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**Scientific Drilling into the San Andreas Fault and Site
Characterization Research: Planning and Coordination Efforts**

Submitted to

U.S. Department of Energy

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PROJECT SUMMARY

This grant was to support efforts of the PI to work with U.S. and foreign scientists and engineers to prepare a proposal to conduct a 4.0-km-deep scientific drilling project into the San Andreas fault zone at Parkfield, California. That effort has now been completed and a proposal was submitted in August, 1998 to the U.S. National Science Foundation, the U.S. Department of Energy and the U.S. Geological Survey, under the auspices of the Interagency Coordinating Group for Scientific Drilling (ICG). The proposal has also been submitted to the International Continental Drilling Program (ICDP).

The fundamental scientific issue addressed in this proposal, obtaining an improved understanding of the physical and chemical processes responsible for earthquakes along major fault zones, is clearly of global scientific interest. By sampling the San Andreas fault zone and making direct measurements of fault zone properties to 4.0 km at Parkfield we will be studying an active plate-boundary fault at a depth where aseismic creep and small earthquakes occur and where a number of the scientific questions associated with deeper fault zone drilling can begin to be addressed. Also, the technological challenges associated with drilling, coring, downhole measurements and borehole instrumentation that may eventually have to be faced in deeper drilling can first be addressed at moderate depth and temperature in the Parkfield hole. Throughout the planning process leading to the development of this proposal we have invited participation by scientists from around the world. As a result, the workshops and meetings we have held for this project have involved about 350 scientists and engineers from about a dozen countries.

The proposal that was prepared follows a preliminary proposal submitted to the D.O.E., the NSF Continental Dynamics (CD) Program and the U.S.G.S. and the ICDP in June, 1996 which laid out the scientific rationale for fault zone drilling and a specific proposal to drill and core to a total depth of 2.5 km in the Parkfield area. In the present proposal we present a revised drilling and coring plan that involves penetrating the fault to a total depth of 4.0 km, thereby addressing one of the principal recommendations of the CD panel to conduct all of the key experiments at depths closer to that of the on-going seismicity. In response to our previous proposal, the CD panel also recommended that we assemble a team of scientists, whose proposals would be evaluated concurrently with this one, to conduct allied investigations critical to the scientific success of this project. Accordingly, in the new proposal we provide summary work plans and budgets from over seventy principal investigators proposing:

- Downhole measurements
- Measurements on core and cuttings
- Analyses of fluid and gas samples
- Geophysical and geological site characterization studies
- Fault zone monitoring

At the present time, this science team includes 33 principal investigators from 19 U.S. universities, about 15 scientists from the U.S. Geological Survey, a number of scientists from Lawrence Berkeley and Lawrence Livermore National Laboratories of the U.S. Department of Energy and scientists from 12 institutions in 4 foreign countries. If the proposed project becomes a reality, these numbers are expected to increase dramatically.

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I. INTRODUCTION: SCIENTIFIC RATIONALE AND EXPERIMENTAL PLAN FOR DRILLING INTO THE SAN ANDREAS FAULT ZONE

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, a myriad of 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 this project is to study the physical and chemical processes that control deformation and earthquake generation within an active plate-bounding fault zone. The overall experiment is explained in detail in the Sections that follow; a schematic diagram of the proposed experiment is shown in Figure 1. The key operational elements of the project we propose are as follows:

1. Rotary drilling a hole to 4.0-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. During drilling we will utilize advanced logging-while-drilling 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 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 which will be left open for fluid pressure monitoring.
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), utilizing 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, fault slip, 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.).

Figure 1. Schematic illustration of the proposed drilling and coring project. The hachured region is a broad zone of very low electrical resistivity indicated by magnetotelluric data (Unsworth et al., 1997; see also Figure 3). The continuous black line represents a rotary-drilled hole that will be drilled vertically to ~2.0 km depth, then inclined through the ~700-m-wide zone of crushed and altered rock with low resistivity and seismic velocity. The four short lines drilled from the main hole illustrate continuously cored laterals to be drilled in a second phase of drilling after a preliminary phase of fault zone monitoring. Earthquake hypocenters (schematically shown in this figure) start at a depth of about 3 km and are mostly to the southwest of a downward-projected vertical fault. Calibration shots will be performed to confirm the earthquake locations before the hole is deviated toward the fault.

The project we propose will provide the kinds of data needed to constrain the many theories currently being debated about fault zone processes. It is not hard to imagine that 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 literally 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.

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 we convened a workshop on San Andreas fault zone drilling 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.

The Problem of Low Strength Faults

Many of the issues to be addressed by drilling into the San Andreas fault have evolved from the long-standing debate regarding the level of shear stress on the fault—that is, the stress/heat-flow paradox (see Zoback et al., 1987, and Hickman, 1991). For about 20 years, geophysicists were completely divided over the fundamental question of the magnitude of shear stress resisting slip on the San Andreas fault averaged over the upper 15-20 km of the fault (the depth range of most earthquakes). This long-term average shear stress is a measure of fault strength. A "weak" fault is one whose strength is on the order of the stress relieved by an earthquake (< 20 MPa) while a "strong" San Andreas would have a substantially greater strength, on the order of 50-100 MPa (e.g., Lachenbruch and McGarr, 1990). Support for a weak San Andreas fault came originally from the absence of frictionally generated heat in shallow boreholes along the San Andreas fault (e.g., Brune et al., 1969; Henyey and Wasserburg, 1971; Lachenbruch and Sass, 1973, 1980). Arguments for high shear stresses on the San Andreas and other active faults come primarily from models for the frictional strength of faulted rock, using laboratory-determined coefficients of friction, μ , ranging from 0.6 to 0.9 (Byerlee, 1978) and assuming hydrostatic pore pressures (e.g., Sibson, 1974, 1983; Brace and Kohlstedt, 1980). This laboratory-based model is often termed the hydrostatic Byerlee's law.

Stress measurements made at many sites around the world (e.g., McGarr and Gay, 1978; Brace and Kohlstedt, 1980; McGarr, 1980; Lund and Zoback, in press) and studies of lithospheric flexure in response to sediment, volcanic and internal loads (e.g., McNutt, 1980; McNutt and Menard, 1982; Kirby, 1983) indicate that differential stresses in much of the Earth's crust are high and approach those predicted by Byerlee's law. Furthermore, as discussed by Zoback and Healy (1984) and Hickman (1991), in-situ stress measurements in a variety of faulting regimes, in conjunction with information on the attitude of nearby active faults, indicate fault strengths in intraplate areas that are comparable to those predicted by the hydrostatic Byerlee's Law. These high-strength faulting sites include the Rocky Mountain Arsenal, Denver (Healy et al., 1968); Rangely, Colorado (Raleigh et al., 1972; Zoback and Healy, 1984); the Nevada Test Site (Stock et al., 1985); the Fenton Hill geothermal site, New Mexico (Barton et al., 1988; Fehler, 1989); Moodus, Connecticut

(Baumgärtner and Zoback, 1989; Mrotek et al., 1988); Dixie Valley, Nevada (Hickman et al., 1997); and to ~8 km depth in the KTB drilling project, Oberfalz, West Germany (Zoback et al., 1993; Brudy et al., 1997). Thus, Byerlee's law, which was established on the basis of simple faulting theory and laboratory friction experiments, appears valid for faults within plate interiors.

Despite the accumulating evidence for strong intraplate faults and a strong crust, other observations provide substantial support for the hypothesis that plate-bounding faults are generally weak. First, analyses of earthquake focal mechanisms and borehole breakouts in central and southern California indicate that the direction of the maximum horizontal principal stress, S_{Hmax} , is at high angles (about 65–85°) to the San Andreas, suggesting that the fault is sliding at very low levels of shear stress (e.g., Zoback et al., 1987; Mount and Suppe, 1987; Jones, 1988; Oppenheimer et al., 1988; Wong, 1990). Furthermore, measurements of stress and heat flow to depths of 3.5 km in the Cajon Pass borehole in southern California indicate high differential stress levels adjacent to the San Andreas (i.e., a strong crust) but suggest that the San Andreas fault itself is relatively weak (Zoback and Healy, 1992; Lachenbruch and Sass, 1992, 1995). An analysis of the Loma Prieta earthquake and its aftershocks reveals an unusually diverse pattern of right-lateral, left-lateral, reverse-faulting and normal-faulting aftershocks consistent with an extremely weak fault zone, perhaps under high pore pressure (Zoback and Beroza, 1993). Observations of stress orientations, heat flow, sea-floor morphology and metamorphic mineral assemblages along a number of other major plate-boundary faults—including oceanic and continental transform faults and subduction zone megathrusts—indicate that these faults may be similarly weak (e.g., Lachenbruch and Thompson, 1972; Oldenburg and Brune 1972, 1975; Kanamori, 1980; van den Beukel and Wortel, 1988; Wilcock et al., 1990; Mount and Suppe, 1992; Magee and Zoback, 1993; Wang et al., 1995).

In summary, while essentially all available data indicates that the frictional strength of intraplate crust is quite high, the frictional strength of the San Andreas, and apparently many other plate-bounding faults as well, is quite low. Taken together, the heat-flow data and the directional constraint (i.e., S_{Hmax} at 65–85° to the San Andreas fault) suggest that the San Andreas fault is weak in both an absolute and relative sense. Despite the fundamental nature of this finding, we have no direct in-situ evidence indicating why this might be so, whether the mechanisms responsible for low strength along the San Andreas are likely to be found in other major fault systems or what role that these mechanisms might play in the processes of earthquake nucleation and propagation.

Implied Fault Zone Properties and Deformation Mechanisms

Numerous theories have been proposed over the past decade specifically related to the weakness of the San Andreas fault. Although the causes for the weakness of the San Andreas fault are unknown, four general classes of explanations have been suggested: elevated fluid pressures, intrinsically low coefficients of friction, solution-transport reactions and dynamic weakening mechanisms. Knowledge of the in-situ frictional properties of the San Andreas and other major, active faults is not only of considerable scientific interest but is also critical for assessing the nature and potential magnitude of static stress transfer and earthquake triggering following large-to-intermediate size earthquakes (see Harris et al., 1998).

