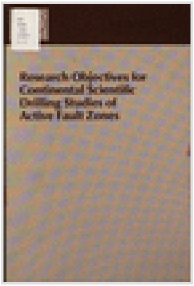

Research Objectives for Continental Scientific Drilling Studies of Active Fault Zones (1987)

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

The importance of a scientific drilling program to study active fault zones and earthquakes has been emphasized in numerous workshops and symposia, including the 1978 Los Alamos, New Mexico, Workshop on Continental Drilling for Scientific Purposes (U.S. Geodynamics Committee, 1979) and the 1974 Workshop on Continental Drilling held at Ghost Ranch, New Mexico (Shoemaker, 1975). This report, prepared by the Panel on Downhole Physical Property Measurements and Fault-Zone Drilling of the Continental Scientific Drilling Committee, both reinforces and expands upon earlier recommendations and provides examples of possible sites.

The Continental Scientific Drilling Committee endorses this report and the recommendations put forth by the Panel on Downhole Physical Property Measurements and Fault-Zone Drilling. The committee welcomes comment from the scientific community and encourages participation in the implementation of research drilling projects to investigate active fault zones.

CONTENTS

1

SUMMARY

The mechanics of crustal deformation and faulting, and the stresses that drive lithospheric plates are outstanding problems in the earth sciences. Our inability to model quantitatively the deformation and physical evolution of the earth's crust results directly from the lack of critical data at depth. Fundamental questions to be answered include: (1) How strain energy is accumulated through plate motion and dissipated through crustal deformation? (2) What are the composition and physical properties of the materials involved in these processes? and (3) Under what stresses and temperatures do these processes occur? Drilling and downhole experimentation are required to answer these key questions about the forces that move tectonic plates and the mechanisms controlling deformation of the Earth's crust.

Because of the diverse nature of faulting and crustal deformation, the data cannot be obtained by drilling at any single site. We therefore recommend the following five sites, in order of priority, where drilling and experimentation would address five different types of crustal deformation: transform faulting--the San Andreas fault, California; crustal extension--the Sevier Desert detachment fault, Utah; continental collision and overthrusting--the San Gabriel fault, California; intraplate faulting--the New Madrid seismic zone, Missouri; and subduction zones--the Aleutian megathrust, Alaska.

In the following sections we explain briefly the scientific rationale used in selecting each of these sites, the specific objectives of each hole, and the types of measurements that should be made both in situ and on recovered rock and fluid samples. In a final section we discuss methods for long-term deployment of downhole instruments for ultraquiet seismic, strain, and

fluid monitoring. Such observations will make it possible to study active tectonic processes directly and to monitor them over time.

2

INTRODUCTION

One of the most critical needs in geology today is for better information about the third dimension of the earth's crust, particularly its composition and the processes that shape and affect it. Virtually all geologic maps and studies must make assumptions about the character and structure of rocks at depth; yet outside the sedimentary basin, we have little direct knowledge and no good control on inferences drawn from indirect measurements.

In no area is this lack of data more critical than in the study of earthquakes and their causes. As pointed out by the U.S. geodynamics Committee in its report on a *Continental Scientific Drilling Program*, the potential of earthquakes for causing loss of life and extensive property damage is a powerful argument for studying seismic processes. In addition, despite good progress in our understanding of earthquakes, we still lack the knowledge of just how they occur; and this lack seriously impedes high priority programs such as the siting of nuclear facilities and major dams.

Holes drilled along or near active fault zones would provide: (1) samples for direct study of materials (including core fluids) close to the faults at depth; and (2) opportunity for *in situ* measurements of physical parameters, many of which can be made only from boreholes. Especially important are stress and its variations in time and space and fluid pore pressure.

In the following sections, we outline some of the important goals of drilling and the measurements and tests to be made, and we suggest five possible target areas. Although each area would emphasize a different objective, all are needed for a more complete picture.

As the highest priority, however, we recommend the San Andreas Fault near Cajon Pass, California.*

*Since the preparation of this report, the Cajon Pass site has been selected as a prime site for the program conducted by DOSECC and drilling has been started.

3.

PROPOSED DRILLING SITES

Sites have been selected according to the following criteria:

1. Geological significance. The holes should be drilled at or near common and important types of faults--e.g., major transform fault systems, large thrust faults, intraplate fault zones, extensional fault systems, or subduction zones.

2. Testing of geological and tectonic hypotheses. Sites should be selected for testing a variety of existing hypotheses or outstanding questions regarding fault mechanics and fault instability. For example, are creeping fault segments due to different properties or to greater stress levels than are present in locked fault segments? Are prominent seismic reflectors observed within crystalline basement actually fault planes?

3. Seismic and tectonic activity. Because our goal is to study active processes, the sites should currently be tectonically active. Such sites will also yield data about temporal changes in such critical parameters as strain and pore pressure, as well as any changes in the physical properties of the surrounding rock mass. These changes might be secular, presumably related to gradual strain accumulation and/or release, or episodic, like those associated with seismically strong earthquakes, slow earthquakes, or creep events.

4. State and composition of fault zone and nearby rocks. Sites should be selected to provide maximum information about the mineralogy, petrography, and rock characteristics, as well as the state of the rocks. Some drilling is planned to intersect fault gouge zones which may be sites of anomalously high pore pressures and low

frictional characteristics.

5. Existing data and available information. Sites should be selected about which substantial geological and geophysical information has already been obtained from surface measurements and observations such as seismicity studies, crustal investigations, geophysical surveys, and detailed mapping. Some sites should be at active faults where seismic activity has been observed, fault strain, creep and displacement have been measured, and seismic soundings have been made to define the geometry of the fault zone.

Five areas--the San Andreas fault, the Sevier Desert detachment fault, the San Gabriel fault, the New Madrid seismic zone, and the Aleutian megathrust--meet these criteria and are recommended for the initial phase of active fault zone drilling because they will provide the best opportunity to answer critical problems of crustal faulting. In each of the five areas, tentative drill sites are recommended on the basis of available geological and geophysical data. Selection of final drill sites would depend on further investigation.

SAN ANDREAS FAULT, CALIFORNIA - Transform Fault

The San Andreas fault zone and its near vicinity is recommended as the highest priority drilling site for four important reasons. First, it provides an opportunity to study the physics of an active transform fault. The results of work at this site will have implications for the mechanical behavior of similar fault systems around the world. Second, it is one of the most active fault system in the United States. The high level of seismicity on the fault will provide an opportunity to detect the largest changes in stress over time (associated both with individual earthquakes and with secular strain due to a seismic fault motion at depth). It also is easily accessible for downhole seismic monitoring. Third, extensive geophysical and geological data are already available, including shallow data (to about 1 km) on in situ stress, temperature, pore pressure, and seismic velocity. Finally, many of the hypotheses and models for the mechanical behavior of the San Andreas fault can be directly tested and evaluated. In addition, the San Andreas traverses area with high population.

As an example, resolution of the debate about the level of shear stress on the San Andreas fault will have important consequences for understanding the forces that drive lithospheric plates, the nature of deformation at transform fault plate boundaries, and the mechanics and prediction of major earthquakes. Existing heat flow data near the San Andreas fault show no discernible anomaly near the fault, suggesting an upper limit for the mean shear stress on the fault in the seismogenic layer. However, stress measurements made near the fault at depths to 1 km indicate a relatively high shear stress gradient on the fault of about 100 bars/km. While consistent with stress estimates based on laboratory friction studies, the measured shear stress gradient cannot persist to more than 2 to 3 km without violating the constraints imposed by the heat flow data. Measurements in holes 5-km deep adjacent to the San Andreas fault would allow: (1) stress measurements to be made directly at seismogenic depths, (2) temperature and conductive heat flow to be determined over a sufficiently great depth range to confirm or deny the possibility of appreciable convective heat transport, and (3) seismic and strain sensitive instruments to be emplaced at seismogenic depths near the fault for fault zone monitoring. Two areas along the San Andreas fault are proposed as initial drilling targets (Figure 1). Each site involves drilling in granitic rocks adjacent to the fault zone to a depth of 5 km.

