United States Department of the Interior
Geological Survey

Parkfield, California, Earthquake Prediction Scenarios and Response Plans

W.H. Bakun, K.S. Breckenridge, J. Bredehoeft, R.O. Burford, W.L. Ellsworth

M.J.S. Johnston, L. Jones, A.G. Lindh, C. Mortensen, R.J. Mueller

C.M. Poley, E. Roeloffs, S. Schulz, P. Segall, and W. Thatcher

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U.S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025

Contents

Role of National Earthquake Prediction Evaluation Council in Development of Earthquake Prediction Scenarios and Response Plans for Parkfield Earthquake

For the past 2 years the National Earthquake Prediction Evaluation Council (NEPEC) has been involved in a major review of the earthquake monitoring and the earthquake prediction experiment at Parkfield, in reviewing a long-term prediction that was brought to it by personnel from the U.S. Geological Survey (USGS), in recommending that a long-term prediction be officially declared by the Director of USGS, and in urging that a decision matrix and response plan be developed to increase the chances of a successful short-term prediction for Parkfield.

In November 1984 the Council reviewed both the earthquake experiment at Parkfield and a draft prepared by USGS personnel in which a long-term prediction was made for a future Parkfield shock. (NEPEC uses the term *long-term earthquake prediction* to refer to a time interval of a few years to about 1 decade.) NEPEC concurred with the general aspects of the USGS prediction and recommended to the Director of USGS that a long-term prediction be issued for Parkfield and that the State of California be notified of its findings. (It should be noted that NEPEC reports to the Director of USGS and that the Director is formally charged with the issuance of earthquake predictions in the United States). NEPEC noted that while the next Parkfield earthquake is most likely to be similar in size to the shocks of 1934 and 1966, the possibility exists that a 25 mile (40 km) segment of the San Andreas fault to the southeast of Parkfield may also be sufficiently advanced in its cycle of strain buildup that it could rupture along with the Parkfield segment in an earthquake near magnitude 7. NEPEC recommended that the highest priority be given to the monitoring and prediction experiment at Parkfield. This was the first instance in which NEPEC has recommended that a prediction of any type be made for a future earthquake in the United States.

In early 1985 the State of California asked USGS to give high priority to making a short-term prediction *(i.e., one of hours to days)* for the next major Parkfield earthquake. In July 1985 NEPEC conducted a review of methods that could be used for short-term and intermediate-term prediction at Parkfield and the reliability of various prediction criteria.

NEPEC concluded that any realistic attempts at short-term prediction in the near future in the United States are likely to be of a probabilistic nature and would not be warnings in which there was certainty or near certainty that a physical observation would be followed shortly by a major earthquake. NEPEC also concluded that under some scenarios there could be an abrupt increase in the probability of the earthquake within a few hours, or less, and response to such situations would need to be planned well ahead of time and delegation of authority worked out. It is not a reasonable expectation to involve members of the Council, many of whom do not live in California, in making such an immediate response. At NEPEC's recommendation, a senior USGS scientist (Dr. W.H. Bakun) was appointed USGS project leader for Parkfield in July 1985.

NEPEC also recommended that USGS develop a decision tree or decision matrix document that would describe possible anomalous conditions, estimate probabilities that various anomalies are either followed by earthquakes or associated with false alarms, and designate actions to be taken for various alarm levels. A draft of this document was prepared by USGS personnel and presented to NEPEC in September 1985.

NEPEC strongly endorsed the general concept of the document and recommended it be presented to the Director of USGS. NEPEC further advised that procedures and criteria be developed for ending a prediction, either by specifying a time frame in the initial announcement or by formally retracting the prediction of an event that had not occurred by a certain date. On March 1, 1986, the Council recommended adoption of a revised document and that this document be reviewed at subsequent NEPEC meetings.

It should be remembered that this is the first time that an attempt has been made in the United States to devise a plan for short-term response to measured physical parameters that may be indicative of a future earthquake. The parameters and criteria will undoubtedly need to be changed as experience accumulates at Parkfield and elsewhere. The Council is of the opinion that the science of earthquake prediction, especially short-term prediction, is very much in its infancy. Nevertheless, it believes that a rational case can be made for realistic short-term prediction at Parkfield. The scenarios and response plans might well serve as a model for other areas in the future.

