Phases 2 and 3 of SAFOD as well as the seismic velocity structure of the upper crust. On average, between two and four microearthquakes per day are being recorded by the pilot hole array in the vicinity of SAFOD (Figure II-3.6).

Prior to the start of Phase 1 drilling of the SAFOD main hole, the existing GERI/OYO seismic array in the pilot hole will be removed and checked for corrosion and wear. Once the array is out of the hole, several hydraulic fracturing tests will be conducted to help constrain stress magnitudes outside the fault zone. Also, other test instruments will be deployed in the hole, such as a vertical, clamping seismic array that is being made available at no cost to this project by Paulsson Geophysical, Inc. Following this, a new, retrievable GERI/OYO string will be deployed with hydraulically clamped strain and tilt meters as well as a high dynamic range seismometer at bottom. As the hydraulically clamped tilt and strain sensors are experimental, it may be

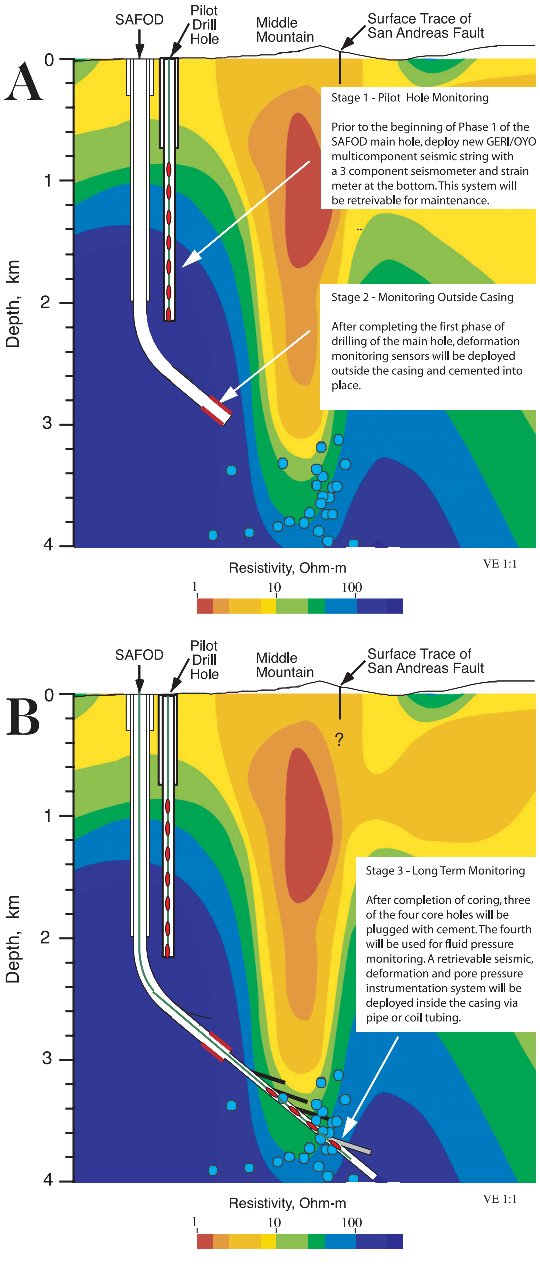


Figure II-3.8. Schematic monitoring plan for SAFOD. a) Stage 1 of SAFOD monitoring involves utilizing the pilot hole for a retrievable vertical array of seismometers with hydraulically clamped strain and tilt sensors and a high-dynamic-range seismometer at the bottom of the hole. Stage 2 will involve the permanent installation of strain monitoring instrumentation outside the casing at 3 km depth. b) During Stage 3 of SAFOD monitoring, a retrievable seismometer, hydraulically clamped strainmeter and tiltmeter, and pore pressure system will be used for long-term fault zone monitoring. A prototype array will be deployed inside the casing during the 2-year period between drilling Phases 2 and 3.

necessary to retrieve this string at a later date so as repair or change these sensors. The pressure and temperature at the bottom of the pilot hole are 20 MPa and 93°C.

The strain and tilt measurements at 2 km depth in the pilot hole will represent the deepest-ever deployment of instrumentation of this type. While the relatively hostile environmental conditions represent a formidable technical challenge, the low noise environment (and proximity to the fault) will reveal new insights into fault behavior. For example, it might be possible to detect episodes of aseismic slip at depth that have never been observable before. The high dynamic range seismometer (possibly MEMS) at the bottom is needed to record strong ground motions that would not be recordable with the vertical array. The Stage 1 monitoring instrumentation in the pilot hole will have other uses as well. For example, while the vertical array will continue to be invaluable for studying small earthquakes, it will also be in place to record surface seismic sources during seismic profiling experiments now planned to cross the fault near the drill site in 2003. This array will also allow “noise” from the drill bit during SAFOD drilling to be used as a seismic source to help better image the near-fault environment.