Although a hole adjacent to the fault zone would not yield samples of fault gouge for analysis, it would optimize drilling conditions and downhole experimentation. A hole in the highly crushed rock and gouge comprising the fault zone will eventually be needed. However, the potential drilling problems and extensive casing required in such a hole would probably preclude many important downhole measurements. Thus, we suggest that a second phase of drilling be undertaken in the fault zone itself after initial holes are drilled in the rock adjacent to the fault zones. In this way the laboratory analysis of fault zone materials and measurements within the fault zone would complement the data gathered immediately outside the fault zone.

One site recommended for fault zone drilling is in the Gabilan Range of central California. Along this section of the fault, numerous small earthquakes occur and the fault is actively moving at the rate of 2 cm/year. As no strain is accumulating here that could lead to a big earthquake, the fault is said to be creeping. The second site is in the Cajon Pass area at the southern end of the fault segment that broke in the great earthquake in 1857. Data from these two sites would help explain the causes of the different styles of deformation seen in these sections of the fault. Is the creeping part of the fault subjected to higher stress? Does it have lower strength, or simply different mechanical properties that allow ductile deformation? Moreover, while the Gabilan site would be ideal for monitoring an actively deforming fault zone with numerous small to moderate magnitude earthquakes and creep, the Cajon Pass site would be better for monitoring secular strain accumulation leading to a very large earthquake. In both areas there has been extensive geologic mapping and a limited amount of seismic reflection profiling. A important advantage of the Cajon Pass site is the existence of a hole 2 km deep which can reopened for study. The hole already penetrates more than 1 km of granitic basement rock (Figure 2), and a number of other holes in the area (Figure 3) have already been used for <u>in situ</u> stress and other downhole measurements.

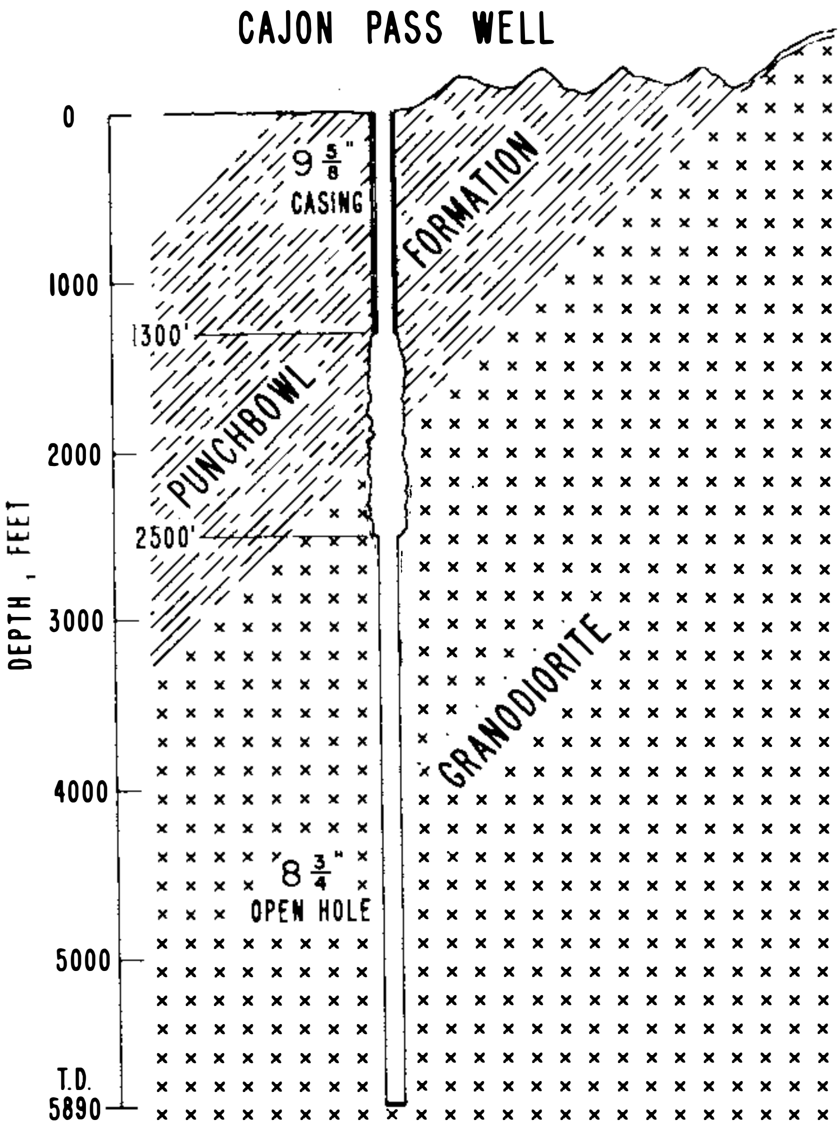


FIGURE 1 Map of California and Nevada showing earthquakes of magnitude 1.5 and greater in the year 1980. The proposed Gabilan research drilling site is in the central section of the San Andreas fault where a seismic creep and numerous small to moderate magnitude earthquakes occur. The proposed Cajon Pass research drilling site is at the south end of the section of the San Andreas fault that moved in the great Fort Tejon earthquake. There is about a 50 percent change for this earthquake to reoccur in the next 30 years.