If the coefficient of friction, μ , is equal to 0.6–0.9 on the San Andreas fault, as predicted by Byerlee's Law, then the heat-flow constraint could be satisfied if the in-situ pore pressure, P_p , is greater than twice hydrostatic (Lachenbruch and Sass, 1980, 1992). However, if one assumes that principal stress magnitudes are constant across the fault zone and that $\mu \geq 0.6$, then high fluid pressures alone cannot explain the directional constraint as

P_p would exceed the least principal stress once the angle between S_{Hmax} and the fault exceeds about 60° (e.g., Zoback et al., 1987; Scholz, 1989; Lachenbruch and McGarr, 1990). It has recently been suggested that large-scale yielding could lead to an increase in the magnitudes of the principal stresses within the fault zone relative to their values immediately outside of the fault (Rice, 1992). If so, this would allow P_p within the fault zone to exceed significantly the external magnitude of the least principal stress (Byerlee, 1990; Rice, 1992). In this manner, permanently high pore pressures within an intrinsically strong (i.e., high coefficient of friction) San Andreas fault zone, in conjunction with much lower fluid pressures in the surrounding rock, could lower the fault strength sufficiently to satisfy both the heat-flow and directional constraints. A model that is, in many respects, similar to that of Rice (1992) was proposed earlier by Byrne and Fisher (1990) to explain the apparent weakness of the basal décollement beneath the Kodiak accretionary prism in southwest Alaska. Magee and Zoback (1993) applied the Rice model to explain the low frictional strength of the subduction zone associated with the M-8.2 Tokachi-Oki earthquake off northern Honshu, Japan. Although not requiring localized increases in stress magnitude, Fournier (1996) has presented a model in which near-lithostatic fluid pressures may be maintained within the San Andreas fault zone at depths greater than about 6-10 km if the maximum deviatoric stress at these depths is quite low (~ 10 – 30 MPa) and the tensile strength of the rock outside the fault zone remains high due to pervasive crack healing at elevated temperatures.

Alternatively, if one assumes that the fault is optimally oriented with respect to the principal stresses and that fluid pressures are hydrostatic, then the heat-flow constraint can be satisfied if μ along the fault is less than about 0.2 (Lachenbruch and Sass, 1992). Similarly, at least in central California where S_{Hmax} is at about 75 – 85° to the San Andreas fault, the heat-flow and directional constraints can be simultaneously satisfied under conditions of uniformly hydrostatic fluid pressures if μ is extremely low—about 0.1 or less—along the fault and Byerlee's Law is applicable outside the fault zone (Lachenbruch and McGarr, 1990; Lachenbruch and Sass, 1992). It is often proposed that the presence of clays or other weak minerals along the San Andreas and other faults might lead to anomalously low frictional resistance (e.g., Wu et al., 1975; Janecke and Evans, 1988; Wintsch et al., 1995). This inference has been supported by laboratory sliding experiments on synthetic clay-rich fault gouges (e.g., Wang et al., 1980; Shimamoto and Logan, 1981; Bird, 1984; Logan and Rauenzahn, 1987), on synthetic serpentinite gouges (Reinen et al., 1994; Reinen and Tullis, 1995) and on synthetic laumontite gouge (Hacker et al., 1995). However, these experiments are all at low-to-moderate confining pressures and temperatures. In contrast, experiments on natural clay-rich fault gouges collected from the San Andreas at depths of less than 0.4 km (Morrow et al., 1982), on synthetic clay-rich fault gouges (Morrow et al., 1992) and on synthetic serpentinite gouges (Moore et al., 1997) at high temperatures and/or confining pressures and hydrostatic fluid pressures indicate coefficients of friction at in-situ conditions that are too high to be reconciled with either the heat-flow or directional constraints. In addition, both natural and synthetic fault gouges deformed in the laboratory generally fail to exhibit the slip-weakening or velocity-weakening behavior required for the generation of earthquakes (e.g., Byerlee and Summers, 1976; Logan and Rauenzahn, 1987; Marone et al., 1990; Morrow et al., 1992; Reinen et al., 1994). Thus, the importance of these materials in the rheology of the San Andreas fault at seismogenic depths is unclear.

Another important class of models that might explain the low long-term strength of the San Andreas, at least along seismically active segments of the fault, have called upon processes directly associated with earthquake rupture propagation. These dynamic weakening mechanisms include shear heating during slip, leading to transient high fluid pressures (Lachenbruch, 1980) or melting (Sibson 1975; Spray, 1987); reductions in normal stress accompanying the propagation of dilational waves along the fault (Brune et

al., 1993); and the fluidization of fault-zone materials due to the channeling of co-seismic acoustic energy (Melosh, 1979, 1996). While such processes may be operative during an earthquake, they do not relate to the problem of how earthquakes initiate and each requires that very specific fault zone conditions exist to be viable. Thus, to assess the likelihood that dynamic weakening mechanisms might operate along active faults we need to compare the structure and physical properties of actual fault zones with parameters required by these various models and to combine these observations with the results of long-term fault zone monitoring in the near-field of small-to-moderate size earthquakes.

The Mechanical Involvement of Fluids in Faulting

A long-standing (and still-growing) body of evidence suggests that fluids are intimately linked to a variety of faulting processes. These include the long-term structural and compositional evolution of fault zones; fault creep; and the nucleation, propagation, arrest and recurrence of earthquake ruptures. The seminal paper of Hubbert and Rubey (1959) stands out by quantitatively applying the effective stress principle to thrust faults weakened by near-lithostatic fluid pressures in sedimentary basins. Recognition of overpressuring at depths of more than a few kilometers in sedimentary basins has since become widespread (Fertl et al., 1976), especially in basins undergoing active deformation, and the belief that much crustal deformation is focused in areas of fluid overpressure is now widespread in the structural geology literature (e.g., Fyfe et al., 1978).

The concept that high fluid pressures and the localization of deformation are linked has recently been reinforced by studies of active accretionary prisms in subduction complexes and their fossil equivalents (see Dahlen, 1990). The low taper angles of many active prisms and fold-and-thrust belts, coupled with direct borehole measurements of fluid pressure in areas such as Taiwan, provide strong evidence for significant overpressuring within the prism and along the basal decollement (e.g., Davis et al., 1983). Additional evidence for superhydrostatic fluid pressures is gleaned from natural exposures of uplifted prism rocks, which contain vein networks filled with calcite, zeolite, quartz and other hydrothermal precipitates thereby suggesting that fluid pressures frequently exceeded the least principal stress down to depths of 45 km (e.g., Platt, 1986; Moore and Vrolijk, 1992; Brown et al., 1994). A point to note is that there is good evidence that seismic rupturing, in at least some instances (e.g., the Western Taiwan fold and thrust belt and the western margin of the Great Valley adjacent to the San Andreas fault), is occurring in fluid-overpressured crust (Davis et al., 1983; Sibson, 1990).

A possibly important recent development from studies of fluid pressure in sedimentary basins has been the revelation from borehole measurements of abrupt transitions, both vertically and laterally, between distinct fluid pressure regimes in some sedimentary basins. These "fluid pressure compartments" are bounded by seals which in some cases are stratigraphic (e.g., shale horizons) but in others are gouge-rich faults or thin zones of hydrothermal cementation which cut across stratigraphy (Hunt, 1990; Powley, 1990; Dewers and Orteleva, 1994; Martinsen, 1997). By analogy with these observations, Byerlee (1993) proposed a model in which contiguous vertical and horizontal seals within a fault zone would lead to discrete fluid pressure compartments (i.e., tabular lenses), the rupture of which might be important in earthquake nucleation and propagation (see Lockner and Byerlee, 1995). Although direct evidence for these fault zone fluid compartments in active fault zones is lacking, negative polarity reflections (bright spots) on seismic reflection images acquired over some accretionary prisms have been interpreted to indicate the existence of high-pressure fluid compartments along the basal decollements (Moore and Vrolijk, 1992; Shipley et al., 1994; Moore et al., 1995b). Recent laboratory experiments by

Zhang and Tullis (1998) indicate that permeability reduction due to shearing of gouge might also lead to the development of fluid pressure seals in fault zones.

The Physics of Earthquake Nucleation and Rupture Propagation

Understanding the physical processes operating during both nucleation and rupture propagation can prove to be critical to the resolution of the stress/heat-flow paradox, especially if dynamic weakening mechanisms are important. By observing earthquakes at very short distances, a few hundred meters or less, we can observe near-field phenomena for earthquakes of $M \sim 1$ or larger, thereby providing a new window into the physics of the earthquake source. Ideally, in addition to instrumenting the hole with seismometers, we would like to place instruments within or immediately adjacent to the active sliding surface to directly monitor fault displacement, deformation, pore pressure and heat generated during sliding. The work of Brune and co-workers on foam rubber models of earthquakes (Brune et al., 1993; Anooshehpour and Brune, 1994) illustrates the advantages of making measurements at or very near the sliding surface. Many of the objectives for near-field observation will be met by sensors placed within a few hundred meters of the earthquake source. At these distances, near-field waves will be of significant amplitude compared to the far-field waves for $M \geq 0$ events, and static strains will be well within the resolution of borehole strainmeters. The site for the drill hole at Parkfield (discussed at length below) was chosen because of the occurrence of shallow seismicity.

The process by which the fault becomes unstable and initiates a dynamically propagating rupture is central to the stress/heat-flow paradox. It has recently been proposed that the very beginnings of rupture for earthquakes in the magnitude range from at least $M_w = 1$ to 8 characteristically involve a period of slow growth of the seismic moment (Iio, 1992, 1995; Ellsworth and Beroza, 1995, 1998; Beroza and Ellsworth, 1996). The characteristics of this process, called the seismic nucleation phase, rule-out self-similar models for the nucleation and growth of rupture including the standard model of a dynamically growing crack (Kostrov, 1964). Although a range of hypotheses have been proposed to explain this slow beginning to earthquakes, far-field observations have thus far proven inadequate to determine if the seismic nucleation phase represents a cascade of smaller events, in which case the dynamically expanding crack model might apply, or if it represents a transition from an aseismic (stable) sliding to dynamic rupture, as required by laboratory-based and theoretical models of rupture initiation (Dieterich, 1992; Ohnaka, 1992). Observations of the nucleation process made within the near-field have the potential to resolve this process, as they will not be distorted by attenuation or scattering, which limits the interpretation of available data (Iio, 1995).

The physics of earthquake rupture propagation has also been the subject of intensive investigation in recent years (e.g., Heaton, 1990; Brune et al., 1993; Melosh, 1996). New data has again drawn into question the standard model of a dynamically expanding crack that heals inward from its outer boundary (Madariaga, 1976). There is now evidence from large earthquakes that the rupture may propagate as a "slip pulse" (e.g., Wald and Heaton, 1994), yet we know little about how such a concentrated slip zone is generated or maintained, or why the fault comes to rest so abruptly. Brune et al. (1993) have further proposed that tensile opening of the fault accompanies the shear displacement in the slip pulse. If correct, it would be a mechanism by which the fault can have high static strength, but slide without generating heat. However, sliding at near-zero normal stress implies that the dynamic stress drop should equal the tectonic stress (see Lachenbruch and Sass, 1980) resulting in near-zero shear stress on the fault after rupture (e.g., Zoback and Beroza, 1993 for the Loma Prieta earthquake). Thus, measuring the dynamic stress drop in the near-field region will give us a direct test of the high static strength/low dynamic friction hypothesis.