It needs to be recognized that predictions that may result from this effort will be probabilistic in nature. A great effort must be made to educate the public and its officials about the nature of probabilistic estimates, to get them to realize that major uncertainties in knowledge exist in earthquake forecasting, and that no technique that presently exists is capable of being used to predict earthquakes with complete certainty or near certainty.

Parkfield represents an area that is relatively well known and well instrumented. It provides an opportunity to test a number of techniques that might be used in the future for earthquake prediction and to provide data for testing hypotheses about fault mechanics, the earthquake-generating process, and changes that may be precursory to earthquakes.

Lynn R. Sykes
Higgins Professor of Geological Sciences
Chairman, National Earthquake Prediction Evaluation Council

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA 22092

In Reply Refer To:
Mail Stop 905

June 12, 1986

Memorandum

To: Director

Through: Chief Geologist

From: Chief, Office of Earthquakes, Volcanoes, and Engineering

Subject: Parkfield Earthquake Prediction Scenarios and Response Plans

The attached subject report has been reviewed and endorsed by the National Earthquake Prediction Evaluation Council. The Council has agreed to review the report periodically and recommend revisions as the science of earthquake prediction and the conditions at Parkfield evolve.

The most significant aspect of this report is that, under the highest alert level, its adoption will delegate responsibility and authority for notification of State officials to the Chief Scientist of the Parkfield Earthquake Prediction Experiment.

Please indicate below your approval of this report and adoption of the procedures it describes.

John R. Filson

Attachment

Approved:

Dallas L. Peck
Director

June 18, 1986
Date

SUMMARY

A magnitude 6 earthquake is expected to occur along the San Andreas fault near Parkfield, California before 1993. The Parkfield section of the fault is closely monitored by a variety of geophysical techniques as a prototype earthquake prediction network. It is the intention of the U.S. Geological Survey (USGS) to attempt to issue a short-term warning *(minutes-to-days before)* of the anticipated shock based on observations of precursory phenomena recorded by elements of the prototype earthquake prediction network. This report defines the anomalous conditions that would change the assessment of the imminence of the expected earthquake and the action that would be taken by the USGS. Thus, this report is intended as a USGS planning document that describes the conditions culminating in a geologic hazards warning from the USGS to the California Office of Emergency Services (OES). Responsibility for communicating these warnings to the public, to local governments and to the press resides with OES.

Because viable deterministic models *(if A occurs, then B* must *follow)* of the earthquake process are not available, we adopt a probabilistic approach to earthquake prediction. That is, we attempt to assess the increased likelihood of the anticipated shock in the near future given the observation of anomalous conditions *(e.g., increased seismicity)*. Couching warnings in a probabilistic framework explicitly allows for the possibility of warnings not followed in the near future by the anticipated shock. For example, warnings will take the form "*There is a 1 in 5 chance (0.22 probability) that the anticipated magnitude 6 shock will occur in the next 24 hours; the probability of the shock in the next 72 hours is at least 0.37.*"

Four types of observational networks are being operated around Parkfield: seismic, creep, continuous strain, and geodetic survey. The data for each type of network are analyzed continually to determine the state of the region. If the state is anomalous with respect to the normal background condition for any network, then an alert is indicated. If anomalous conditions are observed from more than one network, the level of the alert is increased according to a set of formal rules. Preliminary alert level criteria have been established for each network type.

Seismic alert criteria are based on estimates of the probability that an earthquake is a foreshock to the anticipated magnitude 6 event. The criteria for the other 3 network types are based on how frequently anomalous conditions are expected to occur and subjective estimates of the probability that an anomalous condition will precede a magnitude 6 shock at Parkfield.

