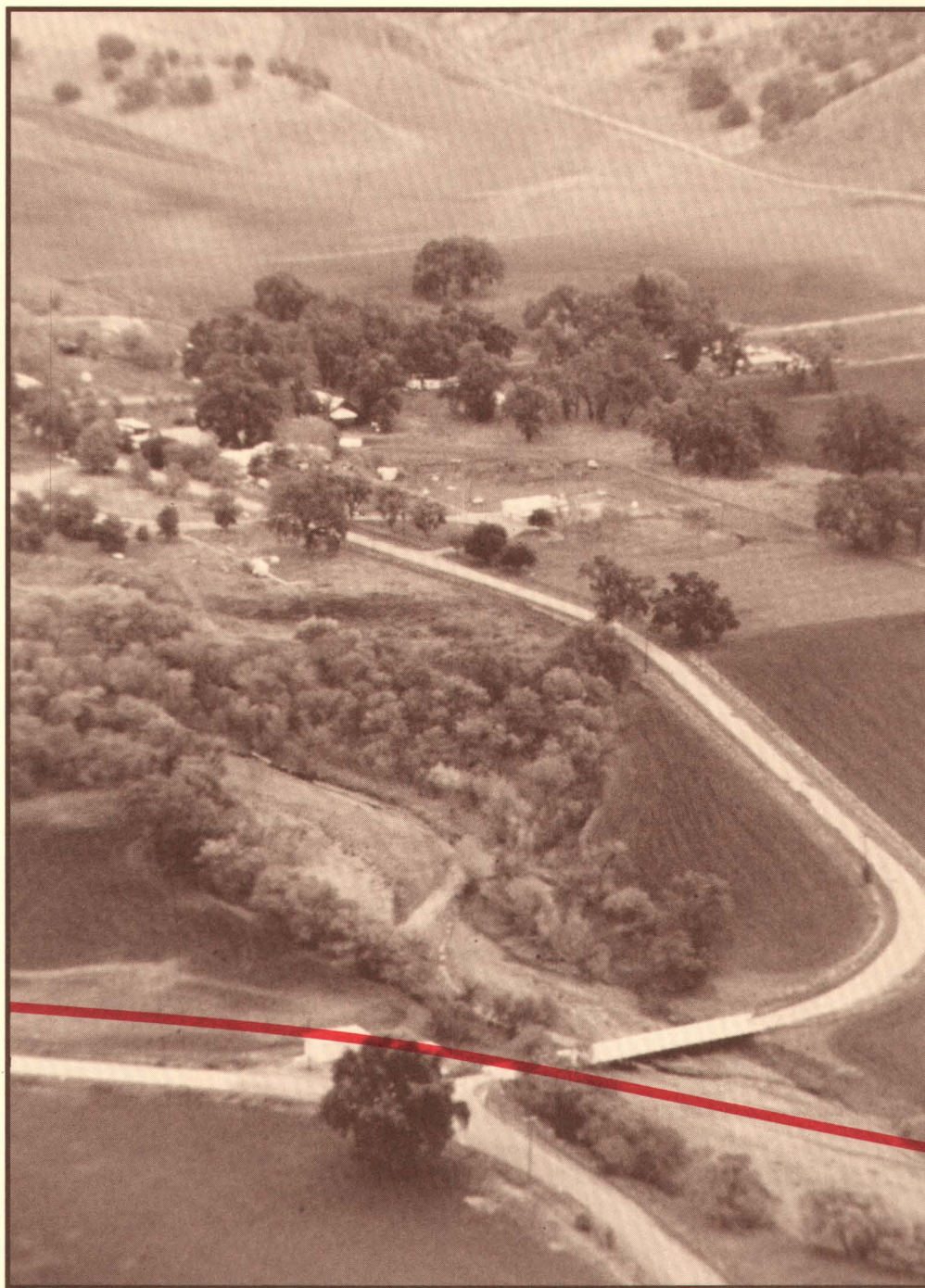


Earthquake Research at Parkfield, California, for 1993 and Beyond—

Report of the NEPEC Working Group to Evaluate the
Parkfield Earthquake Prediction Experiment



National Earthquake Prediction Evaluation Council Working Group

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By National Earthquake Prediction Evaluation Council Working Group

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Cover: A low-angle aerial view of Parkfield, California, looking NNE. In the foreground is the San Andreas fault (red line), the source of the Parkfield earthquakes.

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Earthquake Research at Parkfield, California, 1993 and Beyond – Report of the NEPEC Working Group to Evaluate the Parkfield Earthquake Prediction Experiment

Summary

During the past century, earthquakes of $M \sim 6$ have occurred with remarkable regularity on the San Andreas fault at Parkfield, California. Events occurred in 1857, 1881, 1901, 1922, 1934, and 1966. At least two of these events were preceded by large foreshocks and there is evidence for precursory creep of the shallow segment of the fault prior to the 1966 event. In 1984–1985, scientists developed and published a prediction, based on a model of “characteristic” earthquakes, that the next $M \sim 6$ Parkfield event was expected in a time window centered on 1988, with 95% probability that the earthquake would occur by the end of 1992 [Bakun and Lindh, 1985].

Shortly after the publication of this prediction, with endorsement by the National Earthquake Prediction Evaluation Council (NEPEC), the United States Geological Survey (USGS) initiated the Parkfield Earthquake Prediction Experiment (the *Experiment*). With additional support from the state of California, the Experiment took on a public services aspect, as well as a geophysical aspect.

By late summer, 1992, the predicted event had not yet occurred. NEPEC chartered a Working Group to evaluate the Parkfield Earthquake Prediction Experiment. This group was asked a series of questions which are summarized below, along with the responses of this Working Group.

1) What is the current assessment of the prediction?

a) Is it still considered likely that an $M \sim 6$ earthquake will occur in the short term?

Parkfield is still considered to be the most likely locality identified to “trap” a moderate sized earthquake. Empirically, no other location has demonstrated a sequence of earthquakes with as much regularity and as short an average recurrence time as the Parkfield sequence. The loading of the Parkfield segment of the San Andreas fault is unusually simple, with the creeping segment to the north leading to a continuous accumulation of strain on the locked segment near Parkfield. At this time, about as much strain has accumulated as was released in the previous event [Segall and Harris, 1986].

Estimates of the probability of the Parkfield earthquake occurring in the near future have been generated by a number of scientists. These estimates are based on a number of assumptions about the statistical behavior of faults, but all update the probability estimate to include the informa-

tion that, as of the time of the estimate, the event has not yet occurred. Estimates of the probability of occurrence are clustered around a value of approximately 10% per year.

b) If the event does not occur by the end of 1992, what does that indicate about the original prediction? Was the basis for the prediction in error?

The original prediction was based on a rather specific set of assumptions. These include that the loading rate is constant, that failure of the same patch of the fault occurs at or below a threshold stress level, and that the stress drop is identical for each event [Bakun and Lindh, 1985]. It was the adoption of this specific model that allowed the 1934 event to be ignored when evaluating the expected time of the next “characteristic earthquake,” leading to a small uncertainty in the expected time of the event. This model is now known to be too simple to apply to Parkfield. In retrospect, the original prediction should have included an assessment of the probability that the model assumptions were correct, in addition to considering the uncertainties related to data noise in fitting the assumed model.

But failure of this specific prediction does not negate the consensus of the Working Group that Parkfield is still the most likely place in the United States to trap an earthquake and that there is a relatively high probability that this event will occur on a time scale of a decade or so. In addition, Parkfield is unique because the location of the likely nucleation point can be estimated. And there is a long baseline of measurements already established there.

2) What have we learned during the experiment, both from the scientific and response community aspects? What have been the principal benefits that have come from both of these aspects of the experiment?