Recent observations of microearthquakes in moderately deep boreholes (2–2.5 km) at Cajon Pass, California (Abercrombie and Leary, 1993; Abercrombie, 1995) and in Long Valley, California (Ellsworth, Kasameyer, Ito and others, in preparation) demonstrate that ultra high-fidelity recordings can be made with available technology under temperature and pressure conditions similar to those we anticipate in the proposed hole. An array of downhole seismometers, accelerometers and other sensors will be deployed across the fault zone after drilling. Having an array of seismometers in the borehole has several advantages. Extremely accurate determinations of the radiated energy, seismic moment and earthquake locations can be made, the detailed velocity structure of the fault zone can be investigated, and earthquake nucleation and propagation can be studied with unprecedented detail. The technological risks to the monitoring instrumentation will be minimized by relying on proven technologies, or modest extensions to them, and utilizing instruments deployed in a cased and cemented borehole. The wide dynamic range of the accelerometers will also let us study earthquakes up to at least the $M=6$ characteristic Parkfield earthquake. High frequency signals are expected from the very local events, with good signal-to-noise above 1 kHz. Thus, good sensitivity to the higher frequencies becomes the most important seismic monitoring design criteria. Peak acceleration estimates for a magnitude 1.0 earthquake located at a distance of 1000 m and 100 m are 1 g and 10 g's, respectively. Because the seismometer string will extend from the core of the fault zone to its edge and beyond, it will also be useful for studying wave propagation within the fault zone.

The Need for Drilling

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 outlined above. 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 where 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 (e.g., Kerrich et al., 1984; Parry, 1994; Evans and Chester, 1995).

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 recent USGS Red Book Conference on the Mechanical Involvement of Fluids in Faulting (see Hickman et al., 1995a), 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; e.g., Sibson, 1975; Magloughlin and Spray, 1992), 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 conceptual models 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 between fault zone processes (e.g., fluid pressure fluctuations) associated with fault creep versus earthquakes.

II. THE PARKFIELD DRILLING PROJECT

As explained above, a proposal has been prepared to conduct a 4.0 km-deep fault zone drilling project into the San Andreas fault near Parkfield, CA. The reasons Parkfield was chosen for this project and an overview of geologic and geophysical knowledge of the area are presented below. 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. If deep drilling into the San Andreas fault zone is eventually done, it is likely that it will be done in an area where the fault produces infrequent, but very large earthquakes (such as the sections that broke in the great 1857 and 1906 earthquakes). These sections of the fault are "locked" in the upper ~10 km during the interseismic period. Thus, by having conducted the pilot project in a creeping area we will have set the stage for trying to understand why some sections of the fault creep and other sections are locked. Further, by drilling in an actively slipping portion of the fault, during the monitoring phase of the experiment we will be able to study the nucleation and rupture processes of microearthquakes with near-field seismic recordings, investigate whether temporal variations of pore pressure occur during fault slip (creep and earthquakes) and study the processes responsible for shear localization.

Why Parkfield?

The objectives of this project require a geologic target with clear and attainable scientific goals that will also serve as a fair test of the technology required to drill a deep hole into the fault. Since we first decided to propose drilling a pilot hole, we focused on sites with shallow seismicity, a clear geologic contrast across the fault and good working knowledge of the geological and geophysical environment of the fault.

The requirement for shallow seismicity was key for two reasons. First, we would like to be able to conduct experiments within or very close to seismically active parts of the fault, for the reasons discussed above. Second, we can use the 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 candidate sites we conducted a systematic search of the strike-slip faults in California, identifying all faults that met the shallow seismicity criteria. To our surprise, this 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 a ~3-km borehole from July 11-12, 1994, 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.
- 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. 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. Although this was anticipated by us based on more limited studies (Ellsworth, 1996; Nadeau and McEvilly, 1997) have now completed a thorough documentation of this behavior beneath Middle Mountain. 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.

The San Andreas Fault at Parkfield

Geological and Geophysical Setting. The site we have identified for the 4.0-km-deep drilling project is located on the southwest flank of the central portion of Middle Mountain, about 10 km northwest of the town of Parkfield. This site is located at the northwestern end of the rupture zone for the 1966 $M=6$ Parkfield earthquake, in the transition between the creeping and locked sections of the San Andreas fault. The San Andreas displays a wide range of behaviors at this site. At the surface, the fault is creeping at a rate of 1.8 cm/year, with most of the fault displacement localized to a zone no more than 10 m wide (Burford and Harsh, 1980; Schulz, 1989). 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 (Nadeau et al., 1994; 1995) that have remained spatially stationary for at least the past 20 years (Figure 2), although uncertainties exist in the exact location of the earthquakes, as discussed below.

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 (Nadeau et al., 1994, 1995; Nadeau and McEvilly, 1997). 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. A new—and controversial—prediction for these repeating events is the possibility that they may have localized stress drops in the kilobar range (Nadeau and Johnson, 1998). If confirmed, this will have wide-ranging implications for fault mechanics and the stress/heat-flow paradox.

Almost all events along this fault segment have right-lateral strike-slip focal mechanisms, corresponding to the geologic sense of movement on the fault (Eberhart-Phillips and Michael, 1993). 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 (Zoback et al., 1987). Also, recent heat-flow determinations by Sass et al. (1997) 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 (Lachenbruch et al., 1980) 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.

Beginning in the summer of 1994, members of the Site Selection Working Group for the San Andreas pilot project have conducted a number of relatively small-scale and detailed geophysical investigations to fill critical gaps in our knowledge about subsurface structure and microearthquake locations at the Parkfield site. A temporary seismic network was installed on and around Middle Mountain to calibrate crustal structure and study fault-zone guided waves near the proposed drill site (Li et al., 1997). This experiment included deployment of temporary seismic stations (to augment the permanent local networks), three chemical shot points and a 10-station REFTEK array crossing the surface trace of the San Andreas. Additionally, a small-scale seismic reflection survey was conducted by Peter Malin at Middle Mountain along two 2-km-long orthogonal lines west of the San Andreas fault (see Unsworth et al., 1997). The purpose of this survey, which employed a single vibroseis energy source and 128 receivers per line, was to determine the thickness of Tertiary sediments beneath the proposed drilling site. Two magnetotelluric (MT) profiles were also conducted at Middle Mountain to determine the electrical conductivity structure of the fault zone and its surroundings (Unsworth et al., 1997; M. Unsworth, pers. comm., 1998). Finally, Mike Rymer (USGS) has initiated detailed geologic mapping to ascertain the geometry and recency of faulting near the Parkfield drill site.

At Parkfield we have at our disposal some of the most accurately located catalog seismicity available anywhere. In spite of this, absolute locations for shallow seismicity beneath the proposed drill site derived by two independent analyses of Parkfield 3-D velocity structure (Michellini and McEvilly, 1991; Eberhart-Phillips and Michael, 1993; R. Nadeau, written comm., 1996) differ by up to one kilometer. Ellsworth (1996) performed a simultaneous inversion of arrivals from 6 earthquakes and three chemical explosions recorded by the temporary seismic array at Middle Mountain for earthquake locations and velocity structure. His analysis indicates that the shallowest events comprising a recurring cluster of small-magnitude earthquakes ($M=1-2$) occur at a depth of about 2.8 km below sea level, or 3.5 km beneath the proposed drill site. An independent analysis of these data by R. Nadeau and colleagues at Lawrence Berkeley Laboratory (written comm., 1996) place the depth of these events 300 m shallower. Uncertainties also remain in the epicentral locations of this cluster, which might be directly beneath the surface trace or about 1 km to the southwest. However, given the large (1.6 km) southwest set-back of the drill site from the surface trace of the San Andreas, it is likely that over time, small ($M=1-2$) earthquakes will be occurring within a few hundred meters, or less, of seismometers emplaced in the borehole (see Figure 3, below). The longitudinal cross-section of seismicity shown in Figure 2 was prepared to identify an optimal shallow earthquake cluster to use as a drilling target. The dense cluster of shallow seismicity extending from ~2.5 km to 4.0 km depth at the relative horizontal position of 3.5 km was chosen as the drilling target. As discussed below, calibration experiments will be performed while drilling is taking place at shallow depths to assure the accurate location of these earthquakes prior to drilling the inclined section of the well through the fault zone. If necessary, the well trajectory can be modified slightly to penetrate the fault zone at a position passing close to the microearthquake cluster.

The San Andreas fault is the most prominent structural feature in central California and especially in the Middle Mountain region. Comparison of sedimentary rock and their ages exposed near the fault indicate that the main trace has been in the same place for at least the past 2 Ma. Many other faults, active splays and older traces of the San Andreas are present both southwest and northeast of the main trace. In general, the older traces trend slightly

Figure 2. Longitudinal cross-section of earthquake hypocenters as located by the U.C. Berkeley high resolution seismic network (R. Nadeau, pers. comm., 1998). Both the preferred (primary) and alternate locations for the drill site are shown. The primary drill site is preferred as it will allow us to intersect more and larger earthquakes at relatively shallow depth.

more westerly than the main trace, possibly indicating minor tectonic rotations. More abundant faults and a higher degree of shearing are noticeable as one approaches the main trace of the San Andreas fault from either side, even within the relatively little-deformed Salinian block. In fact, at the proposed drill site on the west side of Middle Mountain, numerous faults are interpreted to cut upper Cenozoic and basement rocks. These faults trend subparallel to the San Andreas and are mapped to the southwest of the main trace by as much as 3 km.

Figure 3 shows an electrical resistivity model of the upper crust through the primary drilling site derived from a recent MT profile conducted by M. Unsworth (pers. comm., 1998); similar results were obtained by Unsworth et al. (1997). The resistivity structure at depth clearly defines the position of the Salinian block to the southwest of the fault (the high resistivity block at about 1 km depth). This depth is in agreement with the depth of reflectors thought to represent the top of basement on the short reflection lines obtained close to the alternate drilling site (P. Malin., pers. comm, 1996; Unsworth et al., 1997). The MT model shows a ~800 m wide, near-vertical low resistivity zone that is correlative with, but somewhat offset from, the surface trace of the San Andreas fault. This low-resistivity zone presumably results from intense fracturing, hydrothermal alteration and/or high pore pressure within the San Andreas fault zone. The MT model also indicates a moderately resistive Franciscan formation to the northeast of the fault.

There are two sets of microearthquake locations shown in Figure 3 based on locations determined in 3-D velocity models by Michellini and McEvilly (1991) and Eberhardt-Phillips and Michael (1993). Note that the Eberhardt-Phillips and Michael locations are systematically further east than the Michellini and McEvilly locations. The hypocentral locations differ because the velocity models and location procedures used by the two groups differ. While the Eberhardt-Phillips and Michael locations are more consistent with the surface position of the essentially vertical San Andreas, the Michellini and McEvilly locations fall along the abrupt (likely fault-controlled) western edge of the broad fault zone. A detailed calibration experiment while the hole is being drilled at depths of ~1.5 and ~2 km (described below) will determine a more exact location for the hypocenters (see also Nadeau and McEvilly, 1997). Monitoring earthquakes with seismometers in the borehole after it is drilled (also described below) will yield extremely precise earthquake locations to guide subsequent coring operations. Given the width and offset of the electrical anomaly seen in the MT results (Figure 3) as well as uncertainties in absolute earthquake locations, we expect that the active trace (or traces) of the San Andreas fault may be encountered anywhere within the inclined section of the hole.