Stage 2: Long Term Monitoring at 3 km Depth

At the conclusion of Phase 1 SAFOD drilling, a 9 5/8” casing will be cemented into place in the 12 1/4” hole at a vertical depth of 3 km and bottom hole temperature close to 120° C (Figure II-3.8a). This will afford us the opportunity to permanently deploy instrumentation outside casing and cement it into place in such a manner as to not interfere with subsequent drilling operations.

Possible instruments for this behind-casing installation include a modified (i.e., annular) Sacks/Evertson volumetric strain meter with the electronics at the surface (hydraulic lines will be strapped to the outside of the casing), fiber optic strain meters and temperature sensors deployed outside the casing and cemented in place, as well as solid-state seismometers and MEMS seismometers that are currently under development. Needless to say, it will be necessary to mechanically protect these lines so that they are not damaged as the casing is deployed. A prototype annular strain meter is being deployed in the Long Valley Exploration Well in the summer of 2003. This instrumentation was developed jointly by NSF and ICDP, in part because of its potential use in the SAFOD borehole.

Because there will be a hiatus of ~9 months between Phase 1 and Phase 2 drilling, it will also be possible to temporarily deploy a seismometer and other instruments via wireline inside the casing for testing and evaluation.

Stage 3: Long Term Monitoring

We will deploy retrievable instrumentation inside the casing in the deviated section of the borehole that will be used for long-term monitoring of the fault zone (Figure II-3.8b). The instrumentation is to be deployed on a small pipe (or coil tubing) to assure retrievability and to provide a source of hydraulic pressure for coupling strain and tilt monitoring instrumentation to the borehole wall and/or casing. This type of locking mechanism has been used for some time in the petroleum industry, although the complexity of this system is admittedly at the edge of available technology. Our discussions with industry do not indicate that there are any insurmountable technical problems with this design. This array will be deployed initially for a two-year period following Phase 2 drilling: from late summer 2005 until the beginning of the Phase 3 coring program in late summer 2007. Following the completion of coring, we will re-instrument the borehole with this removable array for long-term (c.a. 20 years) monitoring of the San Andreas fault zone at depth.

The instrumentation to be deployed will include seismometers, pore pressure transducers, deformation sensors (strainmeters and/or tiltmeters), and temperature sensors. For the long-term installation following Phase 3 drilling, a downhole packer will be used to isolate one core hole for pore pressure monitoring (the remaining three core holes will be sealed with cement after coring). We may also cement instrumentation at the bottom of the hole, but the connection would be lost when the other instruments were pulled out of the hole for maintenance or repair. There are several deep-sea technologies (so-called wet-connects) that might be useful to carry this out. The estimated bottom hole temperature is 150°C.

During the temporary installation after Phase 2 drilling, the removable monitoring array will be pulled out of the borehole after about one year to conduct a high-precision borehole directional survey and ultrasonic cement imaging (USI) log. These measurements will be used to identify any changes in casing shape or cement bond integrity behind the casing to determine if any of the faults crossed by the hole are actively creeping or if broad-scale deformation is occurring. Along with earthquakes located by the removable downhole array, the locations of these actively deforming zones will be used to select locations for the continuous core holes to be drilled in Phase 3. The USI tool uses a rotating acoustic transducer and receiver to measure the internal radius of the casing, the resonance properties of the casing itself and the acoustic impedance of the casing/cement interface. This log yields casing radius to an accuracy of ± 0.2 mm. The gyroscopic directional tool to be used has an absolute accuracy of about 0.1° in azimuth, with repeatability considerably better than this. Repeat measurements of casing ovality and trajectory over time using casing shape logs and gyroscopic directional surveys similar to those we are proposing have identified casing offsets as small as 1 cm over a 5-m-wide shear zone.