While the major scientific impact of the experiment will not occur until the next Parkfield earthquake is trapped in the dense web of instrumentation operating there, there have already been important benefits reaped from the real-time exercise created by the response community interacting with the scientific community. Because of its low population density, Parkfield has been an ideal location to begin this process. The Experiment has been a public policy success, with positive implications for response and mobilization to possible future earthquake alerts elsewhere. Cooperation at Parkfield has produced the *California Short-Term Earthquake Prediction Response Plan*. The “A”-level alert in Oc-

tober, 1992, provided a realistic "fire drill" to test the implementation of this plan. The press has learned how to portray alert levels and associated probabilities.

Several scientific results are also notable. For example, geodetic data have shown resolvable differences between the 1966 and 1934 events; Parkfield events are similar, yet still show differences large enough to violate the specific assumptions of the model on which the original prediction was based. In addition, the fault zone and asperities have been imaged at unprecedented resolution, with the identification of a low-velocity zone, perhaps related to high fluid pressure.

There has also been substantial technology transfer resulting from the Experiment, including increased expertise in siting of borehole instruments, experience with real-time seismic networks, and improved instrument design. These advances have made the installation of other instrumentation, such as that monitoring the Hayward fault, more cost effective.

3) Where should the experiment go in the future? What modifications should be made to scientific monitoring? What research efforts should receive highest priority? Should there be any modification in the agreements that govern the interaction between the USGS and the State of California with regard to hazard warnings?

The science of understanding the earthquake source is limited by the dearth of observations throughout the earthquake cycle. Parkfield is the most likely place yet identified to trap a moderate earthquake in a densely instrumented region and the best locale identified to answer a number of important scientific questions about the seismic source. Because the Parkfield segment of the San Andreas fault is loaded by the creeping section at one end, it provides a setting intermediate in scale between the simplicity of the laboratory and the complexity of most other faults. Substantial resources have been invested in setting up the Experiment and the marginal costs associated with continued operation of the experiment are minimal. Although the estimated annual probability of about 10% per year is the highest proposed for any specific location, and high enough to make the area scientifically and societally interesting, it is not high enough to ensure that an earthquake will occur on a time scale of a few years. Thus the USGS should view the Experiment as a long-term commitment.

In this context, the Working Group recommends that USGS continue the Parkfield Experiment and assign it a high priority. This includes having a committed, long-term Project Scientist with sufficient resources available to deal with the scientific, response planning, and public relations priorities of the Experiment. These aspects of the Experiment are likely to be in a state of high activity simultaneously when alerts are called.

A long-term plan is required for replacing failed or obsolete equipment, in particular, strain meters. This long-term plan should also include periodic peer review of the Experiment, with possible redirection and reordering of priorities.

In recognition of the long-term aspects of monitoring the preparation zone throughout the earthquake cycle, and the problems due to transients and costs associated with new installations, the USGS needs to ensure access to monitoring sites. The USGS should attempt to acquire control of land where instruments are located to avoid disruption when landowners change.

There should also be a commitment to continue the public policy aspects of the Parkfield Experiment through the earthquake cycle. There is still much to be learned about public response to perceived false alarms, perception of risk assessment, and warning thresholds.

Introduction

Before the mid-1980's, the United States' earthquake prediction program was in a reconnaissance mode, with monitoring programs broadly distributed across regions of the nation that had high seismic activity. In 1984, scientists at the USGS began to plan spatially focused earthquake experiments, with a primary goal of evaluating possible precursory phenomena. The issue that had to be addressed at that time was where to use the limited resources available with the best chance for evaluating these phenomena. The immediate question that had to be answered was where to deploy the recently developed dual-frequency laser geodimeter. Sites under consideration included Parkfield and San Juan Bautista.

In 1985, scientists at the USGS published a prediction that the next Parkfield earthquake was expected in a time window centered on 1988, with a 95% probability that the earthquake would occur by the end of 1992 [Bakun and Lindh, 1985]. This prediction was based on a specific model of the "characteristic" Parkfield earthquake, discussed in more detail below. NEPEC reviewed the prediction favorably and the USGS decided to locate their focused experiment in Parkfield.

In April, 1985, the Director of the USGS sent a letter to the Governor of California informing him about the possibility of an earthquake at Parkfield. California and USGS each contributed \$1M to begin instrumentation of the Parkfield area. Over 20 observational networks have been installed, including seismometers, creep meters, borehole strain meters, the two-color laser geodimeter, water wells, and magnetometers. Five of these networks are monitored in real time.

There were two scientific goals for the Parkfield Earthquake Prediction Experiment: 1) To record the geophysical details before and after the expected earthquake; and 2) To issue a short-term prediction. In addition, with the involvement of the State of California, the Experiment took on an important public policy aspect, serving as a test bed for communication between earthquake scientists and public officials. The rural nature of the community made it an ideal location to carry out the Experiment.

A formal series of alert levels has been set up, triggered by phenomena such as fault creep or earthquake activity in

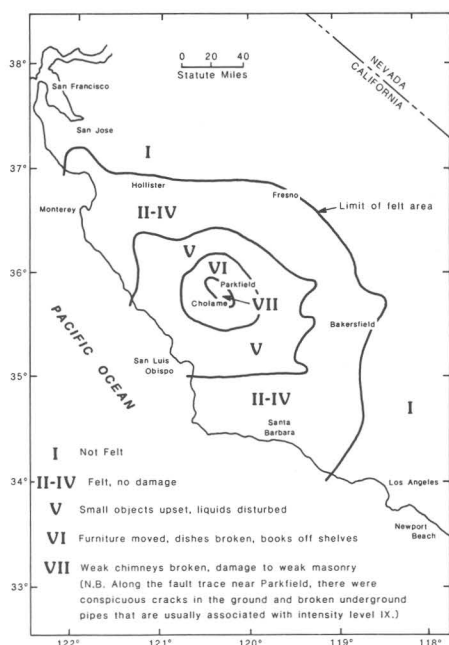


Figure 1. Modified Mercalli intensity pattern for the 1966 Parkfield earthquake.

the "preparation zone." Alert levels range from D (triggered about 100 times since June, 1985) to A (triggered once, in October, 1992, by a $M = 4.5$ earthquake; this alert corresponds to an expected probability of 37% of the forecast event occurring within 72 hours).

Charge to the Working Group

In mid-1992, with the pending expiration of the prediction window, NEPEC chartered a working group to evaluate the original prediction. The charge to the working group was to evaluate the Parkfield Prediction Experiment in light of the following questions:

- 1) What is the current assessment of the prediction?
 - a) Is it still considered likely that an earthquake will occur in the short term?
 - b) If the event does not occur by the end of 1992, what does that indicate about the original prediction? Was the basis for the prediction in error?
- 2) What have we learned during the experiment, both from the scientific and response community aspects? What have been the principal benefits that have come from both of these aspects of the experiment?
- 3) Where should the experiment go in the future? What modifications should be made to scientific monitoring? What research efforts should receive highest priority? Should there be any modification in the agreements that govern the interaction between the USGS and the State of California with regard to hazard warnings?