The Expected M ~ 6 Earthquake

The site we have selected also lies virtually at the epicenter of the 1966 Parkfield earthquake. 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 through our fault crossings. 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

Figure 3. Resistivity structure of the primary drill site based on inversion of continuous magnetotelluric data (Martyn Unsworth, pers. comm. 1988; see also Unsworth et al., 1997). The proposed drill hole is also shown along with earthquake hypocenters (red crosses from Michellini and McEvilly, 1991; blue filled circles from Eberhardt-Phillips and Michael, 1991).

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 (Nadeau et al, 1994; Cole and Ellsworth, 1995). 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 (e.g. Ellsworth, 1975). 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 (Vidale et al., 1994; Ellsworth 1995). 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 (Marone et al., 1995).

III. PROJECT OVERVIEW AND TIMETABLE

In this Section we provide an overview of the key elements of the drilling operations and science plan and the overall sequence of proposed activities. In Section IV we discuss in detail the specific work plans of the different researchers participating in this project as they relate to the activities outlined below. In Section V we present additional technical details on the drilling and operational plan.

Overview of the Science Plan

There are three main components of the science plan: *i*) sampling fault zone materials and fluids, *ii*) downhole and surface-to-borehole measurements of fault zone properties and *iii*) monitoring microseismicity and fault zone processes.

Rock and Fluid Sampling. Our 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.
2. Eight, 10-m-long, spot cores will be collected at convenient locations—five cores will be obtained from the from within the fault zone and three from the Salinian block adjacent to the fault zone.
3. Assuming that hole conditions permit, side-wall cores will be collected (principally from within the fault zone). We have budgeted for a side-wall coring technology—involving drilling a core out of the side of the hole—that will work in “hard” rocks. The use of conventional side-wall coring is contingent on “soft” formation conditions, as the side-wall sampling tool “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 alluded to in Section I (and described in more detail below), a separate continuous coring phase will be conducted 2 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. 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 several 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 KTB-pilot hole and main borehole (see discussion in Section IV). Several different tracers (such as fluorescene) are being considered for use in the mud system to make it easier to identify when inflow occur.
2. After drilling and casing of the rotary drilled hole to TD, a series of 10 Drill Stem Tests (DST's) are planned through perforations in the cemented casing. These tests are described in more detail in the next Section. Each DST should provide relatively large volumes of formation fluid which can be used for subsequent analysis by the various PI's.
3. After each core hole is drilled, fluid samples will be extracted from the core holes after each is drilled.
4. Fluid samples will be extracted from core samples.

Taken all together, these two multiple sampling strategies should provide ample rock and fluid samples for the principal investigators to use in the studies described in Section IV.

Downhole Measurements. Downhole measurements are critical to understanding overall fault zone properties and behavior and a multiple measurement strategy is planned to assure their success.

1. First, hole conditions permitting, a comprehensive suite of geophysical logs will be run prior to casing each section of the borehole. The logs will be acquired commercially using state-of-the-art technology currently used in the petroleum industry. In situ temperature measurements will be made repeatedly by USGS personnel during the project, both before and after the hole is cased.
2. Because physical property measurements are very important to this project and it is possible that unstable hole conditions might constrain the geophysical logging program, a Logging While Drilling (LWD) system will be used in the lowermost section of the vertical hole and throughout the entire interval through fault zone.
3. After the hole is cased and cemented, a detailed Vertical Seismic Profile (VSP) and surface seismic experiment will be carried out as part of site characterization studies. This will allow the observations made on the core and in the borehole to be "scaled up" and extrapolated away from the borehole.
4. 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 the PI's, who have extensive experience with such tests. The

techniques that will be used are relatively standard well-test and hydrofrac techniques that are well-established for determination of the least principal stress.

The pore pressure and stress measurements alone will allow us to test directly several of the hypotheses proposed to explain the weakness of the fault zone. For example, if the Rice (1992) and Byerlee (1990) hypotheses are correct, then both the pore pressure and the magnitude of the least horizontal principal stress should be distinctly higher inside the fault zone than in the adjacent country.

Fault Zone Monitoring and Site Characterization. As discussed above, the opportunity to continuously monitor an active, seismogenic fault at depth and make near-field seismic observations will answer many questions about precursory processes and earthquake rupture nucleation and propagation. While such measurements will continue for a period of at least 20 years after the drilling has been completed, we propose to conduct an initial phase of fault zone monitoring during the two-year period between the rotary drilling and continuous coring phases of the project. There are two principal reasons for doing this. The first is to locate, with extreme precision, the position of the fault patches generating microearthquakes as well as creep within the fault zone. This information will be critical in deciding where to conduct the continuous coring operations during the second phase of drilling. The second purpose for the initial fault zone monitoring efforts is to have seismometers in place within the fault zone during detailed site characterization studies. As explained in Section IV, several different types and scales of seismic imaging experiments are planned for the 2-year period between drilling phases, which will benefit appreciably from having seismometers located within the fault zone.

Project Timetable and Hole Design

We propose that this project be conducted over a six-year period; the generalized timetable for drilling and scientific measurements associated with this project is presented in Figure 4.

Pre-Drilling Site Characterization. A variety of site characterization studies near the proposed drill site have been going on for the past several years. For example, the data shown in Figure 3 were collected as part of these studies. The next significant set of studies at the drill site will begin in October 1998, prior to the work described in this proposal. There will be two principal experiments. First, a 7-km long high resolution seismic reflection profile will be shot across the primary drill site and fault zone. Funding for this project has already been guaranteed by the USGS (Earthquake Hazards Program and Venture Capital Fund) for 1998-99 and will be carried out by a team principally coming from the USGS and Stanford. Twelve portable reflection seismographs will be borrowed to install 700 channels of seismometers along a dense, fault-crossing profile (10 m spacing). As the principal costs of this experiment will be borne by the USGS, this experiment is not discussed at length in this proposal. The main goals of this experiment are to refine the picture of near-surface geology in the drill site area and to assure that the drill site is not located directly above small-scale secondary faults which might needlessly complicate drilling at shallow depth. The second pre-drilling site characterization study will be to deploy a number of additional seismographs in the region surrounding the drill site for earthquake monitoring. This experiment is described at greater length below.

Figure 4. Generalized timetable for operational and scientific activities associated with the Parkfield drilling project.

1999/Year 1. Rotary drilling, downhole measurements and casing of the hole are scheduled to commence in late 1999 and end in early 2000. The recently-developed capability of the petroleum industry to drill “multi-laterals”—satellite wells which drilled from a single “parent” well—has enabled us to make a significant change in our proposed drilling strategy since preparation of Z&H’96. In that proposal, the most operationally challenging part of the project was the necessity to continuously core an inclined hole across the entire fault zone. As the fault zone is likely to be severely crushed and altered to gouge (as well as potentially overpressured), continuous coring of a directionally-drilled hole over such an appreciable distance was going to be a formidable challenge, especially as we needed to maintain sufficient hole diameter to conduct the necessary downhole measurements and deploy fault zone monitoring instrumentation after casing the hole.

Figure 5 presents a simplified view of the rotary-drilled “main hole” penetrating the entire fault zone. After drilling and logging it will be cased and cemented. Rotary drilling, geophysical logging, casing and cementing of such deviated holes is routine in the petroleum industry, even in poorly consolidated and overpressured formations. Thus, by using a rotary drilling strategy to penetrate the entire fault, even if the rock is seriously disaggregated and pore pressures are quite high, it should be possible to drill through the fault zone. After appreciable study of the results from the rotary drilling phase, four, continuously-cored “multi-laterals” will be drilled off of the main hole at carefully selected locations. Additional technical aspects of the drilling plan are summarized in Section V.

As shown in Figure 5, the main hole will be rotary drilled vertically to a depth of ~ 2.2 km and then deviated through the fault zone at a $\sim 50^\circ$ inclination from the vertical to a final depth of 4.0 km. The trajectory shown in Figure 5 was designed to satisfy the following geological and geophysical constraints (see Figure 3):

1. To move the surface position of the hole far enough to the west so that it will avoid a fault trending sub-parallel to—and southwest of—the San Andreas fault zone and be well outside of the low-resistivity anomaly imaged by Unsworth et al. (1997).
2. To get very close to the microearthquake hypocenters, as located both by Michellini and McEvilly (1991) and by Eberhart-Phillips and Michael (1993).
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.

As the hole is being drilled, we will perform two earthquake calibration experiments. Drilling will be stopped for 1 day (after a bit trip at 1.5 km depth and after setting the 13 3/8” casing at 2.0 km depth) and a seismometer will be run into the well. Shots will then be set off at the nearby permanent seismograph stations as well as at the temporary stations to be deployed as part of the site characterization process (see below). This will effectively reverse the path of seismic waves coming from earthquakes near the hole at depth. By “re-locating” the bottom of the hole seismologically, we will be able to greatly improve the hypocenter locations shown in Figure 3 and make minor adjustments to the hole trajectory if needed. While our goal is not necessarily to intersect the very small fault patches that are producing these earthquakes, we do want to be as close to these seismogenic fault patches as possible.

2000/Year 2. Fault zone monitoring begins in the year 2000 and goes on for 2 years. Measurements on core and cuttings will begin as well as analyses of borehole geophysical data.

2001/Year 3. Fault zone monitoring and measurements on core and cuttings continue. In mid 2001 a comprehensive suite of site characterization studies is carried out.

Figure 5. Schematic diagram of the proposed drilling project at Parkfield. The drill site will be located sufficiently far from the San Andreas fault (as determined by surface fault creep, magnetotelluric imaging and microearthquake locations, see text) 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. Rotary drilling and downhole measurements (Phase I) will be conducted in the first year, during which the hole will be cased to a total vertical depth of 4 km. Following a two-year period of downhole seismic and deformation monitoring (Phase II), four 250-m-long core holes will be drilled off of the main hole to obtain rock and gouge samples for laboratory investigations (Phase III). Starting in the fourth year and continuing for about 20 years, the fault zone will be instrumented for long-term monitoring of seismicity, deformation, fluid pressure and temperature (Phase IV).

2002/Year 4. Data from site characterization and fault zone monitoring are analyzed. A comprehensive analysis of all available data will be used to pick intervals for continuous coring. As shown in Figure 5 (heavy black lines), continuous coring within the fault zone will be carried out at four depth intervals through "windows" cut in the casing.

The seismicity rate in the area is such that after 2 years of fault zone monitoring there should be a sufficient number of shallow earthquakes near the drill hole to accurately locate the active fault trace(s) using the clamped seismometer array in the borehole. This information, when combined with the geologic data from spot cores and cuttings, geophysical logs, downhole measurements, fluid and gas chemistry data, pore pressure and in situ stress measurements and the results of site characterization studies will enable the science team to determine the optimal intervals for continuous coring. The advantages of delaying coring until after so much data has been collected and analyzed is clear. Each core will be interpretable in terms of its proximity to active fault traces, the composition and physical properties of the fault zone, pore pressure and stress, etc. The comprehensive scientific measurement program planned for the exhumed core as well as the on-site core-handling procedures are described in detail in Section IV. Following core retrieval, the core holes will be lined with uncemented perforated casing and used for monitoring fluid pressure at depth.

2003/Year 5. When coring activities have been completed at the site, a permanent monitoring string will be deployed in the hole so that the hole can be utilized as a continuous fault zone observatory well into the future. Intensive measurements on core samples are underway.