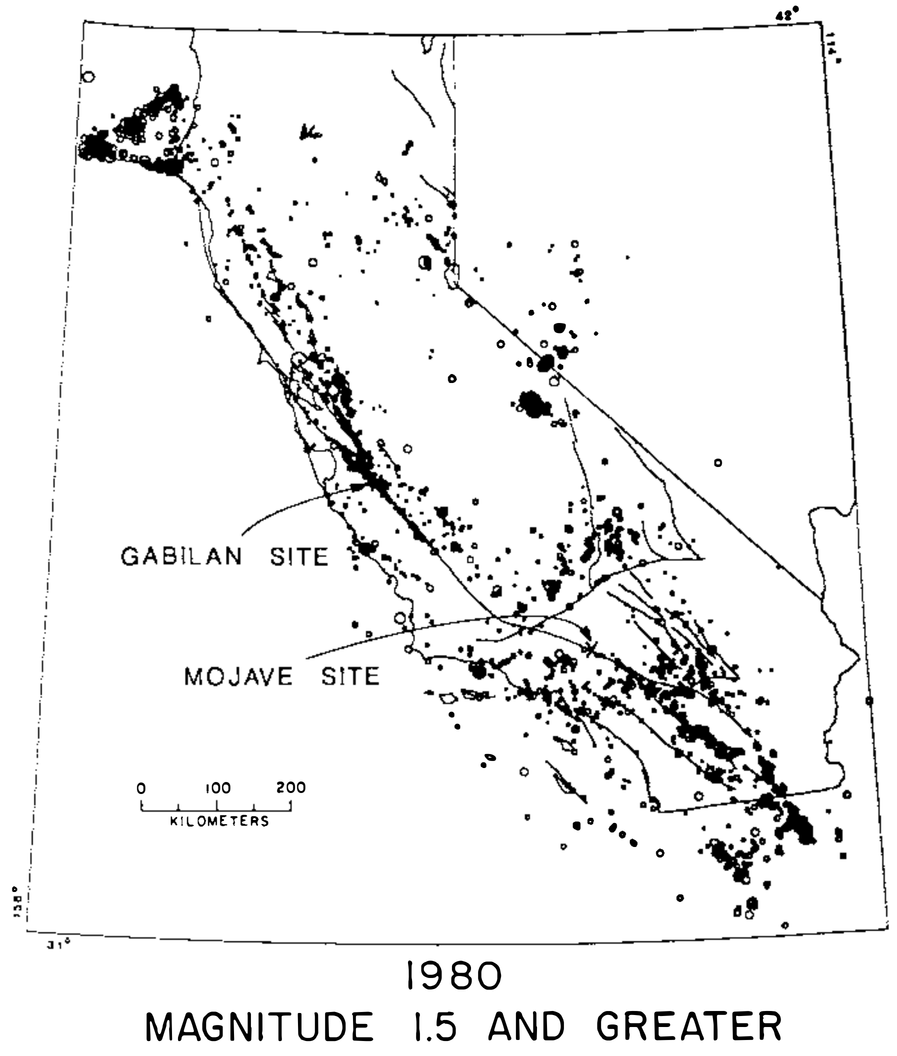


FIGURE 2 Schematic drawing of the Cajon Pass drill hole. The steeply dipping Punchbowl formation (a Miocene terrestrial sandstone) overlies granodiorite to a depth of 700 m. Total depth of the holes is 1800 m.

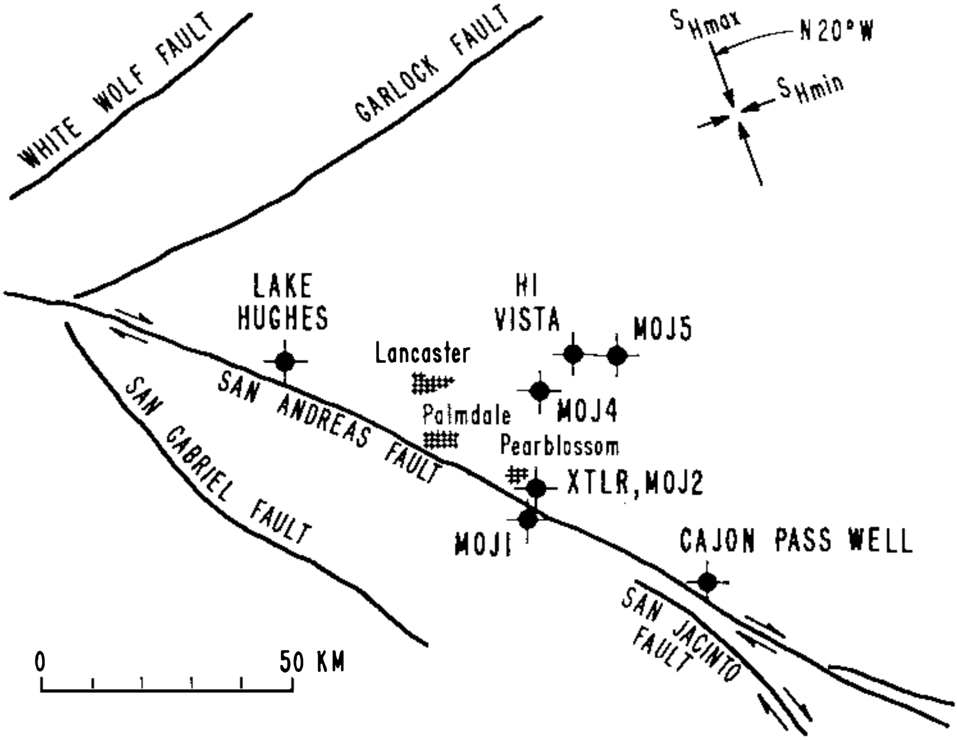


FIGURE 3 Locations of drill holes in the western Mojave desert near the San Andreas fault which have been used for in-situ stress and other measurements. All of the drill holes are in granitic rock except MOJ1 which is in the Punchbowl formation. Figure is after McGarr et al. (1982).

SEVIER DESERT DETACHMENT FAULT, UTAH

An important problem that has recently come to light is the nature of the mechanical interaction between steeply-dipping (50° to 60°) normal faults and shallow-dipping detachment (normal) faults in the Basin and Range province. Numerous low-angle detachment faults with evidence of Miocene- and Oligocene slip are exposed in ranges throughout the province, and recently available seismic reflection data from both industry and COCORP (Consortium for Continental Reflection Profiling) reveal that low-angle detachments may still be active and play a key role in Basin and Range deformation.

Figure 4 shows industry seismic reflection data from the Sevier desert basin in west-central Utah. At this locale, steeply dipping normal faults with known Quaternary movement anastomose with a shallow-dipping detachment fault at 3- to 5-km depth. Data from COCORP indicate that this detachment fault extends over 70 km in a direction perpendicular to the strike of ranges in the area. The detachment fault has an average dip of about 12°, and nowhere do high-angle normal faults offset it.

The conditions of the *in situ* stress field, the values of the frictional coefficients of the respective faults, and the magnitudes of *in situ* pore pressure that could explain fault interaction such as that illustrated in the figure are completely unknown. Conventional values for these parameters will not permit simultaneous slip on these two fault systems. Measuring the parameters would shed light on the mechanism of deformation in the Basin and Range province.

It is proposed that a hole be drilled through a low-angle detachment to measure these values. At an optimal location, such as near the western edge of the area shown in Figure 4, it would be possible to drill through both a high-angle and a low-angle fault. At this site, the rocks both above and below the detachment are well-indurated Paleozoic sediments, which would be ideal for downhole measurements. The heavy vertical lines in the figure represent petroleum exploration drill holes. Efforts are currently under way to obtain drilling histories and geophysical logs from these holes. The hole near the far western edge of the section would have intersected the detachment at a depth of about 5.75 km. The proposed drill site would be ideal for exploratory drilling and downhole measurement because it would have optimal lithologies and would intersect both a high-angle fault and the detachment plane.