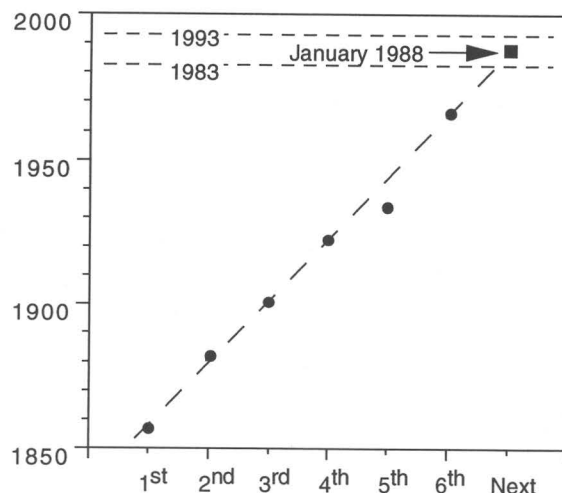


Figure 2. Significant earthquakes have occurred on the Parkfield section of the San Andreas fault at fairly regular intervals – in 1857, 1881, 1901, 1922, 1934, and 1966. The next significant earthquake was anticipated to take place within the timeframe 1983 to 1993.

Assessment of the Prediction

The Working Group addressed two main questions in assessing the Parkfield Prediction. The more important one is whether Parkfield is still viewed as being the most likely place to trap a moderate earthquake. The secondary question is whether the specific prediction that expired at the end of 1992 was correct.

Parkfield is thought to be more likely to experience a moderate earthquake than any other place in the United States. During the past century, earthquakes of $M \sim 6$ have occurred there with remarkable regularity. Events occurred in 1857, 1881, 1901, 1922, 1934, and 1966. The time between earthquakes ranged from 12 to 32 years, with an average of 22 years. The relatively short time between events may result from a near-uniform rate of loading of the Parkfield segment by slip on the creeping segment of the fault just to the northwest.

With the demonstration that for the last two $M = 6$ Parkfield earthquakes the total (co- and post-seismic) surface displacements determined from geodesy are resolvably different [Segall and Du, 1993], it is now understood that the assumptions of the specific model on which the prediction was based do not hold. There is no consensus on the correct physical model to be used for evaluating the probability of the Parkfield event occurring within any given time window. The computation of statistical estimates of occurrence probabilities has become almost a cottage industry, with a variety of models produced using different assumptions about the nature of the appropriate statistics. Most recent statistical models update the estimated probability to include the information that the earthquake has not yet happened as of the time of the estimate. While the details vary, estimates of the probability of occurrence of the event cluster around a value of about 10% per year [e.g., Kagan and Jackson,

1991; *Savage, 1991*]. Such a probability is high enough that continued monitoring of the Parkfield segment is important.

In addition to Parkfield being the most likely place identified to trap a moderate earthquake, Parkfield has other features that make it a good place for a prediction experiment. First, a variety of events that may have been precursors occurred before previous $M \sim 6$ earthquakes there. At least in 1934 and 1966, $M > 5$ foreshocks occurred. In 1966, cracks were observed in the ground and a pipe broke days before the event. The epicenters of the 1922, 1934, and 1966 events are all located close to each other, providing a clear target for siting instrumentation to trap the next event.

From a social and economic perspective, Parkfield is an ideal location for a prediction experiment. The area is sparsely populated and the residents are well educated and relaxed about the occurrence of moderate earthquakes.

The Experiment has made important contributions both to geophysical science and to public policy. But advances in our understanding suggest that the model on which the original prediction was based is too simplistic. The original model of constant loading rate, uniform moment release, and constant stress drop, controversial when it was first proposed, has now been shown not to apply to Parkfield. In retrospect, an estimate of the reliability of this hypothesis should have been included in the original calculation, and would have broadened the window of predicted recurrence. The relatively narrow window that was stated in the original prediction has led to expectations that the experiment would be over relatively quickly, leading to the misconception that the experiment has now somehow “failed” because the narrow time window has closed.

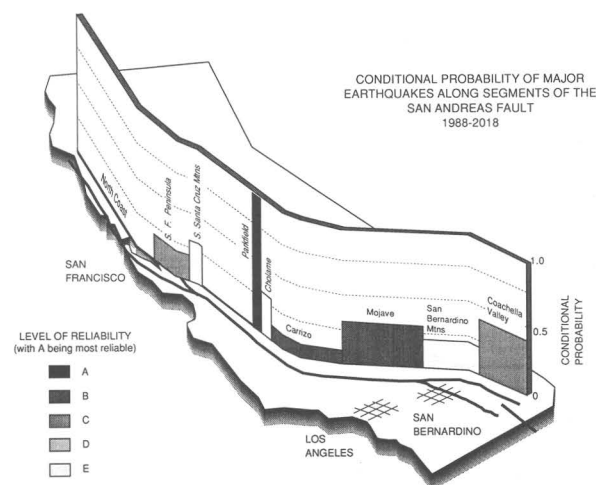


Figure 3. Conditional probability for the occurrence of major earthquakes along the San Andreas fault in the 30-year interval from 1988 to 2018.



Figure 4. Parkfield sign.

What We Have Learned from the Experiment

Lessons for the Scientific Community

Improvements in Monitoring

The Parkfield project was the first concerted effort in the US to implement real-time monitoring of a variety of possible precursory signals and geophysical information in a single earthquake source region. This forced the development of a coherent plan for monitoring instrumentation: alignment arrays, a two-color laser geodimeter, creep meters, ground-water-level transducers, tilt meters, surface and borehole seismometers, volumetric strain meters, tensor strain meters, leveling lines, borehole temperature measurements, an earth resistivity monitoring network, Global Positioning System (GPS) geodetic measurements, magnetic field measurements, ULF electromagnetic measurements, ground water radon measurements, and soil hydrogen measurements. In addition, arrays to measure strong ground motion, liquefaction, coseismic slip, and pipeline response were installed. The result has been the most thoroughly instrumented earthquake source region in the world. The technology required to record and download these data (often in real time) has been a challenge to implement, and during the Parkfield experiment, the knowledge of how to run such a system has improved.

The monitoring done in Parkfield since the start of the earthquake experiment has yielded a very detailed baseline of behavior of all of these phenomena, which will be invaluable for comparison with post-earthquake observations. The baseline observations have permitted a good understanding of the transient results of rainfall events, slow strain events, and tides. In addition, they have provided observations

regarding the response of the Parkfield region to smaller earthquakes nearby, and to larger earthquakes at some distance from the region (*e.g.*, Kettleman Hills; Loma Prieta; Coalinga; and Landers). These observations are extremely relevant to the design of monitoring installations and establishment of alert levels in other regions; they will also contribute to the revision of alert levels for Parkfield.

Scientific Results to Date

The scientific experiments at Parkfield fall into three classes: those designed to monitor possible earthquake precursors, those designed to monitor the behavior of the region around the anticipated rupture nucleation point, and those designed to study the effects of earthquake-induced ground shaking on both natural and manmade structures. Many of the experiments will not yield their full scientific value until the earthquake has occurred, when the difference in baseline before and after the earthquake can be determined, and the effect of the earthquake on manmade structures can be analyzed. However, some of the instruments installed at Parkfield have shown temporal variations (particularly in levels of seismicity) that have led to important scientific advances even during the current pre-earthquake monitoring period.

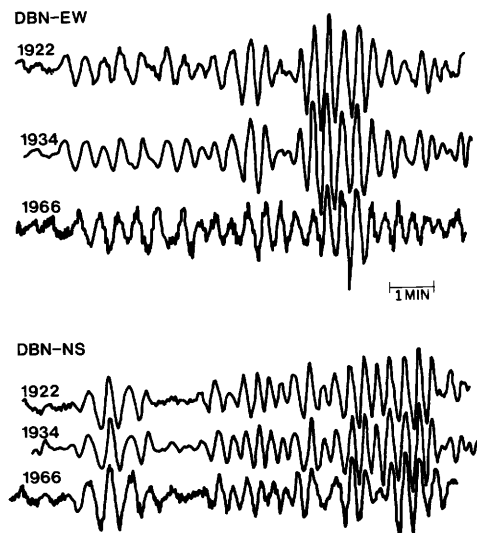


Figure 5. De Bilt, the Netherlands, east-west (DBN-EW) and north-south (DBN-NS) component seismograms for the 1922, 1934, and 1966 Parkfield events. Amplitude and time scales are constant.

