Advancing Our Understanding of Earthquakes

—Drilling into the San Andreas Fault—

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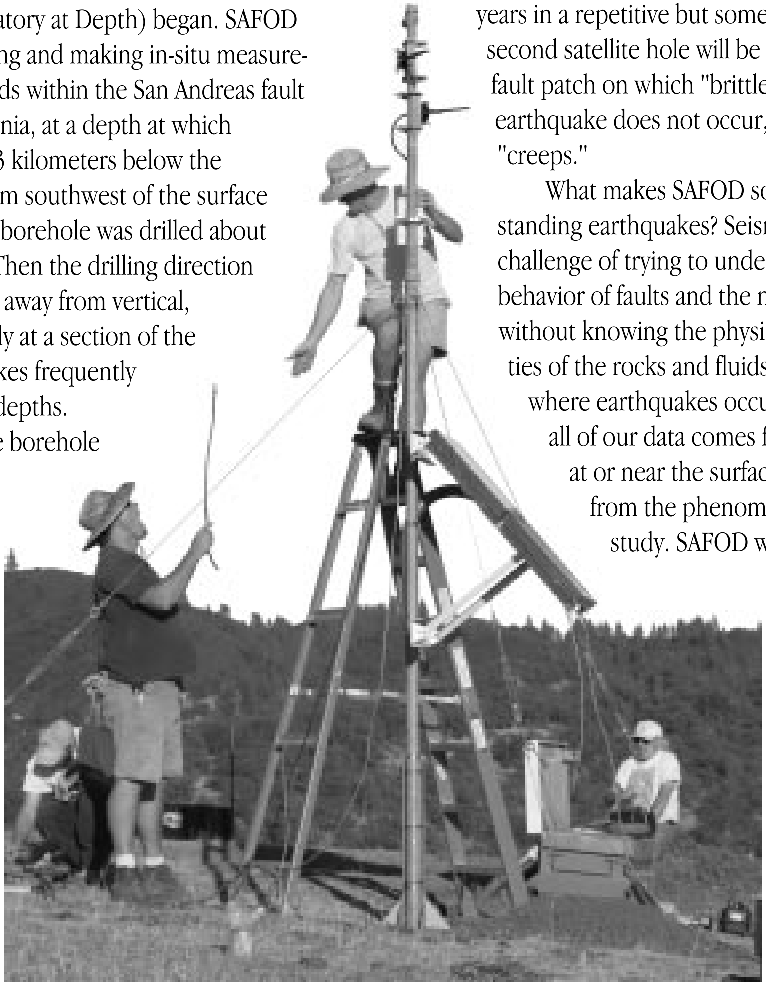
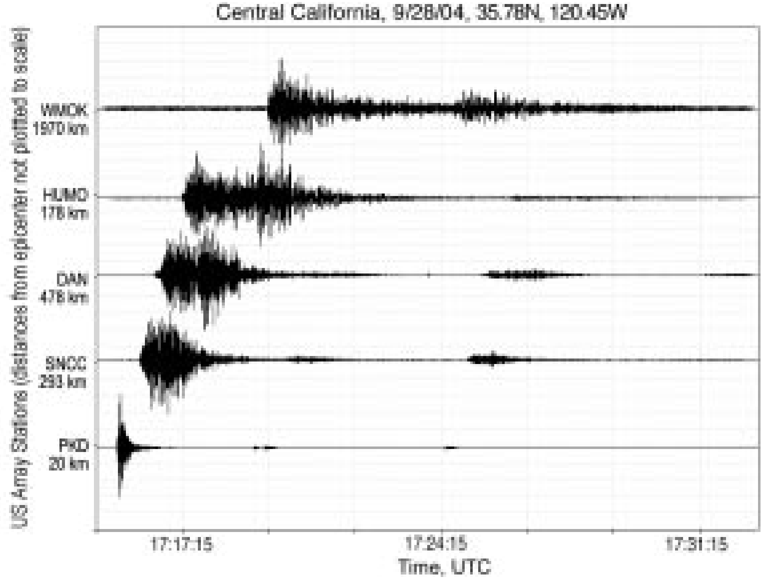
In June 2004, a multi-million-dollar project known as SAFOD (San Andreas Fault Observatory at Depth) began. SAFOD has the objective of sampling and making in-situ measurements of the rocks and fluids within the San Andreas fault zone near Parkfield, California, at a depth at which earthquakes occur (about 3 kilometers below the surface). Starting about 2 km southwest of the surface trace of the fault, a vertical borehole was drilled about 2 km deep into the earth. Then the drilling direction was altered to an angle 50° away from vertical, aiming the borehole directly at a section of the fault where small earthquakes frequently occur at relatively shallow depths. Drilling continued until the borehole reached a depth of 2.5 km below surface in August. In summer 2005, the borehole will be extended completely through the fault zone, eventually reaching the undisturbed rocks on the opposite side of the fault. Two years later, after intensive monitoring and in-situ testing, 3 or 4 "satellite" coreholes will be drilled off the main SAFOD borehole to sample the fault zone in regions of interest within a few hundred meters of the main borehole. One target will be a patch of the fault roughly 50 meters in diameter on which a magnitude 2 earthquake is known to occur every few years in a repetitive but somewhat irregular manner. A second satellite hole will be targeted towards a nearby fault patch on which "brittle failure" in the form of an earthquake does not occur, but instead the fault "creeps."