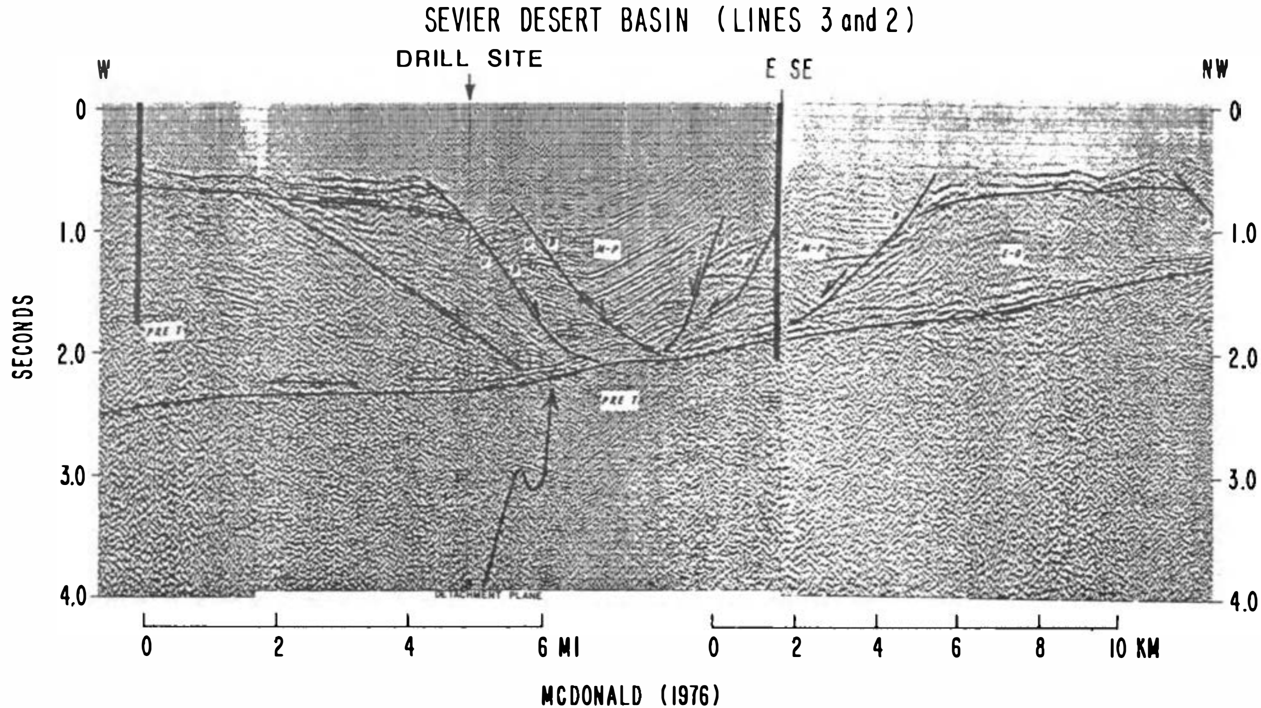


FIGURE 4 Proposed research drilling site in the Sevier Desert Basin in west-central Utah. The proposed location of the drill hole would penetrate two high-angle faults with Quaternary-age faulting as well as the low-angle detachment plane. The heavy vertical lines indicate abandoned petroleum exploration drill holes in the area. The fault interpretation shown is after McDonald (1976).

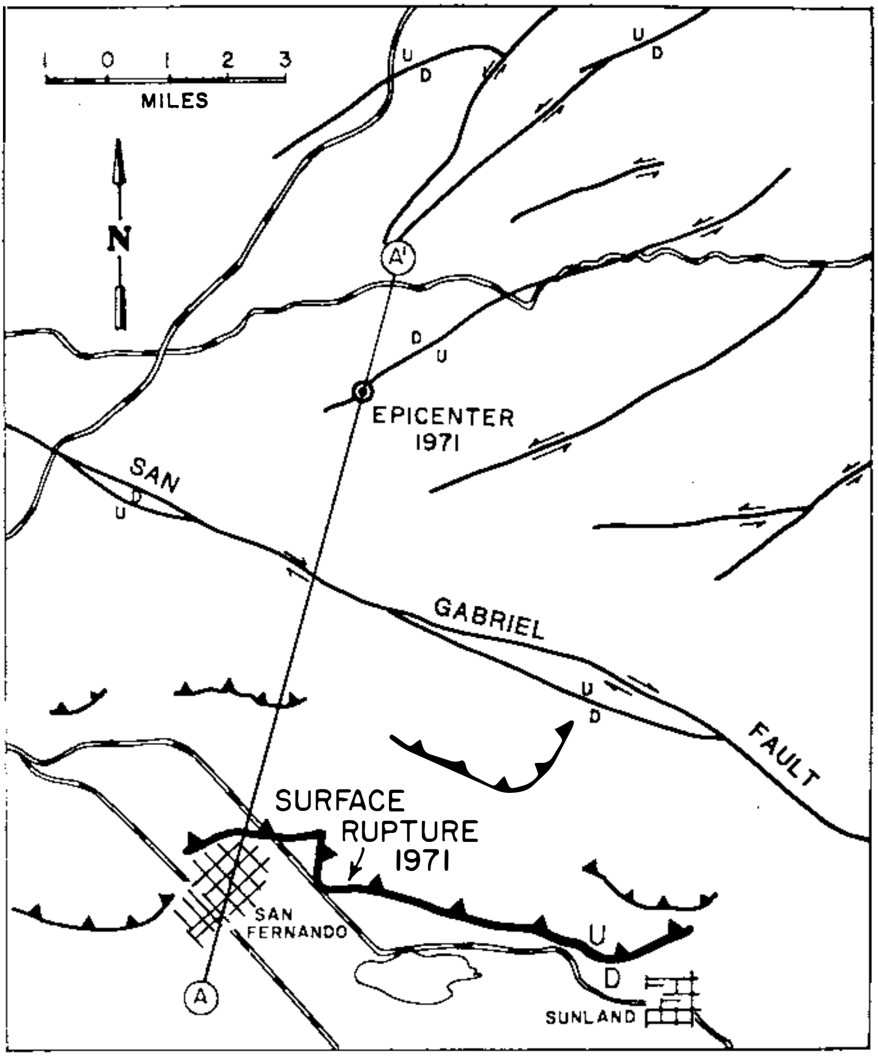
SAN GABRIEL FAULT, CALIFORNIA
Continental Collision and Overthrusting

Thrust and reverse faults constitute an important class of faults characteristic of accreting or convergent continental margins, such as those along the coasts of the Pacific northwest and Alaska, and sinuous transforms like the "big bend" of the San Andreas fault in southern California. Commonly in such convergent zones, displacement has occurred across a series of imbricate fault planes, not all of which may be active at a given time. Imbrication may be particularly pronounced in continent-to-continent collisions where negative bouyancy (i.e., slab pull) is not available to counteract the frictional resistance of underthrusting. A new generation of geologic mapping and high resolution lithospheric studies, e.g. Consortium for Continental Reflection Profiling [COCORP], is beginning to reveal the importance of thrust faulting in the continental evolutionary process.

Fundamental questions include whether the mechanics of thrust faults are similar to those of strike-slip and/or normal faults, and what is the role of fault mechanics in controlling tectonic processes such as regional uplift and the development of geological structures. It is believed that stresses are generally higher on thrust faults than on strike-slip or normal faults at equivalent depths. However, as in the case of strike-slip faults, the roles of fluids and heat production on thrusts are unknown and need to be addressed.

Thrusts, because of their low angle, are ideal deep drilling targets. A particularly attractive target is the San Fernando fault, a strand of the frontal fault system along the southern flank of the Transverse Ranges in southern California and the causal fault for the 1971 San Fernando earthquake (Figure 5). Locations of both the surface rupture and the epicenter are shown in Figure 5. These elements, together with the zone of aftershock activity, define a tongue-shaped fault plane dipping northward beneath the Transverse Ranges and culminating at, or slightly below, the focus. Cross sections from three different studies are shown in Figure 6 (note that profiles in Figure 6a and 6b are keyed to Figure 5).

Two other drilling objectives are made possible by



FAULT MAP OF 1971 SAN FERNANDO EARTHQUAKE EPICENTRAL AREA

(After Oakeshot, 1975) Epicenter after Allen et al (1973).

FIGURE 5 Geological structure map of the San Fernando earthquake epicentral area, showing faults and folds (after Oakeshott 1975). The epicenter is from Allen et al. (1973).