Inclusion of tiltmeters and strainmeters in the removable monitoring array will permit us to critically examine the nucleation process of earthquakes in the target cluster, to document the interplay between interseismic deformation in the fault zone and the rupture of discrete patches in earthquakes, and to unravel the spatial connection between repeating earthquakes at a common centroid. Our experience with borehole strainmeters and seismometers at Parkfield has been uniformly excellent, where instruments of the designs being considered for SAFOD are now well into their second decade of operation. Because a traditional strainmeter must be installed in an open (uncased) hole, we may elect to install it in the bottom open-hole section of the SAFOD hole. We may also elect to install one or more clamping tiltmeters or borehole extensometers in the cased hole, depending on how these devices perform during prototype testing in the pilot hole. Ultra-low noise borehole tiltmeters (1 nanoradian resolution) have been developed by a member of the design team at Lawrence Livermore National Laboratory, who was awarded a Department of Energy (DOE) R&D 100 Award in 1997 for this instrument. Additional sensors that are being considered include thermistor arrays for measuring transient heating from earthquakes, fiber optic Fabre-Perot strain interferometers, and electrodes for measuring differential resistance within the fault zone.

Monitoring Implementation Plan

As discussed in more detail in the Budget Summary, to carry out the plan described above we intend to issue two separate subcontracts for monitoring system integration and deployment. These subcontracts could be issued to universities, research institutes and laboratories, or private companies. The system integration contractor must be able to take full advantage of developments in other countries (Japan and Germany, for example) as well as in other programs (such as the Ocean Drilling Program and the DOE Geothermal Program).

Duke University has been extensively involved in deployment of the existing pilot hole array and is a possible candidate as the system integration contractor for Stage 1. Similarly, Sandia Labs has been working extensively with high temperature sensors and monitoring systems and is a possible candidate as the system integration contractor for Stages 2 and 3. However, no decision has been made in either of these cases and the subcontracts will be awarded on the basis of engineering competence, prior experience and cost.

Downhole Measurements

As shown in Figure II-3.3, the four principal types of downhole measurements to be conducted in the SAFOD hole are LWD, open-hole geophysical logging, cased-hole logging, and stress/permeability measurements.

Logging While Drilling

Using instrumentation located just above the bit, we will conduct MWD and LWD during Phase II of drilling (Figure II-3.7B). MWD data will be acquired starting at the beginning of directional drilling to help the drillers “build angle” properly, whereas LWD data will acquired starting when the final deviation angle is attained and continuing to Total Depth (TD). The three types of LWD measurements we are proposing will provide real-time measurements of geophysical properties across the entire fault zone and will be contracted through Anadrill/Schlumberger or similar companies. The ISONIC tool will provide sonic velocity and natural gamma information, the ADN tool will provide density and neutron porosity information and the RAB tool will provide a 360° resistivity image of the borehole wall.

The logic for running LWD tools is twofold. First, if hole conditions are so bad that open-hole geophysical logging (described immediately below) is impossible or severely restricted, then the LWD program will insure that a continuous profile of critical geophysical measurements are made through the fault zone prior to running casing. The other reason for conducting logging while drilling is to identify zones with anomalous physical properties as they are being encountered. For example, if an overpressured zone is suddenly penetrated by the drill bit it should be indicated by anomalously high porosity, low sonic velocity and low resistivity. This is important to know while drilling is taking place, both for scientific and safety reasons (e.g., as an indication that the mud weight needs to be increased). Several members of our science team have appreciable experience with LWD measurements in the Ocean Drilling Program.

Open-Hole Geophysical Logging

The *in situ* physical properties of the fault zone and country rock will be assessed by conducting a comprehensive geophysical logging program prior to casing each section of the borehole. This open-hole logging program will be conducted in 2 stages, starting at a depth of 2 km (see Figure II-3.3). An initial suite of logs will be run from 2 km to a measured depth of ~3 km, just as the broad fault zone is being entered. A second suite of logs will be run when the well has been drilled to completion at a measured depth of 5 km. These logs will be acquired commercially using state-of-the-art technology currently used in the petroleum industry.

As shown in Figure II-3.3, the measurements to be made include resistivity (AIT), density (LDS), porosity (CNL), P- and S-wave sonic velocity (DSI) and elemental composition (GLT). In addition, ultrasonic televiewer (UBI) and electrical image (FMI) logging will be used to obtain oriented, 360° images of the borehole wall for characterizing fractures, lithostratigraphic variations, stress-induced breakouts, and other features encountered in the borehole. Interpretation and analysis of these logs will be conducted by the SAFOD science team, funded through their respective agencies.