One such example is the borehole seismic array that has been installed at Parkfield. Because of the extremely low noise present on the downhole seismometers, a complete seismic catalog down to magnitude near zero has been recorded for the region. These seismic observations have permitted the recognition of slow, microseismic slip events [Malin and

Alvarez, 1992] and the identification of periods of higher seismicity that may be related to the locations of future slip events [Roeloffs and Langbein, 1994]. Such events would have been impossible to identify with conventional surface seismic arrays, and have illustrated the importance of including downhole installations in other prediction arrays.

Because of the focus on Parkfield as a center of earthquake prediction efforts, the seismic history of the region has been scrutinized during the years since 1985. This has led to major advances in our understanding of the details of the previous Parkfield earthquakes. For example, differences in the extent of the rupture plane between the 1934 event and the 1966 event are now recognized [Segall and Du, 1993]. The pre-1930 historical events in the region have been more closely studied, resulting in the recognition of 10 previously unrecognized events with magnitudes above 5.5 within 100 km of Parkfield [*e.g.*, Topozada *et al.*, 1990]. This new information has led to debate about just how similar the 1934 event and the 1966 event really are, and whether all of the earlier events were on the same fault patch, casting doubt on the validity of applying the “characteristic earthquake” hypothesis, in its simplest form, at Parkfield.

The focus on Parkfield has also resulted in reexamination of the predicted earthquake recurrence interval there based on the simplistic idea of uniform loading rate. For example, earthquakes on nearby faults, such as the 1983 Coalinga event, may have an effect [*e.g.*, Simpson *et al.*, 1988; Tullis *et al.*, 1990]. In addition, the results of viscoelastic relaxation following the great 1857 earthquake may lead to a decrease in recurrence time during the longer-term San Andreas seismic cycle [Ben-Zion *et al.*, 1993]. The possibilities that the segment boundaries at Parkfield are not geometrically well defined [Nishioka and Michael, 1990] nor visible as steps in the seismically defined fault zone [Eberhart-Phillips and Michael, 1992; Michael and Eberhart-Phillips, 1991] and that successive ruptures may overlap in spatial extent has been recognized, along with the tendency for earthquakes to cluster [Kagan and Jackson, 1991]. The rate of strain accumulation since the 1966 event has also been examined, and used to constrain the moment deficit since 1966, which can be used for estimates of recurrence time [see summary by Roeloffs and Langbein, 1994].

Partially due to the focus on Parkfield, understanding of the statistics of “earthquake prediction” (in terms of estimation of recurrence times and their uncertainties) has advanced considerably. If we were to calculate the mean recurrence time and probability of the Parkfield earthquake as of today, we would do it by a more sophisticated technique, and using different uncertainties, than used in 1984. We would also recognize that various models of earthquake recurrence are possible. The question of whether to include the 1934 event in the probability calculation, and how to estimate the variability in the recurrence time (“shape factor”) has led to further evaluations of the details of probabilistic calculations [Nishenko and Buland, 1987; Savage, 1991; Roeloffs and Langbein, 1994]. These advances in understanding of methods of estimation of earthquake probabilities have been

applied to other regions along the San Andreas fault system [e.g., *Working Group on California Earthquake Probabilities*, 1988, 1990; *NEPEC/CEPEC/SCEC Working Group*, 1992; *Jones et al.*, 1991] and elsewhere, including volcanic unrest at Long Valley Caldera [*Hill et al.*, 1991].

Regional studies of crustal structure around Parkfield have been carried out as part of the Experiment. These studies are aimed at (1) characterizing the three-dimensional velocity structure for improved hypocentral determinations and (2) identification of temporal and/or spatial variations in seismic velocity that may be related to fault zone material properties or fluid pressure buildup in the fault zone. The three-dimensional velocity structure obtained by *Eberhart-Phillips and Michael* [1992] and *Michael and Eberhart-Phillips* [1991] suggests the presence of a body with low compressional wave velocity and low resistivity, near the north-east side of the fault, beneath Middle Mountain. They infer that this material may contain high fluid pressure. Low shear wave velocity is also inferred at depths of 5-9 km near the 1966 hypocenter, possibly indicating high pore pressure [*Michelson and McEvilly*, 1991]. In addition, the quarterly vibroseis (polarized shear wave) investigations have shown temporal variations in seismic velocity that may be correlated to resistivity changes and/or slow creep events [*Karageorgi et al.*, 1992].

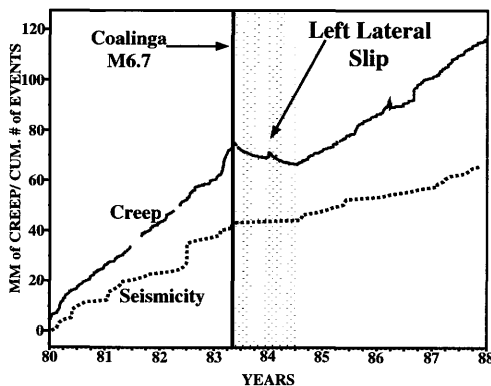


Figure 6. Surface creep of the San Andreas fault at Middle Mountain (in mm) and the rate of seismicity under Middle Mountain (cumulative number of events with $M \geq 1.5$, depths ≥ 6.5 km since 1980) are shown. The Coalinga $M 6.7$ earthquake caused the fault to slip left lateral and stopped the seismicity for slightly over a year.

Possible precursory phenomena have been scrutinized. The Parkfield project required a careful evaluation of various possible precursors, in order to decide what to measure and record at the start of the experiment. During the course of the experiment, it has become clear that some possible precursory phenomena were not being studied (e.g., the ULF electromagnetic signals) and that some other measurements related to precursory phenomena may be relatively problematic (e.g., rainfall-induced creep events). Theoretical modeling of expected strain accumulation prior to rupture [e.g.,

Tullis and Stuart, 1992] has forced a careful look at the time scales and spatial scales over which precursory signals might be visible. This has shown that, for certain scenarios, we would expect to capture precursory signals on the currently designed and located instruments, but for other scenarios we would not be able to resolve these precursory signals. Thus, we have improved our knowledge of optimal experiment design for this location, and can now apply these techniques to future experiment design in other regions.

Technology Transfer

The Parkfield experiment required a working collection of monitoring instrumentation designed to observe long-term and short-term changes in the fault near the inferred point of rupture initiation. As the experiment progressed, equipment failure and changes required modification of both the hardware (e.g., the cable connections on some downhole equipment) and the science plan (e.g., the alert levels triggered by creep events during heavy rainfall). Many of the bugs related to real-time operation of this monitoring system, and related to real-time operation of this monitoring system, and to design and installation improvements, are now worked out. Similar monitoring systems are now being installed along the Hayward fault system, near San Francisco, and along parts of the southern California fault systems. There has been a great savings in cost for these installations because of the experience gained at Parkfield. The real-time aspect of such data collection has been greatly advanced by the expertise gained in the Parkfield experiment, so that Parkfield serves as a starting model for the design of similar, but younger and more sophisticated, systems.