We define the following set of alert levels in order of increasing concern and the corresponding USGS response:

Alert Level	Response	Probability of M6 Parkfield earthquake in next 24 (72) hours	Anticipated time interval between alerts
N (normal)	*Continue normal operation*	*0.0001 to 0.0035 (0.0003 to 0.01)*	--
E	*Alert project personnel; possible maintenance*	-----	---
D	*Alert Parkfield Working Group and Data Collection Operations*	*0.0035 to 0.014 (0.0068 to 0.028)*	*2 mo. - 6 mo.*
C	*Alert Office Chief, and the Communications Officer of OES in Sacramento, and respond to Alert Level D*	*0.014 to 0.059 (0.028 to 0.11)*	*6 mo. - 18 mo.*
B	*Alert Director, USGS, and Calif. State Geologist Calif. Div. Mines and Geology (CDMG) and respond to Alert Level C*	*0.059 to 0.22 (0.11 to 0.37)*	*18 mo. - 54 mo.*
A	*Issue Geologic Hazards Warning and respond to Alert Level B*	*> 0.22 (> 0.37)*	*>54 mo.*

The earthquake probability is greatest immediately after the beginning of an alert and generally is expected to decrease with time to the long-term probability of 10^{-4} to 10^{-3} /day appropriate to the normal background. Alerts defined in this report have a finite lifetime of 72 hours after the end of the last signal that exceeded the alert threshold.

Associated with each alert level is an estimated time interval for normal background conditions between alerts *(e.g., 2 to 6 months for* alert level D *and longer than 54 months for* alert level A). These time intervals can be used to estimate the alert rate for a specific criteria for the individual observational networks. However, alerts can arise from several anomalous conditions on any of the observational networks described in this report. Furthermore, nearly simultaneous lower-level alerts can combine to result in a higher-level alert. Thus, more frequent-than-indicated alerts are likely, particularly for the lower alert levels. Establishment of more accurate alert rates will be based on future analyses of the ongoing Parkfield experiment.

We consider level A alerts to be short-term earthquake predictions. Level A alerts not followed within 72 hours by a Parkfield earthquake of about magnitude 6 *(i.e., the anticipated characteristic Parkfield earthquake)* are false alarms. Lower level alerts (B, C, and D) signify periods of heightened earthquake probability, but are not sufficient to warrant an earthquake prediction.

I. INTRODUCTION

The 25-km-long Parkfield section of the San Andreas fault, midway between San Francisco and Los Angeles (see Figure 1), has experienced moderate-size magnitude 6 earthquakes in 1857, 1881, 1901, 1922, 1934, and 1966 *(Bakun and McEvilly, 1984)*. The mean interevent time of 21.8 years, together with the 20+ years that have passed since 1966, suggest that the next shock is now due; estimates of the probability of its occurrence before 1993 range up to 95 per cent *(Bakun and Lindh, 1985)*.

The evidence supporting the long-term *(few years to several years)* prediction of a magnitude 6 shock at Parkfield was independently reviewed and approved by the National Earthquake Prediction Evaluation Council *(Shearer, 1985)* and the California Earthquake Prediction Evaluation Council. In a letter (dated April 4, 1985) to William Medegovich, the Director of the Governor of California's Office of Emergency Services (OES), the Director of the U.S. Geological Survey reviewed the earthquake hazard situation at Parkfield and promised to notify OES immediately of any changes in the USGS assessment of the situation at Parkfield. A subsequent analysis of line length changes in geodetic networks spanning the Parkfield section suggests that the strain released in the 1966 shock will most likely be recovered by 1984 to 1989 *(Segall and Harris, 1986)*, providing independent support for the prediction of a magnitude 6 Parkfield shock.

It is the intention of the USGS to attempt to issue a short-term *(minutes-to-days)* warning (a geologic hazards warning) of the anticipated Parkfield shock. The USGS warning will be directed to OES which has the responsibility in California to disseminate hazard warnings to the public, to county and local officials, and to the press. Development of explicit USGS plans for issuing a geologic hazards warning to OES are necessary if effective emergency response plans are to be developed by OES. Coordination of the USGS and OES plans to respond to an enhanced earthquake hazard near Parkfield are essential for maximizing public safety.

The purpose of this report is to define those conditions that would so change our assessment of the earthquake hazard at Parkfield that a geologic hazards warning from the USGS to

OES would be warranted. Emphasis is placed on extreme situations that require decisions within a few hours or less; more gradually developing circumstances will allow time for additional data collection, interpretation, and possibly review by the National Earthquake Prediction Evaluation Council. Our intent here is to provide a means for rapid response to certain anticipated alarming conditions, but we do not intend to limit our responses to just those unusual conditions listed here. If other anomalous alarming conditions arise that were not anticipated in this report, then those conditions would be relayed as rapidly as possible to the Director of the USGS so that a timely **geologic hazards warning** might still be possible.