Cased-Hole Logging

Three logs will be run after each section of the hole is cased and cemented. First will be an extremely precise well trajectory using a gyroscopic directional survey (GDS) log. Then, a cement bond log (CBT) and ultrasonic cement imager (USI) log will be run to assure that the cement has filled the annulus between the casing and borehole and that the cement and casing are well bonded. Effective cementing is required both for maintaining hole integrity over time and to facilitate measurements of stress, pore pressure and permeability, and fluid sampling through perforations.

These measurements will be repeated mid-way through the initial two-year deployment of the fault-crossing array (i.e., about one year after Phase 2 drilling is complete) and then again just before the coring program commences during Phase 3 drilling. As discussed above, in conjunction with analyses of seismic data collected by the downhole seismic array, these repeat logs will be used to help identify portions of the fault zone that are actively deforming and, hence, suitable for continuous coring.

Finally, detailed *in situ* temperature measurements will be made repeatedly by USGS personnel after drilling is completed and the entire hole is cased. These measurements, when coupled with thermal conductivity and radiogenic heat production measurements on core and cuttings, will provide important constraints on the thermal regime, hydrologic circulation and sliding resistance within and adjacent to the San Andreas Fault Zone.

Stress, Pore Pressure and Permeability Measurements, and Fluid Sampling

A comprehensive suite of packer tests will be conducted to measure variations in pore pressure, permeability, and *in situ* stress magnitudes adjacent to and across the fault zone. We are planning to conduct three of these tests in the short holes produced during spot coring. However, because of likely hole stability problems, most of the fluid pressure, permeability and hydraulic fracturing stress measurements within the fault zone itself will have to be made after the casing is cemented and perforated, as discussed above. These tests will be conducted using commercially available, drill-pipe deployed casing packer systems by the PI's Mark Zoback and Stephen Hickman, who have extensive experience with such tests.

The experimental procedure will start with a series of tests in "pilot" holes drilled below each casing set point. After the borehole is cased and cemented to measured depths of 2, 3, and 5 km, a 20-m section of hole will be drilled below the casing that will be used first for conducting a drill stem test (DST). During this DST, a packer will be set in the casing and a valve opened to allow flow into the partially evacuated drill pipe. The subsequent pressure buildup will enable us to determine pore pressure and permeability using standard well test procedures and to obtain uncontaminated, large-volume fluid samples. After the DST, each of these pilot holes will be hydraulically fractured to determine the magnitude of the least principal stress. Finally, to make least principal stress and hydrologic measurements at 10 different positions within and adjacent to the fault zone, drill stem tests and hydraulic fracturing measurements will be made through perforations in the cemented casing using the procedures outlined above. Taken together, these tests will result in a complete profile of least principal stress, pore pressure, and permeability measurements across the fault zone. This procedure will also result in a profile of relatively uncontaminated fluid samples across the fault zone; the degree of pore fluid contamination by drilling mud—if any—will be determined by "spiking" the drilling mud with a stable tracer such as fluorescene.

In addition to measuring the least principal stress, we will also determine the full stress tensor along the entire well path using an integrated analysis of hydraulic fracturing tests and borehole image logs. To accomplish this, we will use a series of techniques that Zoback and his colleagues have developed which combine knowledge of the least principal stress, pore pressure, and vertical stress, with observations of compressive and tensile wellbore failure (e.g., borehole breakouts) in borehole image logs. Such observations often make it possible to constrain both the orientations and the magnitudes of the three principal stresses and are especially effective in deviated wells. A detailed methodology and comprehensive suite of software routines known as SFIB (Stress and Failure of Inclined Boreholes) was developed to accomplish this. SFIB is currently being widely used in the petroleum industry for this purpose. One technical note is that it is not necessary to assume that the principal stresses are in a horizontal and vertical plane. Still another method that will be used to assess the complete stress tensor is the measurement of small-scale rotations in breakout azimuth (imaged with the UBI) and resulting from localized stress anomalies caused by slip on small faults penetrated by the hole.

A final set of permeability measurements will be attempted after the four continuous core holes are drilled, using a packer in the main borehole that facilitates the coring process. This packer will seal off the main borehole, making it possible to do a bulk permeability test of each of the cored intervals.

Measurements on Core, Cuttings, and Fluids

Comprehensive sampling of fault zone rocks and fluids will be conducted as part of the SAFOD experiment by scientists at various U.S. universities, the USGS, foreign institutions and possibly DOE labs. Key features of the sampling and analysis protocol we have established for the SAFOD project are presented in this section.