Lessons for the Response Community

Parkfield Successes

The Parkfield Earthquake Prediction Experiment has been a success from the response community perspective as demonstrated by the response of emergency management services, in conjunction with the scientific and media communities, to the October, 1992, "A"-level alert. During the Experiment, the emergency response community has been able to prepare and exercise its response plan for the "A"- and "B"-level alerts, including the notification of local governments. Cooperation at Parkfield between the USGS and the California Office of Emergency Services (OES) has resulted in the State of California Governor's Office of Emergency Services *Parkfield Earthquake Prediction Response Plan* [OES, 1988], which was the basis for the response actions during the "A" -level alert. Based on the *Parkfield Earthquake Prediction Response Plan*, California OES developed and published the *California Short-Term Earthquake Prediction Response Plan* [OES, 1990]. This second document describes state agency and county government actions to be taken in response to any scientifically-driven earthquake alert or prediction at any other location in the state.

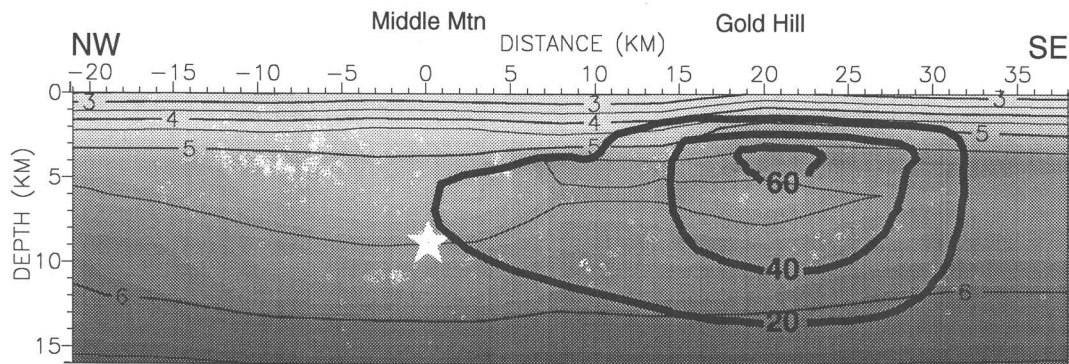


Figure 7. This cross section along the San Andreas fault compares the amount of slip in centimeters during the 1966 mainshock (dark contours from *Segall and Harris, 1986*) to the seismic P wave velocities on the northeast side of the fault (shading and lighter contours in km/s from *Michael and Eberhart-Phillips, 1991*). The mainshock hypocenter (large star) was under a body of low velocity material but most of the slip occurred to the southeast where higher velocity material exists. White areas are small background earthquakes that tend to occur in the lower velocity material and around the edges of the mainshock.

The Experiment has brought scientists together with state and local officials, emergency managers, and the media, in a productive, mutually beneficial relationship. The state established the first scientifically-based state emergency management protocol for a specific predicted earthquake. This interaction has permitted emergency managers to understand the earthquake hazard as well as to understand

the perspective of the scientific community regarding earthquake prediction. USGS scientists now understand the importance of providing timely interpretation of earthquake data to the state and local emergency managers and the public.

Benefits From the Parkfield "A"-Level Alert, October 20–22, 1992

The "A"-level alert was mostly a positive experience. California OES received an initial alert from the USGS regarding a "B"-level alert 18 minutes after the initial earthquake. Six minutes later, the USGS notified OES of the "A"-level alert, triggered by the $M = 4.7$ earthquake at Middle Mountain. Eight minutes later, OES broadcast the alert to state agencies and local governments over the California Warning System and the California Mutual Aid System. Kern County was the first county to activate its Emergency Operations Center, 47 minutes after the OES alert. OES completed its alert of local government and response officials in less than one hour following the earthquake. OES staff went to the USGS offices at Menlo Park, and to the town of Cholame, near Parkfield.

Planning and exercising of the *Parkfield Earthquake Prediction Response Plan* allowed for this timely activation and mobilization of local government and OES. OES' overall assessment of the notification is that they "could not have done it much quicker." The operational response plan worked well because it prescribes simple and straightforward actions. As a result of evaluation of the state and local response to the "A"-level alert, the process of formal notification and validation did not need to be changed. However, key OES staff now carry the USGS alert pager, which will notify OES staff simultaneously, along with the USGS personnel, of Parkfield earthquake activity.

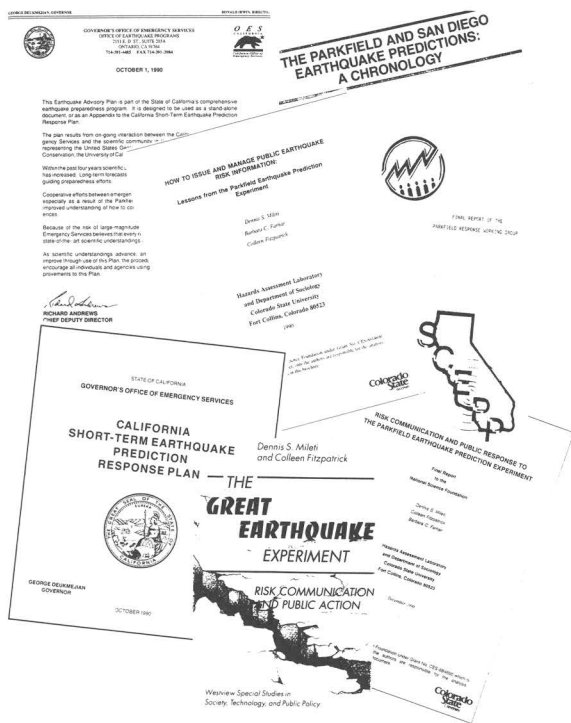


Figure 8. Public Response Plans.

Interaction with the press was one of most valuable benefits of the "A"-level alert. OES was able to explain the purpose of the alert and associated response to the media. The seven counties' response was overwhelmingly positive. Local officials and politicians appreciated receiving the warning

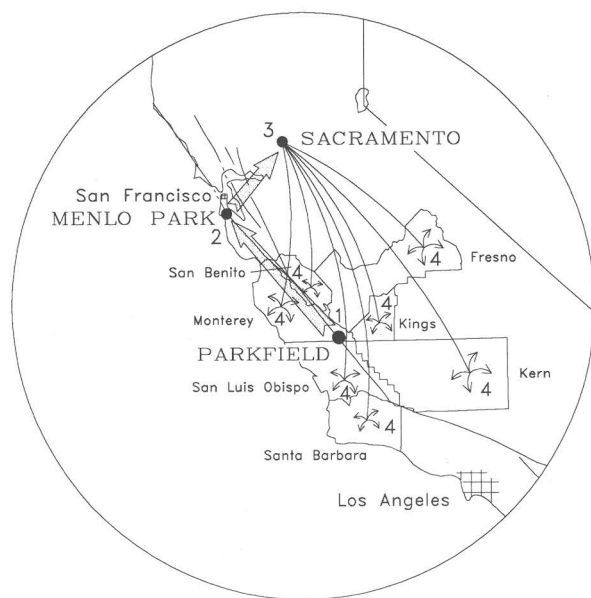


Figure 9. Flow of information resulting from an A-level alert at Parkfield. Signals from USGS instruments at Parkfield (1) are telemetered to the USGS Western Region Headquarters in Menlo Park (2) for analysis by USGS scientists. The California Office of Emergency Services (OES) in Sacramento (3) is notified by the USGS for all A-, B-, and C-level alerts. A-level alerts are immediately transmitted by OES to county governments (4) using established OES emergency communication channels. County officials also have established procedures to relay the warning to such groups as law enforcement agencies, fire departments, utility companies, and school districts.

and the continuous flow of information. The county after-action reports were very positive – nothing of substance was reported as negative.