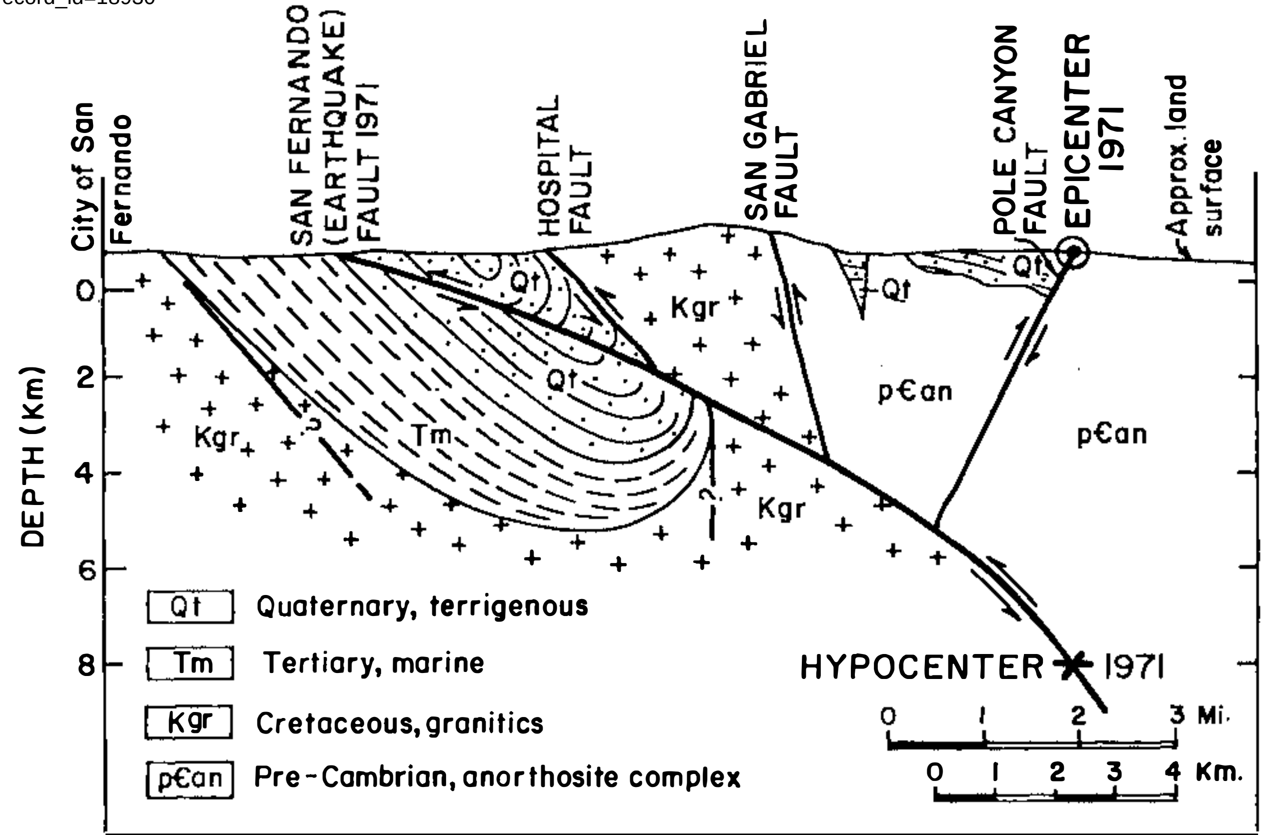


FIGURE 6a Geological structure section through the 1971 San Fernando earthquake epicenter (after Oakeshott, 1975). The hypocenter and epicenter are from Allen et al. (1973).

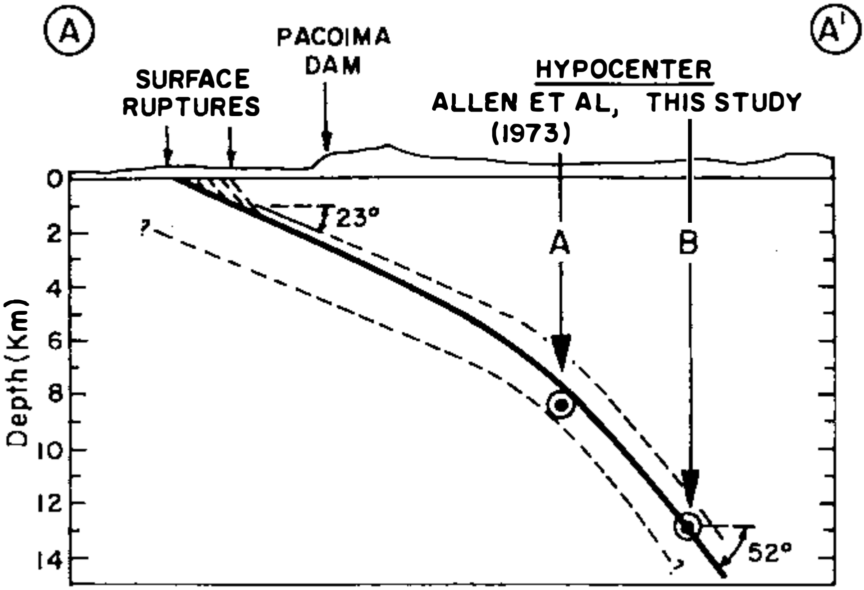


FIGURE 6b A north-south cross section of the epicentral area along A-A′ of Figure 5 (after Hanks, 1974).

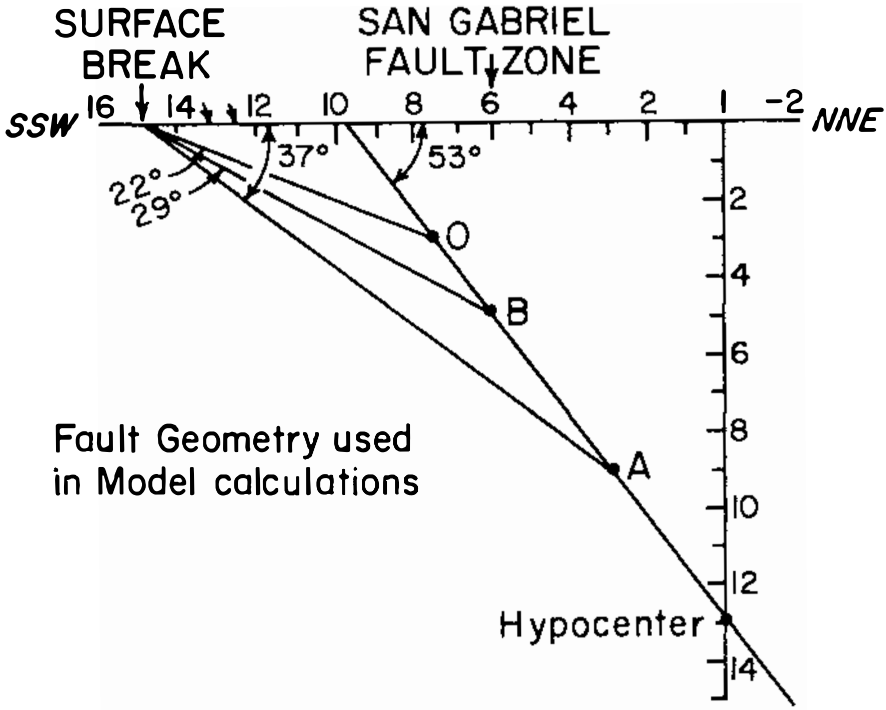


FIGURE 6c Fault geometry of the San Fernando fault (after Langston, 1978).

siting a deep hole along Little Tujunga Road; (1) drill within or whipstock through the dormant San Gabriel fault, and (2) drill through a postulated, pre-Miocene shallow crustal decollement between the overlying allochthonous Mesozoic and Pre-Cambrian plutonic rocks of the San Gabriel Mountains and underlying, subduction-derived Pelona schist. Thus, in principle, three major faults of differing characteristics would be within reach of a single deep hole.

NEW MADRID SEISMIC ZONE, MISSOURI - Intraplate Faulting

In order to understand intraplate crustal deformation and the mechanism controlling localization of seismicity in mid-plate regions, a drill site is proposed in the New Madrid seismic zone (Figure 7). Three major earthquakes occurred there in 1811 and 1812, and numerous earthquakes occur there today. There has also been extensive geophysical surveying in the area, including extensive seismic reflection profiling.