In the 1970s, earth scientists optimistically assumed that earthquake research would permit the definition of deterministic earthquake processes. That is, if certain earthquake percursors were observed, then scientists would be able to predict with near certainty the subsequent occurrence of damaging earthquakes. However no viable deterministic earthquake model capable of reliable short-term predictions is now available. While deterministic earthquake prediction is not now feasible, it is possible to provide specific information that is useful in reducing earthquake hazards. A statistical treatment of anomalous precursory phenomena allows the development of a probability model for earthquake warnings. Rather than warning that an earthquake will occur in the near future, we revise our estimates of the likelihood that a specific shock will occur in the next few days. Such probabilistic warnings can be the basis of meaningful emergency response measures by state and local officials; development of emergency response plans to earthquake prediction in California assumes that the predictions will be couched in probabilistic rather than deterministic terms. The probabilistic models allow for, and permit estimates of, the frequency of warnings without earthquakes (false alarms).

The USGS, in cooperation with the California Division of Mines and Geology of the California Department of Conservation, operates a prototype earthquake prediction network along the Parkfield section of the San Andreas fault. The prototype network has two purposes: *(1) to attempt a short-term warning of the anticipated Parkfield earthquake; and (2) to identify geologic and geophysical techniques that would be generally useful in earthquake prediction net-*

works elsewhere. Whereas foreshocks and precursory fault creep appear to be significant features of the earthquake process at Parkfield (see the following section), they clearly are not a universal feature of the earthquake process. Thus, while foreshocks and precursory fault creep figure prominently in the Parkfield prediction scenarios described in this report, other techniques must be developed and evaluated to satisfy the second purpose of the prototype network at Parkfield. Thus, we include here descriptions of newer continuous strain and geodetic survey networks that have significant potential for earthquake prediction efforts elsewhere. Because we have little experience with them, these newer networks do not figure prominently in the specific Parkfield prediction scenarios considered in this report. However, in future versions of this document our increased understanding of the character and limitations of the continuous strain and geodetic survey networks likely will be reflected in more reliance on them in specific Parkfield prediction scenarios.

Implicit in this discussion is the admission that we do not yet know how to reliably predict earthquakes. Consequently, the Parkfield prototype earthquake prediction network should be viewed as a concentrated attempt to learn how to predict earthquakes both at Parkfield and in general. As we learn, we anticipate changes and refinements in the prediction scenarios described herein. These changes and refinements will be described in subsequent updated versions of this report. (This report is in fact a revision of *USGS Open-File Report 86-365*.)

II. HISTORICAL PRECURSORS AT PARKFIELD

Available evidence *(Bakun and McEvilly, 1984)* is consistent with the hypothesis that the five historic Parkfield main shocks were similar, suggesting that the Parkfield section is characterized by recurring earthquakes with predictable features. The hypothesis of a characteristic earthquake means that the design of a prediction experiment can be tailored to the specific features of the recurring characteristic earthquake. We rely primarily on evidence of changes in seismicity before the 1934 and 1966 Parkfield earthquakes and possible creep *(aseismic slip)* anomalies before the 1966 shock as a guide to potential precursors to the upcoming quake.

A. **Seismicity.** The 1934 and 1966 main shocks were each preceded by prominent foreshock activity *(Bakun and McEvilly, 1979)* located in the **preparation zone**, a 2-km-long section of the fault immediately northwest of the common epicenter of the main shocks (Figure 2). In both 1934 and 1966 the foreshock activity included a magnitude 5.1 shock 17 minutes before the main shock. (There were no foreshocks larger than magnitude 4-1/2 in 1922 and no foreshocks were reported felt in 1881, 1901, or 1922). In 1934 fifteen magnitude 3 and larger foreshocks, including two of magnitude 5.0-5.1, occurred in the 67 hours before the main shock *(Wilson, 1936)*. In 1966 three magnitude 3 and larger foreshocks occurred, including the one with magnitude 5.1, all in the 3 hours before the 1966 main shock *(McEvilly et al., 1967)*.