The widespread news coverage of the Experiment and the October "A"-level alert has sensitized the public in California to the possibility of future earthquake alerts. For example, news media gave the alert front-page and lead-story status in the San Francisco Bay Area. Just as significant, the media also announced the end of the alert window three days later. To prompt media closure of the 72-hour alert window, the USGS, OES, and the California Division of Mines and Geology (CDMG) conducted a news conference. Fortuitously, the next week's "B"-level alert, October 26, 1992, following the "A"-level alert, emphasized to the public that different levels of alert exist with different

associated earthquake probability percentages. Again, the media did a good job in portraying these alert levels with their associated probabilities. The alerts emphasized the prediction issue and hazard reduction issues, both of which will be raised in other contexts during future events.

The "A"-level alert underscored the key steps that local, state, and federal government officials must take when a prediction or alert is issued to the public. As a result, some local governments are now in the process of developing formal short-term earthquake prediction response plans.

Benefits Advancing Public Policy

The Experiment resulted in the development of the following beneficial response-related actions integrating scientific information with public policy:

- 1) It offered the first opportunity for the California Earthquake Prediction Evaluation Council (CEPEC) to validate an earthquake prediction;
- 2) It prompted the California OES to write and issue a public information brochure to the people of the area;
- 3) It prompted the National Science Foundation to fund a study to gauge the effectiveness of this public information brochure;
- 4) It prompted the California OES to write and issue written press statements on the alert prior to the "A"-level alert in October, 1992;
- 5) It contributed to the development of the City of Los Angeles' *Earthquake Prediction Response Plan*;
- 6) It led to the passage of California Assembly Bill 938 in 1985 (California Public Resources Code 2800 *et seq.*), which authorized California to contribute \$1 million in state funds to the Experiment;
- 7) It attracted international public and private scientific participation in the Experiment through the CDMG-sponsored *Turkey Flat Strong Motion Experiment*;

and

- 8) It offered the first opportunity to engage the liability immunity provisions of California's law for state and local agencies and officials involved in response activities. (California Government Code Section 955.1, *et seq.*)

We believe that the California OES and the USGS plan to continue supporting the Experiment. The seven counties also are willing to continue participation in the prediction aspects.

Problems Identified

Although the Parkfield Earthquake Prediction Experiment has been very successful, there have been a few problems that the NEPEC Working Group has identified. These should be addressed as the Experiment evolves.

Lack of Ongoing External Scientific and Emergency Response Review

Perhaps because of initial haste prompted by anxiety that the anticipated earthquake might occur before the Experi-

ment was fully operational, there has been little provision for ongoing review. The annual expenditure and the importance of this project to the prediction community requires periodic external review (suggested annually) to assure its viability and credibility. An assessment of the progress and quality of the project by a panel of experts would ensure that appropriate scientific and response objectives are kept at the forefront of the project and that the Experiment changes in response to new developments, as well as doing much to dispel criticism of the experiment. The review might be done by a subset of the NEHRP Review Panel, which could oversee the general worth of the project in the context of the NEHRP program and give advice on the direction and disposition of financial support.

Scientific Data Not Readily Accessible

There is a perception that some investigators funded under the Parkfield project have been too busy, inadequately supported, or perhaps reluctant to release their data in a timely manner. These delays have reduced the usefulness of the data to the Parkfield team. An implicit philosophy of the Experiment is that all investigators must work in a cooperative effort in order to provide the data in a timely fashion for time-dependent decisions regarding designations of alerts and to assure timely review of data. If data gathered within the Parkfield experiment are important enough to be funded, they are important enough to be made available on a short enough time frame to contribute to the decision making process.

Data Management

The question of data accessibility is also related to the philosophy of data management. It is problematic that there is not now a modern data base management scheme implemented for the Parkfield data. Individuals who wish to examine the data must be familiar with the location(s) of particular data files in USGS computers (which require secure passwords) in order to retrieve the data. The user then must plot the data with his or her own software and has little information on attributes or an understanding of how the data may relate to the earthquake process. This is a serious limitation and does not allow ready access to the user.

While we realize that data acquired in sophisticated experiments must be carefully processed and scrutinized by individual investigators, we suggest that because of the specific NEHRP financial commitment and national stature of the Parkfield Experiment that a modern Data Base Management System be implemented for archiving and managing the Parkfield data. This requires that all on-line recorded data be available immediately after processing and that off-line and low-rate data, requiring editing and processing, should be archived within a sufficiently short time to be useful to the decision makers. This aspect is also important for providing on-line access to designated users. A user-friendly Geographical Information System available with sub-licenses

to the participating Principal Investigators would also be useful to manage, correlate, and display the archived data.

We also note that some additional data, now collected at Parkfield, should be considered for transmission and recording at Menlo Park. These include the electrical resistivity array and the ULF EM measurements.

A possible restriction in the Parkfield data distribution scheme is that the downhole and acoustic data, which are recorded on tape at Parkfield, are then sent to Duke University and UC Berkeley for analysis. Because of these time-consuming steps they are not available to the USGS team in a timely or efficient manner. A plan should be made to make these data more readily available to the USGS in Menlo Park quickly enough to be useful in a short-term alert and prediction mode.

Overemphasis by the Public and Media on the Prediction Aspects of the Experiment

The original objectives as stated by *Bakun and Lindh* [1985] were that the Parkfield experiment was to monitor the details of the final stages of the earthquake preparation process. The instrumental aspect of the Parkfield project was designed primarily as a surveillance project. However, with the involvement of California funding, the Experiment took on a short-term earthquake prediction objective that is perceived by the scientific and emergency response community as the "national" prediction experiment.

The general public now perceives the Experiment primarily as a short-term earthquake forecasting project with an inherent expectation to accurately predict an earthquake, while the scientific community views it not only as a short-term prediction experiment, but also as an effort to trap a moderate earthquake within a densely instrumented network. It is important to educate the public that there is great value to this monitoring effort even if the prediction effort is unsuccessful.

How Should the Experiment be Modified in the Future?

The Working Group recommends that the Experiment continue as a specific coordinated scientific effort in monitoring through the earthquake cycle, as well as in earthquake prediction. Although the annual probability of the expected characteristic event occurring, about 10% per year, is sufficiently high that the Experiment should continue, it is not so high that we can expect the Experiment to be over on a time scale of a few years. Thus, it is prudent to take a long-term perspective in contemplating the future of the Experiment. Issues to be addressed include costs, relocating the Experiment, mechanisms for ongoing evaluation of the Experiment, and future USGS response efforts.

What are the Incremental Costs Associated with the Experiment?

In addressing possible modifications of the Experiment,

it is important to place the budget in context. The internal budget for the Parkfield Experiment is \$1.4 million/year, but this amount is much more than the true incremental cost of the Experiment. The great majority of these expenditures are for salaries of scientists (prorated based on estimates of the fraction of time spent on the Experiment). Since these salaries would continue to be paid if the Experiment were ended, termination of the Experiment would not allow salary costs to be cut, although the effort could be deployed elsewhere. Real-time monitoring is highly automated, making use of computer systems that already exist. In the judgment of the Working Group, turning off the Experiment completely would save less than \$200,000 per year in the internal program. The external program has a budget of ~\$400,000 per year. Thus the total incremental cost of the Experiment is approximately \$600,000 per year – just over 1% of the USGS NEHRP budget.

Should the Experiment be Moved?

USGS is under tremendous pressure to “do something” in more heavily populated areas, such as near the Hayward fault. The argument is made “How can we justify spending money trying to predict an earthquake in an area with as few taxpayers as Parkfield, when so many more people would be affected by an earthquake on the Hayward fault?” In answering this question it is important to remember that we do not at this time know which, if any, of the instruments monitoring pre-earthquake activity will measure premonitory signals. Thus, we do not know the requirements for instrumentation to install to be useful for earthquake prediction in heavily populated areas. It is extremely important to answer this question as quickly as possible. Impatient as we may be with the lack of the expected event, Parkfield remains the most likely place identified to trap a moderate earthquake. It is probable that precursors would only be detected by instruments located quite close to the earthquake preparation area. Parkfield represents one of only a few places where this preparation area has been specifically identified. In addition, the long baseline of measurements already made at Parkfield represents an investment that should be used, not walked away from.