What makes SAFOD so important for understanding earthquakes? Seismologists face the challenge of trying to understand the mechanical behavior of faults and the nature of earthquakes without knowing the physical and chemical properties of the rocks and fluids present in the fault zone where earthquakes occur. Furthermore, virtually all of our data comes from instruments located at or near the surface of the earth, quite far from the phenomena we are trying to study. SAFOD will provide us with samples of the materials present in the fault zone, measurements of the conditions (temperature, stress, fluid pressure, etc.) within the fault zone, and the opportunity to make observations of earthquakes from a distance of a few



Above: *Field crew installing one of the twelve USArray seismic stations around SAFOD, replacing temporary instruments deployed right after the September 2004 Parkfield earthquake (see below). UW engineer Lee Powell (lower right) configures the instrument while Steve Roecker of RPI hands radiotelemetry cable to Glen Offield of UC-San Diego, and UW post-doc Mike Brudzinski (lower left) is preparing the seismometer vault cover.*



Left: *Seismograms of the September 28, 2004 magnitude 6 Parkfield earthquake and two of its larger aftershocks, as recorded by permanent US seismic network stations ranging in distance from 20 kilometers to nearly 2000 kilometers from the epicenter. At the Parkfield station PKD (bottom record), the strong shaking lasted for about 20 seconds. The earthquake was felt from San Francisco to Los Angeles. This earthquake had been predicted to occur in 1988 +/- 5 years, but better late than never for seismologists anxious to learn from its occurrence. Weeks Hall staff deployed 12 seismic instruments around SAFOD, at the north end of the rupture, two days after the earthquake.*

Cliff Thurber at the SAFOD site, in 2002, before drilling started.

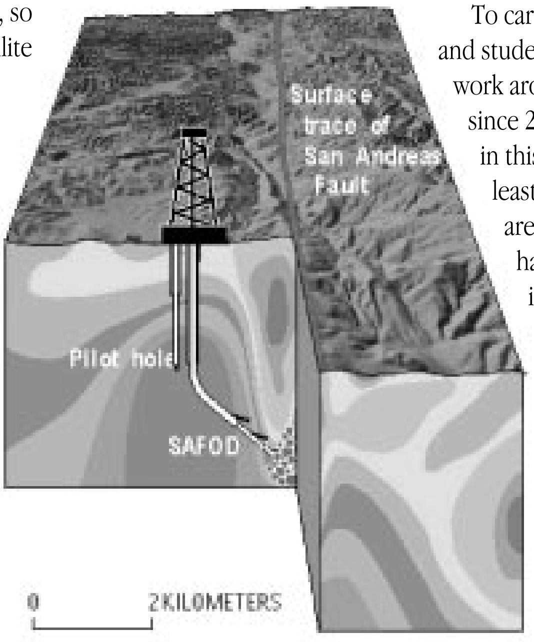
hundred meters or less, instead of from several kilometers or more away. In particular, we expect that differences in fault zone properties on the earthquake patch versus the earthquake-free (creeping) patch will provide us with critical clues to understanding fault mechanics.