Real-Time Gas Analysis

To compliment laboratory analyses of large-volume fluid samples recovered during the packer tests (described above), real-time analysis of gases dissolved in the drilling mud will be carried out. The system that will be used has the capability to do both automated measurements and automated sampling for subsequent analysis. The gases from a mud degasser will be run into an automatic gas mass spectrometer and gas chromatograph and quantitatively analyzed for N_2, O_2, Ar, He, CO_2, H_2S, SO_2 CH_4, C_2H_6, C_3H_8 and C_4H_{10}. A radon spectrometer will also be used to detect ^{222}Rn and ^{220}Rn. Known quantities of pure and mixed gases are added to the mud system before being circulated into the hole for calibration purposes. This real-time study will provide critical samples and analyses of ephemeral gas/fluid pockets penetrated during drilling that might otherwise escape unnoticed, and will provide essential guidance for decisions related to later fluid sampling and *in situ* hydrologic testing.

Core and Cuttings Handling, On-Site Analysis and Sampling Protocol

As outlined previously, both drill cuttings and core will be acquired from SAFOD. Geologists working for a commercial mud logging company will continuously monitor and record changes in cuttings mineralogy, mud chemistry, and drilling parameters (penetration rate, torque, pump pressure, etc.) during both rotary and core drilling and will bag and label cuttings for later analyses by interested investigators.

Three different types of core samples will be acquired during drilling. Three spot cores will be collected during the main (rotary) drilling phase of the experiment: one in the granite country rock, one just outside the fault zone and one at the bottom of the hole. These cores will be approximately 20-m-long and range in diameter from 12 to 17 cm. These spot cores will be supplemented by approximately 100 sidewall cores acquired below a depth of 2 km using a wireline-deployed coring tool (see Figure II-3.3). These sidewall cores will be 1.9 cm in diameter and 5.1 cm long. Finally, during Phase 3 of drilling, four 250-m-long continuous core holes will be drilled off of the main hole (see Figure II-3.7C), providing the bulk of the core to be used in laboratory analyses and mechanical testing. The diameter of these cores depends on the diameter of the casing off of which these sidetracks are drilled, and will be 6.4, 6.7 or 10.2 cm (the smallest core size would be necessitated by use of the 5” contingency casing string during completion of the main rotary hole through the fault zone).

Core handling and processing will utilize a newly refurbished mobile core lab and associated equipment to be supplied by the USGS Core Research Center in Denver. Routine processing of spot, sidewall and continuous core will be performed by graduate students and principal investigators associated with the SAFOD Core and Cuttings Team. As outlined in Figure II-3.9, this processing will include cleaning, reorienting and labeling the core; generating preliminary petrographic descriptions; photographing and scanning the core; and boxing the core for long-term storage at the USGS Core Research Center in Denver. Core will be scanned using a digital color core scanner developed for the German KTB project and available through the ICDP. These scanned images, along with drilling information and other data acquired during core processing, will be entered into a computer data base developed especially for this purpose by the ICDP. In addition to this routine core processing, we anticipate that several members of the science team will be on site during drilling to prepare detailed petrographic and mineralogical descriptions of the core; prepare core and cuttings samples for later laboratory analyses; and conduct XRD studies on selected drill cuttings and rock flour. As was the case during drilling of the SAFOD pilot hole, lodging (i.e., trailers) will be provided at the drill site free-of-charge for visiting scientists.

To meet the sample needs of the current science team, yet retain a sufficient quantity of core for later analyses by these and other investigators, it is clearly essential that we develop a careful yet responsive sampling protocol. Once the SAFOD project is underway, we will establish a sampling committee to review and evaluate requests for