While there are benefits to having the monitoring effort visible to the public, evaluating the possibility of precursors should have highest priority. The best place to find out if they exist is at Parkfield, where the target area is well defined. It is important that adequate resources be made available to keep the Experiment alive and evolving, not placed in mothballs.

Long-Term Aspects of the Project

Commitment for Long-Term Management

There has been an apparent lack of commitment by the USGS for long-term management and identification of importance for the Parkfield project. The project has included

several Project Chiefs whose terms have been less than that of their corresponding USGS Branch Chiefs, with some in that position for as little as one year. The Experiment is sufficiently important that it deserves a commitment by the USGS for a long-term management team with the requirement that those individuals become totally familiar with the objectives and results, and have a good working relationship with participants. A Parkfield Project Chief should remain in that position for sufficient time to be able to make critical decisions based on a broad experience of observations and predictive models. Further she/he should have the status of major contributor of the NEHRP program and be involved in its planning and implementation.

Acquisition of Land Rights at Parkfield

There is apparently a problem with long-term rights of access to instrumentation sites at Parkfield. We believe that the importance of this experiment merits a cooperative commitment from federal, state, and county officials to assure land accessibility and that an effort should be made with private land owners to gain long-term commitments and accessibility. This aspect of the project would be enhanced by a local coordinating committee with members from the Parkfield community. This may require consideration of the instrumentation sites as designated land within a state or federal easement program, as a national earthquake study area, or other designated scientific establishment similar to the Stanford Linear Accelerator, the Superconducting Super-Collider site, etc.

Reassess Project Periodically to Modify, Upgrade and Acquire New Equipment

The scientific objectives of the Parkfield experiment are now reasonably well supported with modern instrumentation. It is imperative that these instruments, particularly the strain meters, be maintained, upgraded, and replaced when they fail. In addition, there are some methodologies that deserve additional consideration at Parkfield:

Broad Band Seismological Studies – An important issue is that there is only one broad-band, continuously recording system at Parkfield, installed in late 1991; it is not apparent to the Working Group how data from this instrument are used by those involved in the Parkfield Experiment. In the past few years, broad-band seismic data, 50 Hz to 0.03 Hz, recorded on wide-dynamic range digital recorders (either on site or via digital transmission) have been shown to be very useful for retrieving source and transmission properties of moderate to large earthquakes. In the recent earthquake for which the “A”-level alert was issued, broad-band techniques could have been used to rapidly obtain accurate source properties (e.g., rupture geometry, time and space properties, relationships to geometrical features of the proposed nucleation site at Middle Mountain, etc.). The Committee was unaware of to what extent, and how rapidly, broad-band data had been used in evaluating this event.

With the availability of new wide dynamic range broad band seismometers (such as Guralps, Streckheisens or equivalent) and 24-bit recording for example with RefTeks, there is a wealth of new information that can be gained by large dynamic range-wide band technology. For example, attenuation (weak vs. strong ground motion) over broad ranges of magnitudes and distances, source properties of small to moderate events, and accurate foreshock and aftershock assessment may yield important information on earthquake precursors. We suggest that a component of wide-dynamic range broad band coverage of the Parkfield area be implemented.

While real-time recording is perceived as costly to some, modern seismological instrumentation has been designed for on-line recording and is standard throughout the world's seismological community. These data would cost the same, if not more, if they were recorded on site or at Menlo Park in a time-delay mode. Moreover, if they were recorded on-site and transmitted to Menlo Park, then the timely nature of the data would be negated for warnings and alert. We suggest that real-time recording of seismological and related high sample-rate data be continued.

Parkfield Network Calibration – A general problem common to most short period seismic networks, including CALNET and hence Parkfield, is the lack of a systematic absolute calibration of the complete seismometer-recording systems for true ground motion. The USGS indicates that calibration pulses are recorded daily on the short period seismometers, but in reality little is done with the calibration data. The short period seismometers are calibrated only when they are brought to Menlo Park for bench tests where they can be absolutely calibrated (presumably very infrequently, *i.e.*, every few years). If there is a large earthquake at Parkfield and the short period instruments have not been calibrated accurately, a major source of information, namely accurate ground motions (for the on-scale events for even small to moderate events), will be lost. This information is especially useful for assessing large ground motions and attenuation.

Network and other instrument calibrations should become part of the Parkfield archive accessible to all users. Additional information in a data base should include a history of each station, model numbers of components, maps of station locations, instrument modifications, calibration constants, etc. The public must be assured that the data acquired from this and any similar project are validated.

Paleoseismicity – The basic premise of the Parkfield experiment is the recurrence of “characteristic” $M \sim 6$ events. However, because there is little trenching information in the Parkfield area (in part due to geography and other logistical problems) the long-term Holocene record has not been evaluated. Thus, we do not know if the typical event size and recurrence interval assumed from the six historic events also dominates the longer-term seismic patterns. For example, if paleoseismological studies revealed the presence of larger events, this would change our view of the typical Parkfield event. This information is crucial for making statistical as-

sessments of earthquake probability and for evaluating the characteristic earthquake model. Some studies have been carried out addressing the feasibility of trenching near Parkfield. These studies need to be documented and critically assessed.

Assessments of Costs and Productivity of the Experiment

The Experiment should continue to evolve, and external review should be part of this process. We suggest that the project be reviewed periodically by a panel of independent scientists. An annual report, discussing productivity and cost, should be prepared and submitted to this panel. The report should contain a summary of the scientific and emergency response aspects of the project, as well as a listing of products (reports, catalogs, data archives, papers, presentations, etc.) supported in part or totally by the Parkfield experiment. This part of the report should be presented at a national meeting such as the AGU or SSA, with consideration of publication in a journal such as *Eos*, to inform the community of the status of the project.

An accurate assessment of the cost of the Parkfield experiments should be included in the report to the panel, assessing individual project costs and related salaries. A review of funds for USGS employees and contract employees should be scrutinized and the USGS management should ensure that funds for the Parkfield project are expended according to their intended use. Equipment acquisitions should be listed and a comparison of operating costs of the network and other systems should be made and reported periodically to the review panel. Further, the report should provide a list of instruments or projects that were considered each year for implementation, continuation, or deletion.

Recommendations for Future USGS Response Efforts

Strengthen the USGS Response Role

The USGS should recognize and provide support for the Experiment as a scientific experiment in the broader integrated context of an actual public policy activity. In general, the USGS must recognize the importance of developing written plans to provide the scientific and public information support that is needed during all stages of public alerts. The USGS should also consider institutional recognition for scientists who are committed to devoting portions of their careers to public policy and education without jeopardizing potential career advancement. The USGS should consider formal and institutional recognition of the important public policy role that scientists can play for all phases of natural hazards prediction and response.

