Earthquake Research at Parkfield

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The USGS and its collaborators have intensively monitored seismicity, crustal deformation, and electromagnetic properties along the Parkfield segment of the San Andreas fault since the mid-1980's in the hope of recording the details of strain accumulation prior to a M6 earthquake as well as of seismic rupture propagation. The earthquake was expected before 1993, but has not occurred. Current estimates of the likelihood of the next Parkfield earthquake are about 10/year.

Even without having a M6 mainshock, the Parkfield data set already acquired addresses several fundamental issues of earthquake physics with direct implications for hazard assessment: the validity of strain-budget balancing, the variability of recurrence intervals, the role of fault trace discontinuities in defining fault segments that can rupture in a single earthquake, the physical linkage of foreshocks to a mainshock, and the synthesis of realistic ground-motion time histories. The scientific community has made extensive use of the data and that use will increase as the data become more completely accessible through the internet which should happen within the year.

When the Parkfield earthquake does happen, it should provide data for at least two audiences. First, a moderate-sized Parkfield earthquake will provide high-quality, near-field recordings of high-frequency seismic ground motions that will allow delineation of the propagating rupture front. This detailed information will help researchers provide realistic ground motion time histories for engineering purposes. Secondly, near-field data before and during a M6 earthquake at Parkfield should provide valuable constraints on fault constitutive laws used in numerical models for faulting. These constraints yield insights into the physics of earthquakes and might be used in short or intermediate term forecasts of future earthquakes that are based upon physics rather than the empirical relationships that are currently being used.

Future plans for Parkfield include two components of NSF's Earth Scope initiative: the San Andreas Fault Observatory at Depth (SAFOD) and the Plate Boundary Observatory (PBO). The major component of SAFOD is logging and instrumenting a 4 km deep borehole into the fault at Parkfield. This will provide valuable data on the in-situ physical properties of the fault zone at seismogenic depths. In advance of SAFOD, a 2 km deep pilot hole will be drilled during the summer-2002. One component of PBO is to expand the existing set of instrumentation currently at Parkfield to address several long-standing issues on strain accumulation and seismic and aseismic release of energy along the Plate boundary. However, many of the current set of monitoring networks installed in the 1980s are either near the end of their operational lifetime and need to be upgraded with newer, more reliable technology. Should we continue to ignore the issue of instrument upgrades, for many of these data sets, which now exceed 15 years in length, we risk losing this valuable baseline which has made Parkfield attractive to Earth Scope.

The Parkfield earthquake research program is an effort to understand earthquake physics through study of of strain accumulation and its release in earthquakes and aseismic creep along the San Andreas fault section with the highest estimated probability of generating a M6 earthquake in the next three decades on any known fault in California. A secondary goal is to detect any anomalies of seismicity, ground deformation, or other physical quantities that might precede the occurrence of earthquakes in the Parkfield area. Improved knowledge of earthquake generation mechanisms will provide a scientific basis for refining estimates of future times, locations, magnitudes, and ground shaking of damaging earthquakes, not only at Parkfield, but also in more populated areas.

Since the Parkfield experiment began in 1985, earthquakes elsewhere in California have caused deaths, injuries, and huge economic losses. Obviously, it would have been beneficial if Parkfield-like data could have been acquired prior to these earthquakes. Unfortunately, a Parkfield-style experiment is possible only where the earthquake's nucleation point is believed known within about a 10-km radius. Consequently, while instruments of the types deployed at Parkfield now also operate in the San Francisco Bay Area and Los Angeles basin, their distribution is too sparse to record aseismic deformation and strong motion well enough to advance our fundamental understanding of earthquake nucleation and rupture propagation. Only at Parkfield is there enough information to focus adequate instrumentation exactly where the earthquake is likely to start. Worldwide, only the Tokai earthquake gap program in Japan approaches Parkfield in density of instrumentation near the source of a potential moderate-sized earthquake.

Instrumentation in the Parkfield area was sparse before the late 1970s, and installation of many additional instruments did not seem justified until *Bakun and McEvilly* [1979] and *Bakun and Lindh* [1985] showed that similar M6 earthquakes in 1857, 1881, 1901, 1922, 1934, and 1966 likely occurred at almost the same location. *Bakun and Lindh* [1985] calculated an average repeat time of 22 years and a 95 confidence that a M6 earthquake would occur before 1993 near the site of the 1966 M6 earthquake (Figure 1). *Bakun and Lindh* [1985] also pointed out that the 1934 and 1966 earthquakes had similar epicenters, fault-plane solutions, and seismograms, and that both ruptures propagated southeastward. Moreover, in both 1934 and 1966, a M5 foreshock preceded the mainshock by 17 minutes, and these two foreshocks also generated similar seismograms. These reasons to anticipate a future M6 earthquake nucleating near the same point in Parkfield were supplemented by geodetic data indicating that the Parkfield fault segment was accumulating strain rapidly enough to generate another M6 earthquake before 1993 [*Segall and Harris*, 1987; *Harris and Segall*, 1987].

In response to these observations and with the concurrence of National Earthquake Prediction Evaluation Council (NEPEC), the Parkfield Earthquake Prediction Experiment [*Bakun et al.*, 1987] was created to add instruments to measure physical properties prior to, during, and after the anticipated earthquake.

Two components of NSF's Earth Scope, the San Andreas Fault Observatory at Depth (SAFOD) and the Plate Boundary Observatory (PBO), would provide new information on earthquake nucleation, seismic rupture, and the overall earthquake cycle at Parkfield.