2004/Year 6. Data analysis and measurements on core are completed. Fault zone monitoring continues.

IV. SCIENCE WORK PLANS: INTEGRATED SCIENCE TEAMS

In this Section we describe how the general scientific objectives discussed above will be met by the principal investigators who are part of the proposed experiment. Table I is a list of these scientists. As mentioned in the Foreword, should this project come to fruition, we fully expect many more scientists to become involved in project. Our overall approach to scientific management has been to create integrated teams of scientists who will address the key programmatic areas. The following teams have been assembled to assure that all key aspects of the science program are met:

- Downhole Measurements
- Measurements on Core, Cuttings and Fluids
- Geophysical Site Characterization
- Fault Zone Monitoring

We summarize the work plans of these different teams of investigators below.

Downhole Measurements

The downhole measurements team consists of:

- Mark Zoback and Steve Hickman (pore pressure, permeability and stress measurements; fracture and fault geometry from geophysical logs)

- Renate Pechinig and Jürgen Wohlenberg (log interpretation and lithology reconstruction)
- Ryuji Ikeda, Yoshihisa Iio and Kentaro Omura (physical properties of fracture zones from geophysical logs)
- Colin Williams, Art Lachenbruch and John Sass (thermal measurements, thermal properties, heat flow)
- David Goldberg and Gerardo Iturrino (interpretation of logging while drilling data for ephemeral fault zone properties)

The four principal types of downhole measurements to be conducted in the Parkfield hole are as follows.

Logging While Drilling. While drilling through the fault zone, measurements while drilling (MWD) and logging while drilling (LWD) will be carried by instrumentation located just above the bit. The MWD data are needed to assist the directional drilling operations and will start at a shallower depth to help the drillers "build angle" properly. The LWD measurements are to provide real-time measurements of geophysical properties. We plan to have three groups of measurements made, that are provided by Anadrill/Schlumberger or possibly other 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 resistivity image.

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 to carry out, or severely restricted due to hole conditions, the LWD program will insure that a continuous profile of geophysical measurements are made through the fault zone prior to running casing. A possibly analogous case was encountered during ODP drilling through the active decollement in the Barbados subduction zone (Moore et al., 1995a). While open hole geophysical logging was impossible due to the extremely poor hole conditions, much was learned about the location and properties of the decollement from the LWD program. The other reason for conducting logging while drilling is to identify zones with anomalous composition or 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). The research proposed by David Goldberg and Gerardo Iturrino is to provide a real-time geophysical interpretation of these data with a particular emphasis on identifying what might turn out to be ephemeral fault zone properties. Goldberg and Iturrino have appreciable experience with such measurements in the ODP program.

Open Hole Geophysical Logging. The open-hole geophysical logging program will be conducted in 3 phases that are coordinated with the drilling and casing program. An initial suite of logs will be run before casing the vertical hole being drilled to a depth of 2 km. A second suite of logs will be run before casing the hole at a true vertical depth (TVD) of ~ 3 km, just as the broad fault zone is being entered. A final suite of logs will be run when the well has been drilled to completion at a TVD of 4 km.

The logs to be run are intended to provide a comprehensive profile of the composition and properties of the fault zone. The resistivity (AIT), density (LDS), porosity (CNL), sonic (DSI) and geochemical (GLT) measurements to be made by Schlumberger will provide the information needed to characterize composition and physical properties. Renate Pechinig and Jürgen Wohlenberg will carry out a detailed analysis of the logs for

reconstruction of a comprehensive lithologic profile. Pechnig and Wohlenberg carried out similar studies as part of the KTB project in Germany. Their proposed studies include a comprehensive check of log quality, comprehensive analysis of logs (closely correlating geophysical logs with cuttings and core) and a reconstruction of lithology. The geophysical logs are also of appreciable interest to the scientists carrying out the laboratory physical property measurements on exhumed samples and the fault zone characterization studies (described below). Ryuji Ikeda, Yoshihisa Iio and Kentaro Omura will analyze the logs to determine physical properties, especially the physical properties of fault zones. They have been recently conducting similar studies in shallow holes drilled through recently active faults in Japan. Mark Zoback and Steve Hickman will analyze the wellbore imaging data to characterize fractures and faults encountered in the borehole and to utilize these data as an integral part of the stress measurement program, as described in detail below. Zoback proposes to support two graduate students in this effort.

Colin Williams, Art Lachenbruch and John Sass will conduct a series of detailed temperature measurements (and corresponding thermal conductivity and heat production measurements on samples) to thoroughly characterize conductive and convective thermal regimes of the fault zone and surrounding crust. They will derive a profile of heat flow throughout the total depth of the hole and integrate the heat flow results with post-drilling temperature measurements in an effort to detect transient thermal signals associated with fluid flow and mass transport.

Cased-Hole Logging. After the hole is cased and cemented three logs will be run. 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 for a number of aspects of the science program, especially the measurements of stress, pore pressure, permeability and fluid sampling described in the next Section.

These measurements will be repeated mid-way through the monitoring program (about 1 year after the first phase of drilling is complete) and then again just before the coring program commences (about 2 years after the first phase of drilling is complete). In conjunction with analyses of seismic data collected by the monitoring array and the site characterization experiments (see below), these repeat logs will be used to help identify portions of the fault zone that are actively deforming and, hence, suitable for continuous coring in the second phase of the drilling program.

Stress, Pore Pressure and Permeability Measurements and Fluid Sampling. One of the most important aspects of the downhole measurement program involves the in situ stress, pore pressure and permeability measurements coupled with fluid sampling. The goal of these experiments is to conduct a series of measurements at different depths and positions with respect to the fault zone. Mark Zoback and Steve Hickman will be responsible for these tests.

The experimental procedures will start with a series of packer tests. After the borehole is cased and cemented at 0.3, 2.0 and 3.0 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). A packer will be set in the casing and a valve will be opened to allow flow into the partially-evacuated drill pipe. The pressure build-up during the DST will enable us to determine pore pressure and permeability using standard well test procedures (e.g., Horne, 1996) and to obtain uncontaminated fluid samples. After the DST, each of the open hole sections will be

hydraulically fractured to determine the magnitude of the least principal stress. This value can be determined with little ambiguity during a hydraulic fracture measurement (Zoback and Haimson, 1982) as minimum energy considerations cause the hydrofrac to propagate away from the well perpendicular to the least principal stress, regardless of the material properties of the formation being hydraulically fractured (Hubbert and Willis, 1954).

After conducting geophysical logging, open-hole hydraulic fracturing tests will also be attempted in the Salinian granite section of the well between 2.0 and 3.0 km depth using inflatable straddle packers. As was the case with the fractured granitic rock in the Cajon Pass borehole (Zoback and Healy, 1992), it is likely that we will be able to determine the least principal stress in these measurements. Finally, to make in situ stress and hydrologic measurements at different positions within the fault zone, drill stem tests and hydrofrac measurements will be made through perforations in the cemented casing using procedures common in the petroleum industry. The basic procedure for these tests is described in Section V. These tests will result in a complete profile of least principal stress, pore pressure and permeability measurements across the fault zone to address the questions raised above. It will also result in a profile of relatively uncontaminated fluid samples (by "spiking" the drilling mud with a stable tracer such as fluorescene, the degree of pore fluid contamination by drilling mud can be easily determined).

While a profile of pore pressure and least principal stress measurements is sufficient to test the Rice (1992) hypothesis, we will also attempt to determine the full stress tensor along the entire well path. To accomplish this, we will utilize a series of techniques that Zoback and his colleagues have developed which combine knowledge of the least principal stress, pore pressure, vertical stress and observations of compressive, shear and tensile wellbore failures observed in borehole image logs (e.g., Moos and Zoback, 1990; Peska and Zoback, 1995; Zoback et al., 1993; Barton and Zoback, 1994; Brudy et al. 1997; Wiprut et al., 1997). The image logs we will be using for this purpose (see below) are the ultrasonic borehole imager (UBI) and electrical formation micro-imager (FMI). Such observations often make it possible to constrain the orientation and the magnitude of the maximum horizontal principal stress. As explained by Peska and Zoback (1995) and Zoback and Peska (1995) these techniques 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 by Peska and Zoback 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 rotations of breakouts (imaged with the UBI) and resulting from localized stress anomalies caused by slip on small faults penetrated by the hole (e.g., Barton and Zoback, 1994; Shamir and Zoback, 1992).

A final set of permeability measurements will be attempted after the four continuous core holes are drilled. While these holes are being cored there will be packer in the main borehole that facilitates the coring process. Because this packer will seal off the main borehole, it should be possible to do a bulk permeability test of each of the cored intervals.

Measurements on Core, Cuttings and Fluids

The team carrying the out broad suite of measurements on core, cuttings and fluids consists of:

- Anne-Marie Boulier, Jean-Pierre Gratier, Eric Pili and Simon Sheppard (crack healing mineralogy and structures)
- Kevin Brown and Mike Underwood (clay chemistry)

- Fred Chester, Jim Evans, Dave Kirschner (mesoscopic mineralogy and microstructure)
- Nick Christensen and Herb Wang (seismic and poroelastic properties, differential strain analysis)
- Jörg Erzinger (real-time gas chemistry and noble gas geochemistry)
- Brad Hacker and James Boles (microscopic mineralogy and microstructure)
- Bezalel Haimson (true triaxial rock strength measurements)
- Miriam Kastner (carbonate veins)
- Dave Lockner, Dianne Moore and Carolyn Morrow (friction, strength, resistivity, permeability)
- Hidemi Tanaka, et al. (comprehensive physical properties)
- Terry Tullis and David Goldsby (friction, microstructures)
- Ernie Rutter and Dan Faulkner (permeability anisotropy)
- Yousif Kharaka and Mack Kennedy (geochemistry of water and gases)
- Tom Torgerson, Martin Stute and Peter Schlosser (rare gases)

This team is proposing 12 projects to study the mineralogy, deformation microstructures, physical properties, and constitutive behavior of rock samples recovered from the San Andreas zone and country rock at depth. They are also proposing 3 projects aimed at studying the chemical and isotopic composition of fault zone fluids and gases.

Mineralogy and Deformation Microstructures. Characterization of deformation mechanisms operating within the fault zone and the role of fluid-rock interactions in controlling fault zone rheology is being addressed by two closely coordinated proposals, working primarily at the mesoscopic (Chester et al.) and microscopic (Hacker et al.) scales. Chester, Evans, and Kirschner will be the primary research group responsible for ascertaining the overall structures and geochemistry of the cuttings and cores, and will be at the drill site during most of the coring operations. They will characterize the mesoscopic and microscopic structures (fractures, faults, cataclasites, microfractures, veins), mineralogy, petrology, major and trace element geochemistry, and stable isotope geochemistry by means of optical microscopy, X-ray fluorescence (XRF) and diffraction (XRD), and other techniques. Their observations and data will be used to determine the nature and extent of structural and mineralogical zonation across the fault; the mechanisms of deformation, recovery and shear localization; the extent of fluid-rock interactions in and across the fault; and questions related to open- versus closed-system behavior. Hacker, Boles and Chen will conduct a complimentary suite of microstructural analyses that include scanning electron microscopy (SEM), electron-microprobe, XRD and transmission electron microscopy (TEM) observations of solid phases at the grain and sub-grain scale; secondary ion mass spectrometry (SIMS) observations on fluid inclusions; and uranium-series dating of carbonate veins. These observations will be used to identify the nature and timing of diagenetic reactions and associated changes in fluid pressure, volume, and chemistry. In addition, their results will determine the grain-scale mechanisms controlling deformation during the interseismic and coseismic periods.