B. **Fault Creep.** Although there were no instruments operating near Parkfield capable of resolving short-term precursory deformation before the historic Parkfield shocks, there were anecdotal accounts of changes in 1966 consistent with significant aseismic slip on the Parkfield section of the San Andreas fault *(Brown et al., 1967)*. First, an irrigation pipeline that crosses the fault trace 5 km south of Parkfield broke about 9 hours before the 1966 main shock. The magnitude of the slip immediately preceding the main shock is unknown. Second, fresh-appearing *en echelon* cracks were observed along the fault trace near Parkfield twelve days before the 1966 shock. If tectonic in origin, these cracks imply 1-to-2 cm of aseismic slip within the three months preceding the main shock. It has been suggested, however, that the cracks were related to desiccation and were not tectonic in origin.

III. POTENTIAL FOR PRECURSORY DEFORMATION

Some theoretical and laboratory models of faulting predict accelerating deformation before the slip instability that constitutes an earthquake. The magnitude and character of the precursory deformation, the time scale of the process, and the dimensions of the fault zone involved in the deformation are major unknowns. While there are an infinite variety of possible precursory scenarios, it is possible to delineate end member cases consistent with what is known about previous Parkfield earthquakes.

A favorable scenario for prediction might involve significant amounts of accelerating fault slip extending over the entire eventual rupture surface for weeks to days before the earthquake. This would be revealed by foreshocks in the hypocentral region, accelerating surface fault creep, and changes in the local strain field. The large magnitude, extent, and time scale of such a precursory process would permit detection with current instrumentation.

A much less favorable scenario for prediction might involve a limited amount of preseismic deformation localized to a small section of the fault at depth near the expected main shock hypocenter. Such a process might be manifest solely by small foreshocks with low-level strain changes that would be difficult to measure and interpret with existing instrumentation. These examples emphasize the uncertainties involved in formulating precursory scenarios without a widely accepted physical model of the failure process.

IV. SUMMARY OF CURRENT INSTRUMENTATION

The current instrumentation at Parkfield (Figure 3) is divided into four networks: *(1) seismic, (2) creep, (3) continuous strain, and (4) geodetic survey.* Data from these networks will provide valuable information about the earthquake process even if a short-term warning of the anticipated Parkfield shock is not possible. Note that we restrict our attention in this report to established instrumentation for which there is a history of reliable observations; we do not consider here suggested precursors *(e.g., radon concentrations and animal behavior)* that are too poorly understood to be of use in predicting the next Parkfield earthquake.

A. **Seismic.** The seismic instrumentation (Figure 4) consists of seismographs and force-balance accelerometers (FBA) of the USGS Central California seismic network (CALNET), the borehole seismographs operated in cooperation with P. Malin of the University of California at Santa Barbara (UCSB), the strong-motion accelerograph array operated by the California Division of Mines and Geology (CDMG), and the FBA and seismometers recorded on GEOS (a broad-band, high-dynamic-range recording system).

CALNET: There are currently 18 high-gain, short-period, vertical-component (Z) seismometers located within 25 km of the town of Parkfield; seven of these sites have 2 or 3 additional components.

CALNET Site	Component	Location relative to Parkfield
Antelope Grade (PAG)	*Z*	*23.4 km S39°E*
Castle Mtn. (PCA)	*Z*	*9.8 km N62°E*
Curry Mtn. (PCR)	*Z*	*23.8 km N TRUE*
Gold Hill (PGH)	*Z*	*11.9 km S43°E*
Harlan Ranch (PHA)	*Z*	*8.4 km S21°E*
Hog Canyon (PHO)	*Z + low-gain 3 comps*	*6.3 km S49°W*
Hope Ranch (PHP)	*Z + 2 horiz comps*	*19.6 km N61°W*
McMillan Canyon (PMC)	*Z + low-gain 3 comps*	*21.7 km S18°E*
Middle Mtn. (PMM)	*Z + 2 horiz comps*	*9.8 km N43°W*
Maxie Ranch (PMR)	*Z*	*23.8 km S52°E*
Portuguese Canyon (PPC)	*Z + 2 horiz comps*	*17.5 km N69°W*
Parkfield (PPF)	*Z*	*2.8 km S34°E*
Smith Mtn. (PSM)	*Z*	*26.6 km N39°W*
Scobie Ranch (PSR)	*Z*	*16.1 km S72°E*
Stockdale Mtn. (PST)	*Z*	*9.1 km N67°W*
Turkey Flat (PTF)	*Z + 2 horiz comps*	*2.1 km S71°E*
Vineyard Canyon (PVC)	*Z + 2 horiz comps*	*10.6 km N42°W*
Work Ranch (PWK)	*Z*	*13.3 km S38°W*