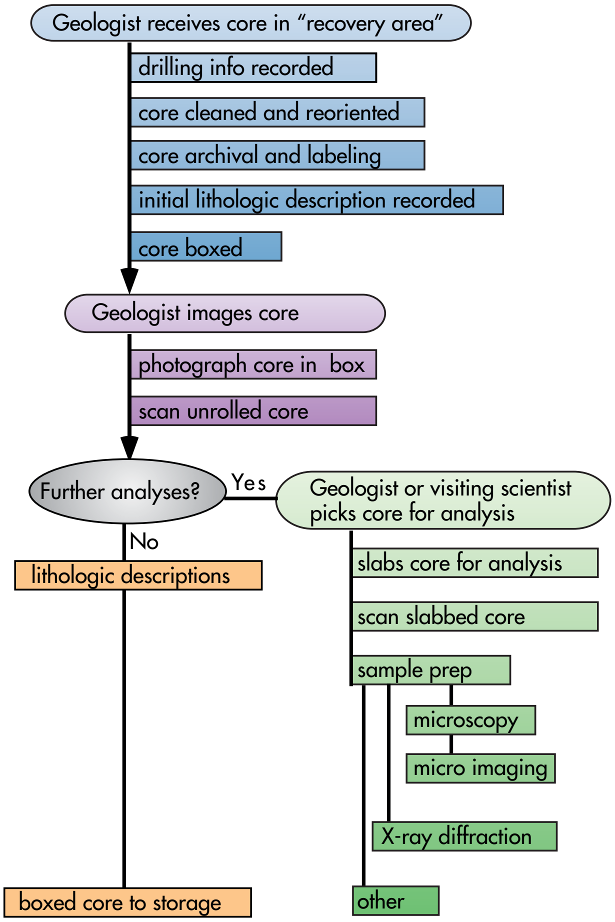


Figure II-3.9. Flow chart illustrating the handling, processing and archiving protocol to be used on core and cuttings samples from SAFOD.

core, cuttings and fluid samples. The sampling procedures and protocol we employ will be based upon our experience with other large, international drilling projects (e.g., the KTB and Long Valley projects) and will be developed in close consultation with the ICDP.

On-Site Technical Personnel

The detailed drilling plan and budget includes a number of cost items associated with personnel. While budgets are presented and discussed below, there are several points to note here because of their overall affect on operations. First, the budgets include all supervisory personnel associated with drilling. Thus, in addition to the personnel provided by the drilling contractor(s), there will be personnel on site 24 hours/day representing the project science team who will be providing supervision of drilling operations, keeping track of progress and expenditures, and working with the scientific project management team to assure that the goals of the project are met on time and on budget. Special equipment, such as the gas collection/gas chromatograph/mass spectrometer system, requires dedicated on-site personnel that will be provided by the responsible PI.

Finally, we have budgeted for two graduate students to function as data managers, who will be on site during the entire rotary drilling and continuous coring phases of the project. These individuals will be able to assist the science team with the innumerable on-site technical activities, including:

- Keeping track (for the science team) of the cuttings, fluids and gases being sampled continuously.
- Preparation of samples and conducting x-ray diffractometry on selected cuttings and core samples.
- Helping with handling of the three spot cores and approximately 100 sidewall cores to be obtained during rotary drilling.
- Maintaining the DIS (Drilling Information System)—a complete digital database of all downhole data, sample descriptions, and drilling parameters from this hole. The DIS database system is to be provided by ICDP.
- Assisting with the appreciable continuous core handling activities during Phase 3 of drilling and entering of this data into the ICDP database. This includes scanning core, describing core, and preparation of digital input for DIS.

Operations at Long Valley and the Hawaii deep drilling project indicate that a three-person staff is needed on a 24-hour basis to keep up with continuing coring operations. As a member from the PI team will be on site continuously, the two positions budgeted here will assure that adequate personnel will be on site to handle incoming core. The budget includes costs for trailers to provide on-site office space and housing for both supervisory and scientific personnel.

Activities in Conjunction with ICDP

A proposal will be submitted to the International Continental Drilling Program to provide assistance in the following areas:

- Maintaining a Comprehensive, Real-Time Database and Archive: A great deal of engineering and scientific data will be obtained from a wide variety of sources over the life of SAFOD. The Drilling Information System (DIS) developed by the ICDP for organizing real-time drilling and scientific data, and making these data available over the Internet, will be of great help to this project. We plan to use the DIS software system for maintaining a comprehensive data base, providing tools for manipulating and plotting data and for disseminating SAFOD data and results to interested scientists and the public.

- Core Handling: The experience obtained with core handling during the KTB project and ICDP projects preceding this one (Hawaii, Long Valley, etc.) will be very beneficial to SAFOD. We hope to take advantage of available ICDP equipment and personnel in SAFOD core handling operations. This includes having the ICDP provide and train us in the use of their 360° digital core scanner.

- National and International Scientific Participation: If the proposed project becomes a reality, it will be a source of scientific opportunity for scientists from around the world. Our hope is that the ICDP will provide a key link to the global scientific community in two regards: (1) to let them know about the scientific opportunities presented by this project through the ICDP web site and ICDP-sponsored workshops, and (2) to help provide funding for SAFOD-related science through proposals submitted to the ICDP by scientists in ICDP-member countries.