Two projects are focused specifically on crack sealing, solution-transport deformation and the geochemistry of vein-filling minerals. In the first of these projects, Kastner will conduct detailed analyses of the mineralogy, major and minor element chemistry, and isotopic composition of carbonate vein-filling minerals within and adjacent to the fault zone. This study will involve optical microscopy, cathodoluminescence (CT), SEM, XRD, and microprobe analyses of the geometry, chemical zonation, and timing of vein-filling

episodes, augmented by mass spectrometry (MS) and inductively coupled plasma (ICP) atomic emission spectrometry for minor and trace-element geochemistry and isotopic ratios. Kastner will use U-Th-Radium techniques to provide high-resolution dating of carbonate veins ranging from 350,000 years to a few years in age and will examine P/T relationships, bulk chemistry and isotopes for both fluid and solid inclusions. In the second proposal, to be submitted to the French government, Boullier, Gratier, Pili and Sheppard will perform optical, SEM and CT observations of crack healing structures; microprobe, infrared spectroscopy (IR) and bulk chemical characterization of sealing minerals; fluid inclusion studies; stable isotope studies of sealing products and fluid inclusions; and laboratory experiments on the kinetics of dissolution/precipitation reactions under stress. This project is highly complimentary to the Kastner proposal, in that it deals with the kinetics of fluid-rock interactions, the interpretation of pressure-solution microstructures (stylolites, indented grains, etc.), and analyses of fluid inclusions. Taken together, these two projects will provide critical constraints on the nature and origin of fluids associated with the San Andreas fault zone, their physical and chemical roles in the faulting process, and the timing of fluid pressure transients and their possible relationship to the earthquake cycle.

The presence and relative abundances of hydrated clay phases (smectite, illite/smectite mixed-layer clay, and chlorite-smectite mixed layer clay) and their possible impact on fluid pressure generation and the seismic-to-aseismic transition will be the focus of a coordinated pair of proposals by Underwood and Brown. Using XRD and SEM/EDS techniques, Underwood will determine the mineralogy and chemistry of clays found in fault gouges and variously deformed and altered wall rocks collected from the Parkfield drill hole (cuttings and core) and from surface outcrops along different transects of the San Andreas fault system in central California. Brown will then conduct laboratory experiments on these samples at realistic in-situ temperatures and fluid chemistries to determine the stability of these clay phases, the hydration state of any smectites present, and the kinetics and physical manifestations of clay-mineral hydration/dehydration reactions. These experiments will be critical in addressing long-standing controversies regarding the presence or absence of smectites along the San Andreas fault zone at depths greater than a few kilometers and the effect that this might have on frictional properties (e.g., Figure 3).

A broad range of geochemical and microstructural investigations on cores and cuttings are being proposed by nine different investigators from Japan, headed by H. Tanaka (Ehime Univ.). Members of this project, who will be requesting funding from several different funding agencies in Japan, will conduct mineralogical and geochemical investigations (optical, SEM/EDS, XRD) and microstructural observations to determine the mode and extent of hydrothermal alteration and deformation in the fault and wall rocks, the relative rates and pathways of fluid exchange within the fault zone, and the formation temperatures of fault rocks. One important aspect of this group's involvement in the Parkfield project is their experience in analyzing and interpreting cores from shallower fault-zone drilling experiments already conducted or underway in Japan.

Physical Properties and Constitutive Behavior. The physical properties and deformational behavior of fault-zone materials and country rock will be determined in several different rock physics laboratories in the United States and abroad. In most cases, measurements will be made on intact core samples at stresses, pore pressures, temperatures and pore fluid chemistries appropriate to the conditions from which the samples were recovered.

Christensen and Wang will be making acoustic measurements on cores at elevated confining pressure, fluid pressure and temperature to determine P- and S-wave velocities, attenuation, elastic constants and the magnitude and orientation of seismic anisotropy. Petrofabric observations will be used to differentiate between mineralogical and structural controls on seismic anisotropy, if it exists. This team will also conduct differential strain

analysis to identify the geometry and impact of microcracking induced during core recovery and to relate these effects to the in-situ stresses. Finally, they will conduct extensive measurements of poroelastic properties at realistic in-situ conditions to help understand fluid pressure changes induced during seismically induced stress changes. These results will be "scaled up" through integration with physical properties determined from wireline logging, LWD, drill stem tests and surface-based geophysical imaging to provide critical input to structural and mechanical models for the San Andreas fault system.

Measurements of the frictional and fluid-flow properties of recovered core samples will be conducted by two groups, using complimentary state-of-the-art rock mechanics facilities at Brown University and the USGS. Both groups will obtain data at room temperatures and at realistic in situ conditions of temperature, normal stress, fluid pressure and pore fluid chemistry. Tullis and Goldsby will use a unique rotary shear apparatus to determine the frictional constitutive relations and permeability of fault rocks and gouge as a function of shear displacement, normal stress and direction of fluid flow, to a total displacement of up to several meters. These experiments will include velocity stepping and slide-hold-slide tests to determine important parameters in the rate- and state-dependent friction laws. Slip velocities will range from 0.001 mm/s up to 3 mm/s, the latter to test for possible weakening effects associated with rapid slip and shear heating. Lockner, Moore and Morrow (of the USGS) will use high-pressure and temperature triaxial deformation apparatuses to determine a broad range of rock strength and hydraulic parameters, including intact rock strength, frictional sliding strength, matrix permeability and complex electrical resistivity. They will also investigate pore pressure changes due to inelastic processes occurring during shearing and normal compaction, to better understand the physics of rupture propagation and fault interaction. Sliding experiments will be carried out to total displacements of about 1 cm, at rates ranging from 0.01 mm/s to 32 mm/yr. At these lowest rates, which are comparable to the long-term slip rate on the San Andreas fault, Lockner et al. will be able to study time-dependent processes associated with fault creep and long-term weakening. Both the Tullis and Goldsby and Lockner et al. groups will be conducting petrographic studies using SEM, TEM and optical microscopy to identify deformation microstructures, mineral assemblages and microfabrics before and after deformation.

In a related study, Rutter and Faulkner (University of Manchester, England) are proposing laboratory permeability measurements on recovered fault gouge as a function of core orientation, confining pressure, pore pressure, differential stress and temperatures up to 250° C. Their work is specifically focused on understanding the possible roles of low-permeability clay-rich fault gouge in controlling permeability anisotropy and the entrapment of fluids under high pressures in fault zones. Measurements will be conducted using both water and argon as the pore fluid, to determine the effects of different pore fluids on permeability. A key component of this study is comparison of the results obtained with similar measurements made by these investigators on surface samples from fault zones in southeast Spain.

Detailed knowledge of rock strength and failure mode is needed for the estimation of in-situ stress magnitudes using borehole breakouts. Toward this end, Haimson will be making measurements of rock strength and stress-strain behavior on cores recovered from the Parkfield hole. Haimson will use his unique polyaxial deformation apparatus, allowing him to investigate rock deformation and failure under true triaxial conditions (i.e., where the three principal stresses are not necessarily equal in magnitude), thereby better replicating the in-situ stress state. Experiments will be conducted under dry and wet conditions and at temperatures up to the in-situ temperature. These experiments will also be important in constraining the onset of dilatancy under triaxial stress conditions—an important parameter in some hydromechanical earthquake models.

Fluid Chemistry. Three teams of investigators will be conducting chemical and isotopic analyses of pore waters and gases. The first team, Kharaka and Kennedy (of the USGS and LBL, respectively) will determine the geochemistry of bulk water and gases encountered during drilling of the Parkfield hole, by measuring the concentrations of selected major, minor and trace elements as well as stable and radiogenic isotopes (e.g., $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $\delta^{34}\text{S}$ and $\delta^{87}\text{Sr}$; ^3He ; ^3H , ^{14}C , ^{36}Cl and ^{129}I). Fluid samples will be obtained during drill stem tests (see below) using flow-through and closed down-hole samplers. Drilling fluids will be tagged to ascertain the extent of formation infiltration during drilling, so that these results can be extrapolated to "pristine" pore fluid conditions. The objectives of this study are to ascertain the origins, pathways and transport rates of pore water and solutes; the nature of water-mineral interactions within and adjacent to the fault zone; and the role of volatiles (CO_2 , CH_4 , N_2 and noble gases) from mantle and deep crustal sources in the faulting processes.

Torgersen, Stute and Schlosser will use rare gas dating techniques on cores to determine the magnitude, direction and rates of fluid transport within the San Andreas fault zone. This involves measuring the concentrations of radiogenic elements (U, Th, K, Li) in the solid phases and the concentrations of rare gas daughter products (isotopes of He, Ne, Ar, Kr and Xe) in both the solid phases and the pore fluid. Results will be used to determine the apparent ages of the pore fluid and the enclosing rock and compared with model calculations to estimate the length/time scales of fluid-rock interaction. In addition to spiking the drilling fluids (see above), this team will employ secondary coring and vacuum packaging operations at the drill site to obtain relatively undisturbed samples of the matrix pore fluid. Step-heating experiments and fluid-flow modeling will also be performed to determine the rates of diffusive exchange of rare gasses between the solid and fluid phases.

Real-time analysis of gases dissolved in the drilling mud will be carried out by Jörg Erzinger of GeoForschungZentrum, Potsdam, who carried out similar studies in the KTB pilot hole and main borehole. The system he will use 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 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. Erzinger will also make a suite of geochemical measurements on the discrete samples collected through perforations. As mentioned below in the context of collecting, describing and archiving the core and cuttings, a second geologist is being contracted for through the mud logging company. After training by Erzinger, these geologists will be responsible for operation and maintenance of the automated gas analysis system. Because gases will be introduced into the mud column throughout the open-hole interval, this apparatus cannot substitute for the discrete spot sampling and analyses proposed by Kharaka and Kennedy, Torgersen et al. and Erzinger. However, the proposed 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 the proposed hole. 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. Eight spot cores will be collected during the main (rotary) drilling phase of the experiment: three in the granite country rock and five in the fault zone. These cores will be approximately 10-m-long and range in diameter from 12 to 17 cm. These spot cores will be supplemented by approximately 150 sidewall cores acquired below a depth of 2 km using a wireline-deployed coring tool. These sidewall cores will be 1.9 cm in diameter and 5.1 cm long. Finally, at the conclusion of the short-term monitoring phase of this experiment, four 250-m-long continuous core holes will be drilled off of the main hole (see Figure 5), providing the bulk of the core to be used in the laboratory analyses described above. 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 13 cm contingency casing string during completion of the main rotary hole through the fault zone). Both the spot cores and the continuous cores will be oriented by comparison of fractures and other features in the core with FMI and UBI logs (see Downhole Measurements Section).