The involvement of the Weeks Hall seismology research group in the SAFOD project falls into three main categories: high-accuracy location of earthquakes; determining the rupture geometry of small earthquakes, and high-resolution seismic imaging of fault zone structure. These topics are of both practical and fundamental scientific importance. In order to properly target the SAFOD drilling, especially the "satellite" coreholes, the location of the target earthquake and the geometry of the patch of the fault that undergoes slip when that earthquake occurs (the "rupture patch") must be known with extraordinary accuracy. When scientists locate an earthquake, what they are pinpointing is the place at which the slip on the fault initiates (the hypocenter). Fault slip spreads out along the fault until it terminates, presumably due to either diminished stress or increased fault strength around the rupture patch. Thus locating SAFOD's target earthquake only tells us part of the story—we also want to know the geometry of the rupture patch, so that we can strategically hit it with a satellite corehole. It is also critical to know in advance the drilling conditions to be encountered along the SAFOD borehole trajectory. In particular, an estimate of where the main borehole may enter or emerge from competent bedrock and penetrate the weaker rocks of the fault zone is required for designing the drilling plan.

A means of testing a controversial hypothesis could emerge from the study of a large set of earthquakes in the vicinity of SAFOD. It has been hypothesized that differences in the elastic strength of rocks on opposite sides of a fault may play a fundamental role in the spreading of fault rupture during an earthquake. To provide an analogy, a carpet layer moves and makes taut a carpet being installed not by tugging horizontally on the carpet as it lies flat on the floor but by inducing a pulse-like ripple in the carpet and simultaneously tugging on it. The carpet layer overcomes the frictional resistance of the carpet against the floor by creating the ripple, which travels across the carpet. Earthquakes may result in part from a comparable process. It has been suggested that, as a fault begins to slip, the rocks on the weaker side of the fault may "ripple," reducing friction on the fault and thus allowing fault slip to occur more easily. This theoretical model predicts that the rupture will spread preferentially in the direction that the weaker side of the fault is moving during the earthquake.

We will be able to test this controversial hypothesis directly using the results of our planned work on earthquake location, rupture geometry, and high-resolution fault zone structure. We already know the predominant direction of fault movement—the Pacific side of the fault is moving to the northwest, bringing LA ever so slowly closer to San Francisco. We will be able to locate (i.e. determine the hypocenters of) many small to medium-sized (magnitude 1 to 5) earthquakes and then use a technique known as "Empirical Greens' Function Deconvolution" to determine the rupture patches of the larger events (magnitude 3 to 5) using the seismograms from the smaller events (magnitude 1 to 3). The spatial relationship between the hypocenter and the rupture patch then provides direct information about the predominant direction of rupture propagation. From the high-resolution model of the seismic velocity structure, we can determine which side of the fault is weaker (the side with slower seismic velocity). If the predicted and observed rupture propagation directions are shown to be different at a statistically significant level, this will provide compelling evidence against the "rippling fault" hypothesis.

To carry out this project, Weeks Hall staff and students have been doing seismic field work around Parkfield almost continuously since 2000. Many people have taken part in this effort, which will continue until at least 2007 when the SAFOD coreholes are drilled. Soon thereafter, we may have answers to some of the most important scientific questions about the nature of earthquakes.



Cartoon showing the drilling plan superimposed on a resistivity model of the San Andreas fault zone. Drilling will penetrate throught the granite body underlying SAFOD, reaching the earthquakes about 3 km below the surface.