Numerous hypotheses have been proposed to explain the mechanism responsible for large intraplate earthquakes. These include suggestions that localized high stresses exist in the region (due to a variety of hypothetical mechanisms), that the region has anomalously low strength, that there is unusually high pore pressure at depth in the region, and that the region has unusually high secular shear strain due to concentrated a seismic deformation at depth. Measurements made in a drillhole could determine which of these hypotheses is correct and what forces are important. In addition to being of fundamental scientific importance, understanding the physical mechanisms controlling intraplate earthquakes is very important for seismic hazard evaluation throughout the central and eastern United States and has direct relevance for similar areas around the world.

ALEUTIAN MEGATHRUST, ALASKA - Subduction Zones

An opportunity exists to obtain data on deformation within an actively consuming plate margin by drilling on Middleton Island, near the eastern end of the Aleutian Arc (Figure 8). The site would provide information on the state of strain in the upper plate of the Aleutian megathrust, along which there is near-orthogonal convergence at an average rate of 5.8 cm/yr.

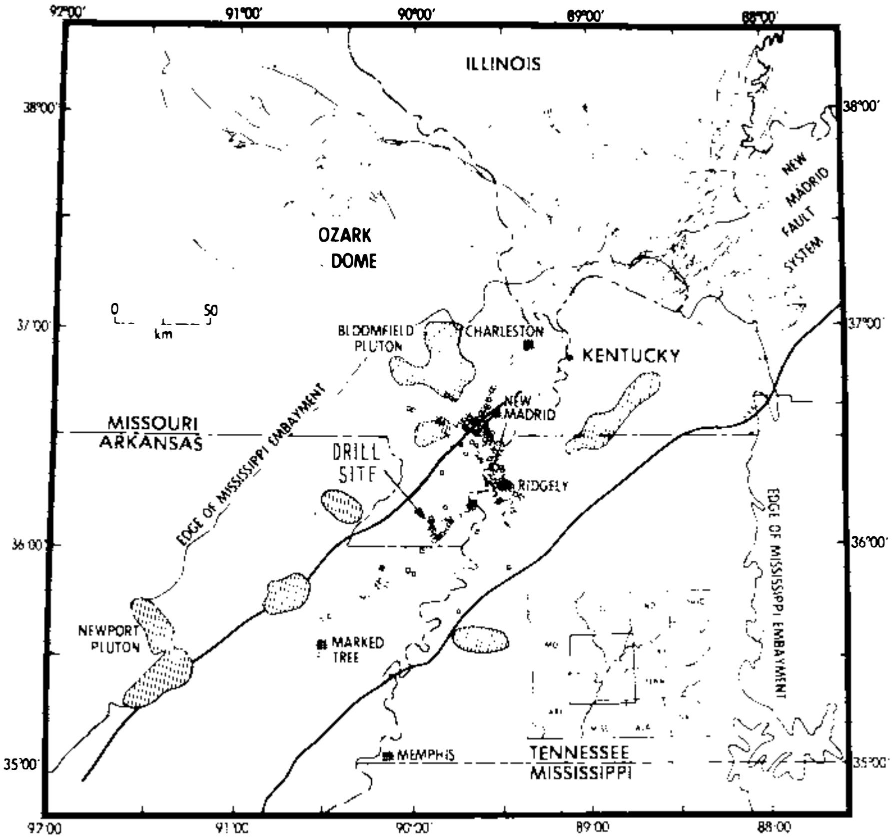


FIGURE 7 Seismicity and tectonic features of the New Madrid seismic zone. The proposed research drilling site is along a major northeast-striking strike-slip fault that was responsible for three major earthquakes in 1811-1812. The heavy subparallel lines mark the approximate boundaries of a late Precambrian/earth Paleozoic mid-crustal rift zone.

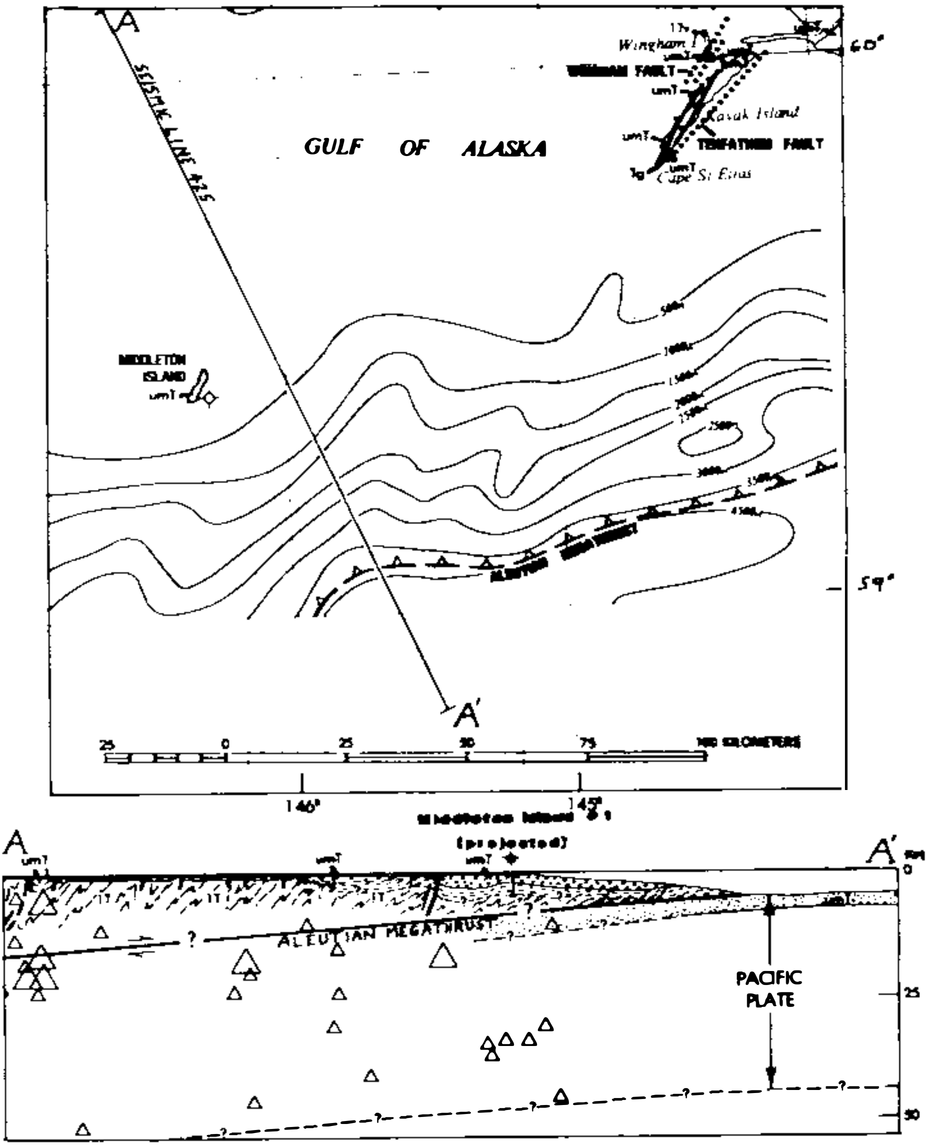


FIGURE 8 Proposed research drilling site at Middleton Island in the Gulf of Alaska. The proposed drill hole would penetrate the active upper plate of the Aleutian megathrust to reach the subduction zone beneath it. The Tenneco Middleton Island #1 hole and U.S. Geological Survey seismic reflection line #425 are shown. The structure section, showing Upper and Middle Tertiary rocks (umT) underlain by Lower Tertiary rocks (lT) and earthquake hypocenters, is after Plafker et al. (1982).