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. Much of the routine processing of spot, sidewall and continuous core will be performed by two people—a geologist and a technician—to be hired under the drilling contract (see attached Drilling Program and Cost Estimates), with on-site assistance from principal investigators associated with the Core and Cuttings Team. 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 Core Research Center. Core will be scanned using a digital color core scanner developed for the German KTB project. These 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 International Continental Drilling Program (ICDP). This system—the Digital Information System (DIS)—and all other components of the mobile core lab, have been extensively repaired and updated for use in the Long Valley Exploratory Well during the summer of 1998, and should be thoroughly operational before they are needed for the Parkfield project.

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. These investigators will be assisted by the contract geologist and technician, who will slab the core samples, scan the slabbed core, help prepare thin sections, and perform other tasks as needed. For example, co-PIs from the Chester et al. proposal will be on-site throughout the continuous coring operation to perform detailed geological and geochemical logging of the core as it comes out of the hole. They will be assisted in this effort by Jeff Hulén (Energy Research Institute, Univ. Utah), who has considerable experience in working with core recovered from scientific drill holes. Lodging (i.e., trailers) will be provided at the drill site free-of-charge for visiting scientists, which can accommodate up to four people at one time.

In order 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 Parkfield project is underway, we will establish a sampling committee to review and evaluate requests for 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 project) and will be developed in close consultation with the ICDP.

Geophysical and Geological Site Characterization

The site characterization team consists of:

- Claus Prodehl and Trond Ryberg (refraction/wide-angle reflection profiling)
- Simon Klemperer, John Hole, Manik Talwani, Karl Fuchs and Martin Karrenbach (3-D seismic reflection)
- Tom McEvilly, Robert Nadeau, Lane Johnson, Jaime Rector and V. Korneev (drill bit imaging, 3-D tomographic modeling)
- Steve Roecker and Cliff Thurber (absolute locations, 3-D tomographic modeling)
- Yong-Gang Li and Keitti Aki (fault zone guided waves)
- Michael Rymer and Ramon Arrowsmith (geologic mapping)
- Mike Rymer, Rufus Catchings and Gary Fuis (high-resolution reflection survey)
- Peter Malin (geophysical mapping and drill bit VSP)
- Martin Karrenbach (theoretical 3-D wave propagation studies)

We have assembled a science team divided into nine separate projects that will perform a suite of complementary investigations of the geophysical and geological environment of the San Andreas fault zone surrounding the borehole. These investigations have been selected to provide a high-resolution image of the earthquakes and physical environment of the fault zone and upper crust beneath the Middle Mountain drill site. Overall coordination between the projects, and scheduling of the field work will be provided by Bill Ellsworth. The relative timetable and phasing of the site characterization studies has been designed to maximize the coordination between experiments. Because our primary objective in these experiments is to image the crustal volume containing the drill hole, there is a high degree of overlap between the experiments and methods. Since each of the methods complements the others, the overlap will contribute to the development of a more complete and robust image of the subsurface structure.

These nine projects will address two distinct objectives. The first is to provide technical information that is critical to the siting and drilling of the borehole. The principal siting questions we need to resolve are 1) the location of the repeating earthquake cluster we will attempt to intersect with the borehole, and 2) the presence of shallow geologic complications at the drillsite that could be avoided or mitigated by a slight resiting of the drillsite. Our second objective is to create a comprehensive structural and physical model of the fault zone. Detailed knowledge of the physical environment of the fault will be essential to the interpretation of structures and properties observed in the borehole.

Although locations of earthquakes beneath Middle Mountain have been studied using fully 3-D velocity models obtained from local earthquake seismic tomography (e.g. Michélini and McEvilly, 1991; and Eberhart-Phillips and Michael, 1993), there are significant discrepancies between these results (Figure 3). The best estimates of the horizontal position of the targeted earthquakes at the drillsite differ by nearly 1 km between these two studies. We must resolve the true location of the target repeating earthquakes with an uncertainty of 100-200 m before deviating the borehole toward the fault if we are to have a high probability of hitting them.

Roecker and Thurber propose to solve the absolute location problem using a two-step approach. The first step will consist of a monitoring experiment, beginning 6-12 months before drilling, to collect traveltimes data from shallow events in and near the target zone on

a tight network of temporary (and permanent) stations surrounding the borehole on Middle Mountain. These data, together with existing explosion and earthquake data will be analyzed to construct candidate 3-D structures and earthquake locations. The second step will be to conduct traveltimes calibration experiments when the vertical section of the borehole is being drilled. A borehole seismometer, provided by LLNL, will be briefly installed in the hole when it is approximately 1500 m and 2000 m deep. Small explosive charges will be detonated immediately beside the temporary and nearby permanent stations, and the traveltimes to the borehole will be measured. By reciprocity, these traveltimes are the same as if the source were in the borehole. Because the location of the borehole is known, we can use this "virtual earthquake" to test and refine candidate locations and perform joint hypocenter determinations for the target earthquakes as recorded by the temporary network. The results from the 1500 m calibration will be used to set the kick-off point for the hole, and the 2000 m calibration will be used to refine the trajectory and azimuth of the deviated hole.

In another project that addresses the first objective, Rymer, Catchings and Fuis will conduct a high-resolution seismic reflection/refraction profile in the fall of 1998 along a 7 km-long line that runs across Middle Mountain at the drill site. The very high fold and short group interval (10 m) of this explosion survey will provide detailed structural and physical information (V_p and V_p/V_s) in 2-D within the upper 1.5 km of the crust, and reflection information to several times this depth. We will use the results of this survey to select a drill site free of near-surface faults or other potential geologic complications that should be avoided in the drilling of the vertical upper 2 km of the borehole. This work will be performed by the USGS, with important assistance provided the Oyo Corporation.

Our second objective, to create a comprehensive 3-D model of the fault and its environment, will be addressed by all nine projects. Most of these projects will be conducted during the approximately 2-year-long hiatus in drilling between the completion of the main hole and the drilling of the core holes. At this time, we will deploy a multi-sensor seismic monitoring string in the borehole. The borehole array will contain 80 3-component sensor packages distributed along the inclined borehole, and is described in more detail in the Section on Fault Zone Monitoring below. By making simultaneous surficial and borehole recordings of both earthquakes and controlled sources, we will be able to study the fault and its environment in great detail. We will coordinate the timing of the active source experiments to field as many of them as possible at the same time to maximize the observation (and potential scientific return) of each experiment.

During the 2-year interval between the completion of the main hole and the drilling of the core holes, we will be studying the structure and properties of the fault zone using a variety of active source and passive seismological techniques. Roecker and Thurber are proposing to install a dense 2-D surface array and image the V_p and V_p/V_s structure using basically the same experimental design employed to study the San Andreas fault 100 km to the northwest (Thurber et al., 1996, 1997). Their work plan includes much of the explosion seismology work being proposed. Li and Aki will also field the same type of dense linear arrays they have used to study fault zone guided waves at many locations around the world. Li has previously successfully coordinated this type of study with Roecker and Thurber's active/passive tomography experiments (Li et al., 1997). The permanent stations of the U.C. Berkeley and USGS networks will also be integral data sources for the tomographic studies, and McEvilly et al. Will be working in concert with Roecker and Thurber, and others in the development of 3-D models.

McEvilly et al. are also proposing to augment the 2-D array of Roecker and Thurber with a linear array of seismometers that will most probably re-occupy the refraction line of Rymer, Catchings and Fuis. Recording earthquakes along this line will permit us to tie their

detailed shallow structure model to the 3-D seismic tomography. Prodehl and Ryberg will conduct a wide-angle seismic reflection survey using the roll-along procedure along a 50 km-long line centered on the drill site. This profile will give critically needed velocity constraints and detailed structural data to depths of 10-15 km, or to the base of the seismic zone. Klemper, Talwani and Hole are proposing to conduct a 3-D seismic reflection survey above the hole in the region of detailed geologic and geophysical mapping by Rymer and Arrowsmith, and by Malin. By scheduling this survey during the time when the monitoring string is in the hole, we will have detailed tomographic coverage from the 2-D shot pattern to the borehole array, which should provide critical constraints for the interpretation of the 3-D seismic reflection data.

Additional site characterization plans that do not need to be tightly coordinated with the controlled source work are those of Rymer and Arrowsmith, and Malin. Rymer and Arrowsmith will conduct detailed geologic and geomorphic mapping of the immediate environment of the hole, and relate surficial geology and processes to those encountered in the borehole. Malin proposes to conduct a detailed potential field geophysical survey of Middle Mountain in the same region. Together, these studies will provide a solid framework for interpreting the results of the seismic imaging experiments. Malin also proposes to field a seismic imaging array during the first drilling phase. He will conduct an "inverse" VSP with the array, using the drill bit noise as a source.

Fault Zone Monitoring

The fault zone monitoring team consists of:

- Peter Malin (seismic monitoring string design, seismic waves)
- Phil Harben (seismic monitoring string design and manufacture)
- Tom McEvelly, Robert Nadeau, Lane Johnson, Jaime Rector and V. Korneev (seismic waves, earthquake source process, monitoring string design)
- Malcolm Johnston (borehole strain, aseismic processes)
- Evelyn Roeloffs (fluid pressure, poroelastic effects)
- Bill Ellsworth and Art McGarr (seismic waves, earthquake source processes and energetics)

The goal of the fault zone monitoring work 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, as described above. We expect to observe multiple earthquake cycles for repeating earthquakes ($M \sim 2$) in the target zone at distances of less than a few hundred meters to about 1.5 km over 20-year lifetime of the experiment. We may also observe the rupture of the fault in a large-magnitude event over this same time period.

Following completion of the first stage of the drilling program, we will begin an initial 2-year-long period of intensive monitoring using a re-deployable monitoring array consisting of seismometers, accelerometers and a fluid pressure monitor. The removable monitoring array will be pulled out of the borehole after about 1 year to conduct a high precision borehole directional survey and ultrasonic cement imaging (USI) log—to identify any changes in casing shape or the cement bond integrity behind the casing—in order to determine if any of the faults crossed by the hole are actively creeping, or if broad-scale deformation is occurring. 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, which is automatically

corrected for acoustic velocity and impedance of the borehole fluid, 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. Following the completion of coring, we will re-instrument the borehole with a modified borehole array that will be augmented with additional pressure transducers, a borehole strainmeter and possibly other sensors, as described below.

The construction and deployment of the borehole monitoring systems presents many technical challenges. We have assembled a team of scientists and engineers with extensive experience in the design, manufacture and installation of borehole instruments. The design team will be led by Phil Harben (LLNL), who has extensive experience in the design, fabrication and deployment of borehole instrumentation systems. Peter Malin (Duke) will play a leading role in the design and deployment of the re-deployable monitoring array. Malin has deployed a similar system at Parkfield in the 1.5 km-deep Varian well. Tom McEvilly (UCB) co-developed the Varian system with Malin, and in addition has extensive experience in the design and construction of borehole seismometers, particularly those that employ high-frequency piezoelectric sensors. Malcolm Johnston and Evelyn Roeloffs (USGS) will play a leading role in the design and deployment of strain and pressure monitoring instrumentation. They both have extensive experience with these systems at Parkfield and elsewhere.