The USGS should establish a formal protocol describing agency functions and personnel functions required to adequately support the media, the state and local governments, and the emergency management community, after issuing earthquake predictions. This protocol should be written in

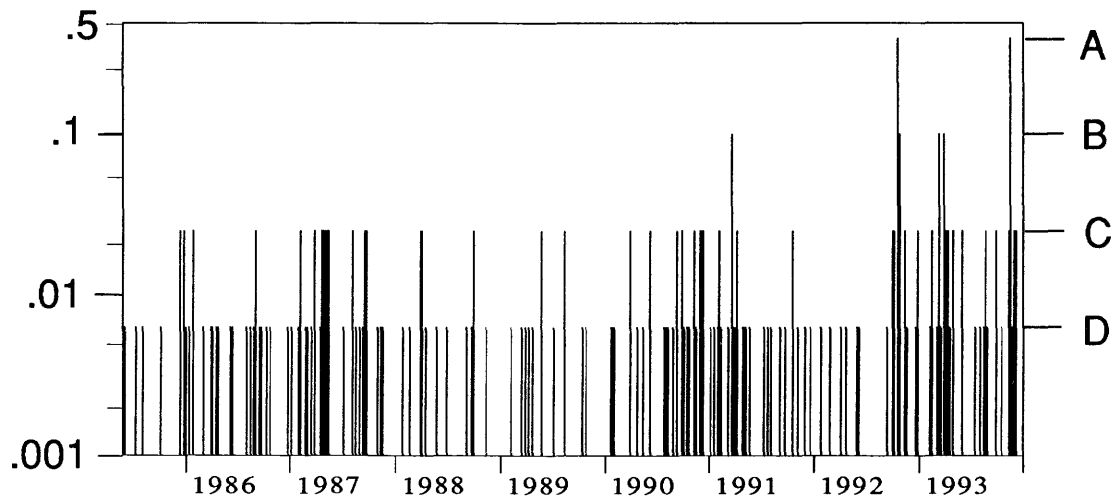


Figure 10. The time of Parkfield status level, D through A, and their corresponding 72 hour probability of a M 6 earthquake are shown for period from the start of the experiment in 1985 through 1993. Although this report described a single A-level alert in late 1992, the experiment went to its second A-level in November 1993. The 72 hour probability for each status level is discussed in Parkfield Earthquake Prediction Response Plan [1988].

the form of a *Standard Operating Procedure* which describes the tasks to be performed by dedicated USGS personnel during earthquake alerts. The USGS should develop these *Standard Operating Procedures* by querying representatives of the media, state and local governments, and emergency management who depend on earth science information during alert periods. In the case of Parkfield, the USGS should be committed, as an institution, to preparing for an "A"-level alert. To date, the USGS has relied on individual scientists to provide a presence and continuity for interaction with state and local government officials. Even though individual Parkfield scientists have had a continuous commitment to providing earth science information to the media, the USGS was unable to provide adequate representation to address media questions regarding the prediction during the "A"-level alert.

The USGS has strengthened its response role since the October, 1992 "A"-level alert by recognizing that the Parkfield Chief Scientist, Project Chief, and the Public Information Officer roles must be adequately covered by three scientists rather than one scientist, as has been the case for most of the duration of the Experiment. The Parkfield scientists at the USGS, Menlo Park, have already implemented this additional coverage of duties at least until the closure of the fiscal year, September 30, 1993. For additional "A"-level alerts, one scientist will run the field laser experiments, one scientist will coordinate the Menlo Park operations, and a three-scientist team will mobilize to Parkfield to provide earth science information to the media.

Review the Threshold Criteria Determining Alert Levels

The USGS should review the probability percentages, which act as threshold criteria for the Experiment alert levels, with respect to the following three concerns:

- 1) the level of accuracy and the statistical uncertainty associated with these probability percentages;

- 2) the effect of "false alarms" on the credibility of the earthquake prediction process; and
- 3) the appropriate actions for the public and response community as reflected by these probability percentages and alert levels.

An "A"-level alert for the Experiment has been assigned a 37% probability for the occurrence of an earthquake of $M \sim 6$ within 72 hours. The public and the media infer that the accuracy of this percentage is very high, reasoning that it has not been stated as, *e.g.*, 36% or 38%. Since the uncertainty in this estimate is much larger than the reliability associated with a probability expressed to two significant digits, the scientists are implying to the public unrealistic accuracy. This leads to the misperception that scientists believe their probabilities to be more accurate than they are.

There is also a problem in the public perception of the Experiment created by the highest level alert – the "A"-level alert. The alert scale is saturated at a low probability level. It is easy (albeit incorrect) to associate the highest available alert level with a high absolute level of probability and the need for media attention. When the expected event does not follow the posting of the highest available alert level (as should usually be the case for the alert levels as defined), the alert is easy to perceive as a false alarm. Will the frequency of *perceived* false alarms associated with future alerts diminish the intended response and preparedness actions of the public, as well as begin to discredit the scientific credibility of the earthquake prediction process? The false alarm rate needs to be more fully understood by local governments and the public. Perhaps the most straightforward remedy would be to define a new alert scale, *e.g.*, I – V, with the current "A"-level assigned level II. (Level I might be triggered, for example, by the "early warning" system under study.) Although this is more of a public relations issue than a science issue, public relations are an important aspect of the Experiment.

An "A"-level alert results in notification of the state and local governments and the public, and triggers response agency mobilization. Are the public and response actions appropriate? Should future notification and mobilization be triggered at higher probability percentages to minimize false alarms and justify mobilization? For example, should an "A"-level alert be the basis for canceling employees' leave, or lead to the evacuation of hazardous buildings for one week? Are the social, economic, and political impacts appropriate? The USGS must work closely with state and local governments and private industry to review and possibly devise alert levels which are sensitive to the actions that the alerts inspire.

Fund Understanding of Societal Impacts of False Alarms

Repeated future alerts at Parkfield, which result in perceived false alarms, could have a negative "cry wolf" effect on the public. Since the Experiment will continue to teach us about the impact of perceived false alarms on the public, funding should be provided by some agency to determine the societal impact of false alarms. The societal impact of earthquake prediction and associated public alerts also includes unknown political and economic consequences. California OES believes that emergency managers still have a great deal to learn about the implications of "A"-level alerts in terms of what occurs as the public and emergency management goes through these cycles.

Improve Communication of the Hazard Potential to the Public

The USGS should support studying how to most effectively communicate the predicted earthquake hazard to the potentially affected population, as well as to populations located beyond the area of concern. During the "A"-level alert, some people who were unfamiliar with the Experiment and located long distances from Parkfield became unduly concerned for their safety. The alert stirred some to call for a shut down of Diablo Canyon nuclear power plant, located 50 miles southwest of Parkfield. Residents were concerned as far away as San Francisco. The OES *Earthquake Safety Information Center Hotline*, located in Pasadena, received numerous calls from residents in southern California counties. During alerts, the message to the public might also include appropriate warning and preparedness information to those located beyond the areas likely to be affected. Since there is virtually no part of California that is immune to earthquake damage, the public needs to receive the message that they can reduce potential damage from future earthquakes by mitigating risk and that they cannot "go to some place where they will be safe from the shaking."

The USGS might convey information using a map format to define areas of expected strong ground shaking and provide damage estimates out to the probable limits of felt ground shaking. Map displays that show where the earthquake will not be felt should be offered to the public



Figure 11. Scientists from the USGS and officials from the California OES met with reporters on the lawn of the Parkfield Cafe for regular briefings during the level-A alerts in October 1992.

as well. The USGS should investigate how to better communicate risk information to the public, the media and local government officials, not just earth science specialists.

Concluding Remarks

Parkfield remains the best identified locale to trap an earthquake. The consensus is that the annual probability for the expected "characteristic" event is about 10% per year. At this level, the Working Group concludes that the Experiment should be continued, both for its geophysical and its public response benefits.

Although this probability is relatively high, it is not so high that we can have confidence that the event will occur on a time-scale of a year or two. Thus the Experiment should be viewed with a long-term perspective. The Experiment should not stagnate: rather it should continue to evolve. This will require adequate resources. In view of the long-term commitment required, consideration should be given to a separate NEHRP funding status. Further, the project should be periodically reviewed for its merits and progress.

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