Large-scale tectonic displacements occurred along this plate boundary during the 1964 Alaska earthquake and during at least five other major seismotectonic events in the past 4,200 years. In addition, seismic reflection and earthquake data suggest that subducted oceanic crust, with its overlying 3.5-km-thick sedimentary cover, is subhorizontal, and the top of this zone may be as shallow as 8 km below Middleton Island (section A-A' in Figure 8). If so, this may be the only place in the world where it will be possible to drill into an active zone of subduction from an onshore site.

A petroleum exploration hole, drilled 3 miles (5 km) southeast of Middleton Island to a depth of 12,002 feet (3658 m), indicates a normally stacked sequence that bottoms in early to middle Eocene marine strata. Locations of the Middleton Island hole and part of the U.S. Geological Survey's multichannel seismic reflection Line 425 are shown on Figure 8. By using the island as a drilling platform, the properties of the rocks and pore fluids deep within a subduction zone could be determined without tying up a drill ship for long periods of time in a hostile environment.

4

PRINCIPAL MEASUREMENTS

The status of current technology is such that state of stress, pore pressure, hydraulic properties, and temperature regimes can be measured with acceptable accuracy under favorable conditions. However, most researchers active in this area believe that the techniques can and should be improved. The methodology associated with each of the measurements is briefly discussed below.

IN SITU CONDITIONS

State of Stress

The magnitudes of the stresses in and near fault zones need to be measured to establish the boundary conditions for the loading of the lithospheric blocks that move during an earthquake. It is simply not known whether the forces that drive plate motion overcome great or little frictional resistance at transform faults, whether subhorizontal faults can accommodate crustal extension in areas of active rifting, or whether intraplate fault zones are anomalously weak zones in the crust. Drill holes to a depth of 5 km or greater provide the possibility of measuring the absolute state-of-stress at depths where earthquakes are currently occurring. Laboratory measurements of the frictional strength of rock indicate that, with normal hydrostatic fluid pressure, shear stresses of 1 to 2 kilobars are required for shear failure on faults like the San Andreas. However, from the absence of an anomaly in heat flow over the fault, one may infer that the shear stress should be 100 to 200 bars, (100 to 200 x 10^8 Pa) assuming predominantly conductive transfer of heat to the surface. If the shear stress is closer to the lower estimate, the fault zone must be pervaded by fluids at pressures very near the magnitude of the least principal stress, or the rocks in the fault must have an abnormaly low coefficient of static friction. These inferences, if correct, will have profound implications for plate driving forces and the nature of the instability that leads to great earthquakes.

Other key questions concerning the behavior of faults include the transition from stable to unstable sliding. Also, the differences between the sections characterized as creeping or locked are of fundamental importance to an understanding of the physical processes leading to earthquakes. Are parts of the fault creeping at low stresses, or are those segments highly stressed, and is the current seismicity premonitory to a major earthquake? Is the relative stability of the failure process in the creeping section of the San Andreas fault due to the level of stress, to some intrinsic difference in mechanical properties, or to pore pressure?

Of techniques currently available for measuring stress, hydraulic fracturing is most reliable in deep drill holes. A number of investigators have demonstrated that, under favorable conditions, the method will yield:

1. magnitude of the least principal stress, probably with an accuracy of 10 percent;
2. magnitude of the maximum principal stress (to an accuracy less than that of the least principal stress); and
3. orientation of stress tensor.

Hydraulic fracturing is not without problems. The current technique requires that the rock be unfractured to obtain the maximum principal stress and the orientation of horizontal components of the stress tensor. Further research may make it possible to obtain these quantities in fractured sections. The orientation of the hydraulically-produced fracture must be measured to obtain the orientation of the stress tensor. Current methods that use either impression packers or the downhole televiewer, a sonic device, yield reliable orientations of the fracture in perhaps one out of two or three measurements. Further research may improve this reliability, but other methods are being developed to determine the orientation of the stress field, such as the orientation of stress-induced wellbore breakouts.

Pore Porosity and Permeability

The magnitude of subsurface pore fluid pressure is critical to understanding the mechanics of active faulting. Fortunately, pore pressure is one of the easier measurements that can be made in a drill hole, assuming that the rock strata have at least modest permeability (greater than 1 millidarcy). Perhaps the simplest and most reliable pore pressure measurement is made by isolating an interval in the drill hole and allowing the drill pipe to fill until the pressure in the fluid column balances the pore pressure. The rate at which fluid flows into the hole is dependent upon the hydraulic diffusivity (the ratio of the permeability to the compressibility of the rock plus the pore fluid) of the rock in the vicinity of the hole. The higher the permeability, the more rapid the fluid exchange between the hole and the surrounding rock (the rate at which the hole fills is used to measure hydraulic diffusivity). Unfortunately, in rocks of low permeability the time necessary for fluid in the drill hole to reach equilibrium may be long. However, extrapolation techniques can be used to estimate static pore pressure.

Many theories of fault behavior involve pore fluid movement. To test these ideas, permeability must be measured. Permeability is highly dependent on fractures, so in situ measurements are of primary significance. Some laboratory values should also be obtained, particularly if the in situ values are very low and close to the detection level of drill hole methods.

Techniques to measure in situ permeability are well developed. In the drill stem test, a method widely utilized by the petroleum industry, an interval of interest is isolated and fluids are allowed to flow into the drill string. Pressure is measured continuously at the base of the fluid column. The rate of flow is known from the rate at which the drill column fills. Results of the test yield the permeability, and hydraulic diffusivity values of permeability ranging from 10 to 10^{-13} cm/sec can be measured.

Enough permeability measurements have been made under a wide variety of conditions to suggest that those media that behave even approximately as porous media--which includes a number of fractured media--yield good values of permeability. In fractured media, the current status of the technology is less certain. For the single fracture the theory is developed, but for the case of multiple fractures the results are much less clear.

Temperature and Heat Flow

Measurements of temperature and heat flow in the drill holes proposed here would have several applications. First, the thermal state of a fault zone is directly related to the ambient shear stress acting during creep or earthquakes. Thermal transients developed during earthquakes are proportional to the absolute shear stress. Second, the mechanical behavior of the fault zone rocks and fluids is strongly dependent on temperature. Third, the influence of mass transport of heat laterally from the fault, a mechanism that has been invoked to explain the absence of a distinct thermal anomaly over the fault, can be determined in deep drill holes slanted across the fault. Finally, the distribution of heat flow over the region of the plate boundary needs to be determined (in shallow holes) to characterize the thermal-mechanical machine that produces great earthquakes.

Downhole Logging

A broad suite of commercially available geophysical logs should be run including comprehensive sets of P- and S-wave seismic velocity, resistivity and induction logs, nuclear density and porosity logs, spectral gamma logs, and dipmeters. These logging techniques provide information on the composition and properties of the rock and the pore fluids. Although interpretation of these logs is well understood for sedimentary rocks, much research remains before we can fully comprehend the responses of the logging tools in crystalline, igneous, and metamorphic rocks. In addition to these logs, use of a borehole gravimeter to provide estimates of density with depth would be especially desirable.

It has been shown that the creeping part of the San Andreas fault zone has large lateral P-wave velocity gradients, with the central fault zone consisting of the lowest velocity material. Attenuation of seismic waves in the fault zone is so severe as to make longitudinal seismic profiles to any distance difficult with explosive charges of acceptable size. These observations indicate the presence of pervasive fracturing to considerable depth, but detailed interpretations of the seismic velocity structure in the fault zone itself currently seem beyond the reach of surface measurements. Interval velocity, surface-to-bottom hole velocity, and hole-to-hole velocity would be of considerable value in clarifying our understanding of the nature of the elastic properties and seismic attenuation in fault zones. Taken together, downhole measurements of stress, pore fluid pressure, elastic properties of the rocks, and temperature and seismic velocity structure should, when combined with material properties, provide the first set of adequate observations needed for the formulation of a realistic model of failure and instability in earthquakes.