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 80, 3-component seismic sensors of proven design for long-term deployment in deep boreholes. Thirty of the sensor packages will contain gimbaled 3-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. Fifty of the sensor packages will contain internal fluid-damped, 3-component accelerometers with (undamped) frequencies around 30 Hz. Overdamped accelerometers of this design have been in operation in the 1 km deep Varian well for over a decade, where they provide wideband acceleration response for recording in the nearfield.

We have elected against installing active electronic devices in the removable monitoring array, such as feedback accelerometers, because of the relatively high temperatures ($> 100^\circ\text{C}$) we anticipate. We may, however, install a limited number of very high frequency sensors, either piezoelectric accelerometers or hydrophones to sample the multi-kiloHertz frequency band, if suitable high-temperature sensors can be identified. All data will be digitized at the surface using a dedicated data collection platform with high sample rate, high-resolution digitizers. We have considerable practical experience with recording data in this manner from borehole instruments at several km depth (e.g. in Long Valley, Varian). Formation pore pressure will be monitored in the open hole below the monitoring array with a packer and pressure transducer system.

The removable monitoring array will be deployed on coiled tubing and hydraulic pressure will be used to activate multiple hole locks that will hold the sensors in place. 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. It is our intention to build and test a prototype of the instrumentation packages and packers at an early date in one of several available deep boreholes that will provide a real-world test of the design. Either the Long Valley

Exploration Well or the Cajon Pass deep borehole would be suitable for this test, and both boreholes are under the control of the USGS.

The long-term monitoring system that will be deployed following the core drilling is being designed to operate for up to 20 years. Our experience with borehole strainmeters and seismometers at Parkfield has been uniformly excellent, where instruments of the designs being considered are now well into their second decade of operation. The main augmentation we intend to make to the removable monitoring array will be the addition of at least one strainmeter (of either the dilatometer or tensor design). Because the strainmeter must be installed in an open (uncased) hole, we plan to install it in either one of the core holes or in the bottom open hole section, if it is still accessible. We may also elect to install one or more clamping tiltmeters in the cased hole. Ultra-low noise borehole tiltmeters (1 nanoradian resolution) have been developed by a member of the design team, Roger Hunter (LLNL), who was awarded a DOE R&D 100 Award in 1997 for this instrument (Wright et al., 1998). Additional sensors that are being considered include thermister arrays for measuring transient heating from earthquakes, fiber optic Fabre-Perot strain interferometers, and electrodes for measuring differential resistance within the fault zone.

During the 2-year observation window between the two drilling phases we will make high-resolution, nearfield observations of earthquakes between M -2 and 5 in the frequency band from below 1 Hz to over 1 KHz. These data will provide critical constraints on the radiated seismic energy budget, dynamic stress acting during faulting, and the spatial organization of the locked zone itself. They will also be critical to the testing of the source model hypothesized by Nadeau and Johnson (1998) and to determine if there is a minimum earthquake size at Parkfield.

The long-term monitoring program that will begin after the core drilling is complete will extend the frequency band to periods of weeks with the addition of tiltmeters and strainmeters. This 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.

Should a M~6 Parkfield mainshock occur, we anticipate that the accelerometers will be on-scale during the passage of the rupture by the array. This will provide unique information on dynamic friction during faulting, and permit a direct measurement of the displacement weakening distance of the San Andreas fault. The time history of displacement of the fault will also have direct engineering application, because of the new importance being placed on source displacements in engineering design following the Landers and Northridge earthquakes.

V. DRILLING OPERATIONS AND PROJECT MANAGEMENT

In the sub-Sections below, we first provide additional operational details for the phases of the project associated with rotary drilling and continuous coring. This includes the "rig-related" activities associated with downhole measurements of pore pressure, permeability and stress through perforations, as described previously in this proposal. We then discuss the plan for on-site technical personnel, summarize the services requested from ICDP (to whom this proposal is also being submitted) and outline our strategy for project management.

Rotary Drilling

A detailed drilling and operational plan has been prepared for this project. Figure 6 shows a detail of the planned trajectory for the rotary hole in both cross-sectional and plan views. Together with the geologic and geophysical criteria summarized in Section III, a number of practical and engineering considerations were used in designing this directional drilling plan:

- Entering the geophysically imaged fault zone (as defined in Figure 3) at a true vertical depth of about 3.0 km (labeled as Target 1).
- Passing out of the fault zone at a depth such that the hole trajectory passes as close as possible to the microearthquakes, incorporating the uncertainties in their exact locations (Target 2).
- Starting the hole at a surface position that avoids known faults and landslides and is accessible.
- Drilling straight through the fault zone to make subsequent continuous coring and workover operations as simple as possible.
- Having a deviation from vertical such that deployment of logging tools and monitoring instrumentation is not difficult but still “gets across” the fault zone as rapidly and directly as possible.
- Utilizing reasonable build-angles from a drilling and engineering perspective.

The hole sizes (drill bits) and casing diameters shown in Figure 7 were similarly designed on multiple criteria:

- To yield a hole of sufficient size at the bottom (8.5” open hole with a 7” casing) to make coring, downhole measurements and fault zone monitoring possible.
- To drill open-hole sections of reasonable length.
- To set casing at geologically reasonable depths.
- To allow sufficient annulus in each section for good cement jobs.
- To allow for a contingency program to be used if necessary that will still accomplish the project’s scientific objectives.

Testing Through Perforations

The procedures associated with the fluid sampling and pore pressure, permeability and least principal stress (i.e., hydrofrac) measurements through perforations are somewhat complicated. 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.

Figure 6. Vertical cross section (main figure) and horizontal plan view (inset in upper right corner) showing direction drilling program for the Parkfield hole.

Figure 7. Drilling and casing program for the proposed Parkfield hole.

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.

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 these tests are complete, the composite packers left in the hole 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, 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.

Continuous Coring

Once we know where coring will provide the most useful information about the fault zone (from a combination of geological, geophysical and seismic observations), the series of multilateral core holes described above will be drilled. We propose to bring in a separate rig for the coring phase of the project. If possible, we would like to use the DOSECC deep coring system that is being used for the first time in the Long Valley drilling project at the time this proposal is being written. As the ultimate capabilities of this system are not known at this time, we have not based the coring plan on using this system. However, if it can be used for this project, we will want to do so.

We estimate that it will take 53 days to obtain the desired core. The procedures for core handling are described in the previous Section. Our current plan is to leave each core hole open (with a slotted liner in it) to enable pore pressure to be monitored at multiple sites in the fault zone.

On-Site Technical Personnel

As this project requires extensive efforts related to real-time sampling of cuttings and gases, the drilling budget calls for an additional geologist to be provided by the mud logging contractor. This means that there will be 2 people on site 24 hours/day to assure that sampling and sampling equipment are functioning properly. Special equipment, such as the gas collection/gas chromatograph/mass spectrometer system being provided by PI Jörg Erzinger requires special manpower and attention.

Finally, we have budgeted for 2 geologists/technicians to be on site a total 135 days during the rotary drilling phase of the project and the full 50 days associated with coring. 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 8 spot cores to be obtained in the rotary-drilled hole.
- Assisting in maintaining the DIS (Digital Information System)—a complete digital data base of all scientific and engineering results from this hole, to be provided by ICDP.
- Assisting with the appreciable continuous core handling activities during the final phase of the project and entering of this data into the ICDP data base. This includes scanning core, describing core and preparation of digital input for DIS.

Operations at Long Valley indicate that a 3 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 2 positions budgeted here will assure that adequate personnel will be on site to handle incoming core. As described in the Drilling Report, the drilling plan includes costs for trailers to provide onsite office space and housing for both supervisory and on site scientific personnel.

Services Requested from ICDP

This proposal is being submitted to the International Continental Drilling Program as well as the National Science Foundation, the U.S. Geological Survey and the U.S. Department of Energy. The ICDP can provide invaluable assistance in a number of areas:

- Engineering - As mentioned above, engineering personnel of the ICDP were very helpful in developing preliminary drilling plans for this project. Additional help provided by ICDP engineers as the project progresses would be very beneficial.
- Maintaining a Comprehensive Data Base and Archive – A great deal of engineering and scientific data will be obtained from a wide variety of sources over the life of this project. We plan to utilize the ICDP software system for maintaining a comprehensive data base, providing tools for manipulating and plotting data and for disseminating the data to interested scientists.
- Real-Time Data Base – The DIS data base developed by the ICDP for organizing real-time drilling and scientific data, maintaining it in a data base and making software tools available for data analysis will be of great help to this project. In addition, we want to make use of the software systems ICDP has developed for

making information about the project available to the global scientific community via the world wide web.

- Core – 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 this project. It is our hope to take advantage of both available equipment and personnel in the core handling operations in the proposed project.
- 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 global scientific community in two regards. First, to let them know about the scientific opportunities presented by this project. Second, to help provide an interface with these scientists to allow them to participate in the project to the degree possible.

As mentioned above, we have budgeted for onsite technical personnel to interface with the ICDP data base systems. They will need training and periodic supervision by ICDP personnel.

Project Management

The management team of this project consists of Mark Zoback, Steve Hickman and Bill Ellsworth. Working together, these three individuals have hosted numerous planning meetings and workshops, represented this project at even more numerous national and international scientific meetings and special symposia, and worked closely together to develop this proposal. The responsibility for overall project management and interfacing between the scientific and operational personnel will be shared by Mark Zoback and Steve Hickman.

As representatives of the different science teams, these three individuals will continue to coordinate the various groups of scientists as follows:

- Downhole Measurements – Mark Zoback
- Measurements on Core, Cuttings and Fluids – Steve Hickman
- Geophysical Site Characterization - Bill Ellsworth
- Fault Zone Monitoring - Bill Ellsworth

Steps to be taken to assure optimal project management are as follows:

- Establish a Scientific Advisory Board – The purpose of this board is to provide independent advice to the project on an as-needed basis. Participants will come from both within and outside the project science team.
- Planning workshops – We will be convening project-wide, three-day-long planning workshops in the San Francisco Bay area during the first, third and fifth years of this project. Members of our science team have been asked to budget travel and per diem to attend these workshops.
- Annual sub-group meetings – We will also be holding annual meetings of smaller groups of principal investigators to discuss operational and scientific details associated with downhole measurements, core and fluids studies, site characterization, fault zone monitoring, etc. These meetings will be timed to coincide with the Fall AGU meeting in San Francisco.
- Special sessions – Special sessions will be held at national and international scientific meetings (AGU, GSA, SSA, IUGG, etc.) as appropriate.

- NSF/USGS reviews – To be held at the discretion of NSF and USGS. NSF requires a review after 3 years for all projects that extend more than 3 years.
- Sampling committee – To develop protocols for handling and distribution of core, fluid and gas samples

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