The SAFOD initiative [*Zoback et al.*, 1998] proposes to drill 4 km to penetrate and sample the San Andreas fault just north of the 1966 M6 nucleation point. Downhole logging and geophysical experiments will determine physical properties of the fault zone as it undergoes small repeating earthquakes as well as aseismic creep. The relatively shallow instrumentation currently at Parkfield provides a context for SAFOD's examination of the physics of faulting at depth. The Parkfield experiment could be altered to better complement SAFOD by deploying more geodetic instrumentation near the anticipated M6 nucleation zone.

In contrast to the single-borehole focus of SAFOD, the PBO experiment will examine the mechanics of faulting (and volcanism) on a regional scale, distributing new Global Positioning System (GPS) stations and borehole strainmeters broadly along the boundary between the Pacific plate and its adjoining plates from Southern California to Alaska. Most of these sensors will be deployed in clusters that target specific tectonic problems in detail and with some instrumental redundancy. The USGS experiment at Parkfield can be viewed as a PBO prototype which has already accumulated 15 years of data from strainmeters and other crustal deformation instruments.

At Parkfield, we currently have several instrument networks that record a variety of geophysical data. The location of the instruments that comprise these networks are shown in Figure 1. The status and the focus of each network is:

- Creep: There are currently 12 creepmeters in operation with data spanning between 16 and 35 years in length; a significant portion of the seismic cycle. However, most of these meters are near the end of their operational lifetime. In addition, many of the meters are noisy since they use shallow monuments. Ultimately, the environmental noise limits the long-term precision of these instruments. As part of PBO, new instruments should replace many of the existing meters and these new instruments should incorporate similar monuments that use deep anchoring such as those employed by Southern California GPS network.
- Two Color Electronic Distance Meter (EDM): This network has been in operation since 1985 giving a complete record of strain accumulation and slip on the reach of the San Andreas fault 5 to 15KM southeast of the nucleation zone of the 1966 earthquake. However, this network will go off line in favor of GPS because of the difficulty in maintaining this one of a kind EDM.
- GPS: There are now about a dozen continuous GPS sites operating in the Parkfield region; of these, seven of the GPS sites are co-located with two-color EDM which should provide continuity in baseline-length changes for a portion of the EDM network. Eight of the new GPS sites were installed in the summer 2001 using mini-PBO funds coordinated with UCSD. Most of the GPS sites use deeply anchored monuments. In addition, campaign style GPS has been conducted periodically since the early 1990s over the region from the Central Valley to the Coast to measure the regional strain accumulation. Prior to GPS, these measurements were made with EDM since the 1960s. The campaign data are useful in mapping the spatial distribution of slip on the San Andreas fault.
- Dilatational Strain: Of the eight borehole dilatometers installed in the mid- to late-1980s, five remain in operation. Three of the instruments are within a few kilometers of the nucleation zone of the 1966 earthquake; the other two are located 40 to 50 km to the southeast. Numerous strain events correlated with creep have been recorded. In addition, with the occurrence of several M4 to M5 earthquakes at Parkfield, no premonitory strain has been detect in the minutes to seconds preceding these events which constrain the size of any pre-seismic slip on the fault.
- Tensor Strain: Of the three, three-component strainmeters installed in late-1980s, all are working. A long-term change in shear strain detected by these instruments and confirmed with EDM data suggest a slight speed-up in slip rate in the mid-1990s under Middle Mountain. This period corresponds to a period of increased seismicity as evident by the occurrence of a few M4 to M5 earthquake under Middle Mountain.
- Water Wells: The changes in levels of several water wells in the Parkfield area have been recorded since the mid-1980s. Short-period changes in these wells, have been shown to be equivalent to measurement of dilational strain.
- Northern California Seismic Network (NCSN or Calnet): This network has been reliably locating earthquakes to less than the M1 level since the mid-1980s. Most sites consist of short-period seismometers and the data are telemetried to Menlo Park in real time using analog technology. Along with the location of earthquakes,

data from this and the HRSN (below) have been used to make a 3-D seismic velocity map of the area.

- High Resolutions Seismic Array: In the mid-1980s, ten seismometers were installed in boreholes to improve the level of detection of micro-earthquakes. The data were recorded digitally. Lately, this network has been upgraded by three new sites as part of SAFOD site characterization studies and the old digital recording system has been replaced. Many advances of our understanding of the characteristics of micro- to small- earthquake have made with data from this network.
- Calif. Strong Motion Instrumentation Array (CSMIP): Strong motion instruments have been installed in approximately 30 locations to record the rupture details of any moderate to large sized earthquake in the Parkfield area.
- Electromagnetic networks: Changes in the magnetic field, resistivity, and electric field, have been recorded at several sites since the late 1980s.
- Other Geophysical measurements: As part of the SAFOD site characterization studies, several of measurements have been made to gain a better picture of the subsurface geology and some of the physical properties of the fault zone. These measurements include seismic refraction and reflection surveys, M-T surveys, gravity and aero-magnetic surveys. In addition, there is now a high density seismic network spanning Middle Mountain and the SAFOD site to improve our ability to accurately locate earthquakes and to improve the map of the 3-D velocity structure.

The data already obtained at Parkfield along with the future set of measurements from SAFOD and a PBO cluster at Parkfield should increase our understanding of faulting; in particular, since Parkfield is situated at the transition between the creeping and locked section of the San Andreas fault, we should be able to either observe or infer the differences in the physical properties that cause the fault to be either creeping or locked. With the deep borehole data from SAFOD, the surface geophysical measurements that have been done prior to SAFOD, and with the current and proposed monitoring with strainmeters and GPS, Parkfield is an ideal earth-scale laboratory in rock mechanics.

Parkfield Monitoring Sites