MATERIAL PROPERTIES

A thorough investigation of the structural state and mechanical properties of material in the fault zone is necessary for an understanding of the nature and origin of earthquakes.

Composition of Core and Pore Fluid

The materials and conditions near the source of earthquakes may be compositionally unique and quite unlike either surface exposures of rocks or fault gouge of the sheared material on ancient faults exposed at the surface or in mines or tunnels. On faults like the San Andreas, large shear strain has been concentrated in a narrow zone of crushed rock. Based on microscopic study of highly sheared fault gouge produced in laboratory experiments, grain sizes may range down to 100 A° (10^{-8} m) or less. Fine grain size means rapid alterations, particularly at the higher temperatures prevalent in the deeper part of the seismic zone. The natural gouge could be highly altered to clay minerals, contain glass, be completely unconsolidated, or be highly indurated. The mechanical properties of material in the fault zone will depend strongly on these different, unpredictable possibilities.

Samples of the actual material are badly needed. The most important characteristics obtained from the core include; (1) spacing of discontinuities at all scales, (2) mineralogy, particularly of finer-grained sections, (3) grain size and porosity in typical sections of the core, (4) glass content and composition, (5) degree of induration, and (6) pore fluid chemistry. In addition, trace element and isotopic studies may reveal thermal history and relative permeability of the fault zone material. Some of these characteristics such as items 1, 5, and 6 above may not be accessible if drill core is badly broken or even lost; however, many characteristics can be observed in fragments or cuttings, and the latter should be preserved as carefully as intact core.

Physical Properties

In addition to studying composition, we need to study the physical properties of core samples collected from the holes. Critical measurements include: (1) seismic and electrical properties as a function of pressure and temperature, (2) elastic and deformational properties under different pressure-temperature conditions and at different strain rates, (3) microcrack structure, and (4) hydraulic properties. Very few samples have been available from depths greater than 1 or 2 km, especially in igneous and metamorphic rocks. No samples of crushed and altered rock from depth in and near an active fault zone have been available for study.

Most of these properties require intact core at least a few centimeters in diameter. Great effort may be required to obtain intact core in typical fresh fault gouge, but mechanical behavior of the fault zone material as a whole may be dominated by characteristics of the finest grained, least consolidated portions. A few undisturbed samples of these portions are vitally needed.

5

CONTINUOUS MONITORING EXPERIMENTS-DEEP EARTH OBSERVATORIES SEISMIC OBSERVATIONS

Once completed, a deep hole offers the possibility of measuring changing conditions with time at depths where earthquakes occur. Monitoring seismicity with time in a deep hole could be extremely productive. Given the relatively noise-free environment at the bottom of the drill hole and the lack of near-surface attenuation of high-frequency seismic energy, fundamental advances could be made in understanding the process of fault rupture initiation, propagation, and termination. Monitoring seismicity at depth and away from cultural and meteorological noise will also advance the limit of detectability of small events. If very high-frequency downhole seismometers are deployed in conjunction with a recording system capable of preserving data up to 100 Hz, very small earthquakes approaching magnitude 0 in size could be analyzed in hopes of identifying small-scale fault heterogeneity. Changes in earthquake location, number of small magnitude events, frequency of seismic waves, and stress drop could also be sought with much smaller earthquakes than are now used, which would add greatly to the resolution of such techniques.

A variety of measurements made near the earth's surface suffer from serious environmental noise. The bottom of deep drill holes is essentially noise free. A variety of relatively trouble free instrument packages is available that can be deployed for measuring volumetric and tensor strain, tilt, and vertical strain.

PORE PRESSURE AND STRAIN MONITORING

If fluid from a hydraulically isolated zone in a hole is allowed to rise, monitoring pore fluid pressure is straightforward. Transients in pore fluid pressure related to earth tides or earthquakes will provide useful data on the intrinsic properties of the fault zone and a sensitive measure of volumetric strain in the rock. In fact, pore pressure measurements of volumetric strain are so sensitive that earth tides are commonly observed in deep holes. Since the tidal dilatational strain is of the order of 10^{-8}, sensitivities of one part in 10^{9} are readily achievable even with old style mechanical water level recorders, which have been in use for 50 years. With good pressure transducers, one part in $10\omega^{0}$ should be achievable.

Unfortunately, pore pressure is also known to vary with other causes such as barometric fluctuations and ground water recharge and pumping. These effects must be separated from those caused by strain; best results could come from deep holes hydraulically isolated from near-surface transients. Also, digital filtering techniques can effectively remove much of the noise in the data.

In summary, the group of instruments for physical and chemical monitoring includes (but is certainly not limited to):

1. three-component wide-band downhole seismograph,
2. pore pressure monitor,
3. volumetric tensor and vertical strainmeters,
4. downhole tiltmeter,
5. self-potential (piezoelectric) experiment,
6. deep hole temperature/heat flow measurements,
7. water chemistry measurements of deep circulating fluids,
8. high-frequency acoustic emission to detect microseismic tremors, and
9. airgun or vibroseis stacking experiment for high-gain, high-precision seismic velocity monitoring.

Not all these measurements are compatible in a single hole. Some need casing perforation, some do not, and others can best be done without casing. Although many of these instruments are under continuing development, an operational version of each system is now available.

RECORDING AND TELEMETRY

When a deep hole is instrumented, the site itself will constitute a field observatory of a type never available before. A security enclosure with adequate thermal insulation will be built over the wellhead to allow for wire line service when necessary for instrument recovery. The power consumption of on-site recording instruments and data telemetry devices will be high enough to call for a-c power. On-site standard time reference will be required. On-site digital recording will be needed that can be augmented by data transmission in the band of 0.1 to 50 Hz through radio links using standard FM telemetry techniques. For data of slow sampling rates, such as pore pressure, tilt, strain, self potential, temperature, and radon, we anticipate a sample every 1 to 10 min. On-site recording can be computed by telemetry via satellite to a central location. Such a system can be inexpensive, and it will be ideally suited to long-term downhole monitoring.

6

CONCLUSIONS AND RECOMMENDATIONS

Drilling and downhole experimentation are essential to help answer fundamental questions about the mechanics of crustal deformation and the stresses that drive the plates of the lithosphere.

The Continental Scientific Drilling Committee therefore recommends: a three-fold program for active fault zones consisting of (1) numerous in situ physical property measurements, (2) extensive analysis on core samples, and (3) physical and chemical measurements after drilling, using the drill hole as an ultraquiet observatory. Such a program would provide a wealth of new data on the mechanical behavior of crustal faults and result in a major step forward in our understanding of factors controlling crustal deformation.

Because of the diverse nature of faulting and deformation, drilling at any single site will not yield all the critical data. The Committee therefore recommends, in order of priority the following five sites: (1) the San Anderas fault near Cajon Pass, (2) the Sevier Desert detachment fault, (3) the San Gabriel (California) fault, (4) the New Madrid (Missouri) seismic zone, and (5) the Alentian megathrust.

Theese sites represent locations for that would yield the greatest scientific reward. However, these recommended sites require preliminary efforts. A two-phase drilling program along the San Andreas fault is recommended, and multiple holes will probably be needed at several Basin and Range and intraplate sites to answer questions involving the mechanisms of faulting in these areas. A program of active fault zone drilling and downhole measurements is the only way to make a major advance in our understanding of the physical processes controlling the mechanical evolution of the earth's crust.

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