This array permits routine location of M>0.8 events along the Parkfield section of the San Andreas fault from data continuously telemetered to the USGS offices in Menlo Park. The Menlo Park real-time processor (RTP) provides estimates of earthquake locations and magnitudes within 3-5 minutes of their occurrence *(Allen, 1978)*. The seismic network is well suited to the detection of potential M>1 foreshocks at Parkfield.

Telemetered Force-Balance Accelerometers: There are 7 telemetered (3-component) FBA located within 10 km of the fault trace along the Parkfield and Cholame sections of the San Andreas. An additional 6 telemetered FBA are planned, for a total of 13 telemetered FBA near Parkfield.

Telemetered FBA	Date Installed	Clipping Level	Location Relative to Parkfield
Antelope Grade	*11/86*	±2 *g*	*23.4 km S39°E*
Car Hill	*9/86*	±2 *g*	*1.4 km S8°E*
Gold Hill	*11/86*	±2 *g*	*11.9 km S43°E*
Hog Canyon	*10/86*	±1 *g*	*6.3 km N49°W*
Joaquin Canyon	--	±1 *g*	*4.9 km N2°E*
Middle Mtn.	*9/86*	±2 *g*	*9.8 km N43°W*
Palo Prieto Pass	--	±2 *g*	*36.4 km S38°E*
Reason Mtn.	--	±1 *g*	*13.3 km N20°W*
Scobie Ranch	*12/86*	±1 *g*	*16.1 km S71°E*
Simmler	--	±2 *g*	*87.0 km S31°E*
Smith Mtn.	*12/86*	±1 *g*	*26.6 km N39°W*
Stockdale Mtn.	--	±1 *g*	*17.5 km N59°W*
White Canyon	--	±1 *g*	*21.7 km S26°E*

The outputs of these FBA are telemetered to Menlo Park using the procedures developed for the CALNET. The outputs are then processed in a RTP II unit. The RTP II is in development so that the full capabilities of the telemetered FBA are not yet available. The purpose of these FBA is to provide a means to establish rapidly the location and magnitude of large (M > 3-1/2) potential Parkfield foreshocks. The high gain CALNET stations saturate at about M 2-1/2 at distances less than 50 km. Rapid estimates of location and magnitude for potential Parkfield foreshocks are necessary to implement the A and B seismic alert levels defined in this report.

Borehole Seismograph Network: Eight 3-component borehole seismometers *(Malin, 1985)* have been installed at Parkfield. The borehole seismographs are currently in the test/evaluation phase; For M > 0 shocks in the Parkfield area, they should provide high-gain high-frequency seismic information not obtainable from the CALNET systems. A digital radio telemetry system *(500 samples/second, 16 bit resolution)* operated in cooperation with the University of California, Berkeley, (UCB) is used to record the borehole seismographs at a central site near Car Hill (Figure 4).

Borehole Seismometer Site	Installation Date	Depth (feet)	Location Relative to Parkfield
Gold Hill	*Apr 1986*	*205*	*10.5 km S48°E*
	(1983-Apr 1986)	*(605)*	
Joaquin North	*Apr-May 1985*	*735*	*4.9 km N2°E*
Vineyard Canyon	*Apr-May 1985*	*655*	*10.6 km N42°W*
Eades	*Nov-Dec 1986*	*805*	*1.0 km S65°E*
Middle Mtn.	*Nov-Dec 1986*	*720*	*9.8 km N43°W*
Stockdale Mtn.	*Nov-Dec 1986*	*925*	*17.5 km N59°W*
Froelich	*Nov-Dec 1986*	*930*	*6.0 km N42°W*
Reason Mtn.	*Nov-Dec 1986*	*240*	*13.3 km N20°W*

Strong-Motion Accelerograph Network: Nearly 50 SMA-1 strong-motion accelerographs are operated by CDMG in the Parkfield area *(McJunkin and Shakal, 1983)*. This network is designed to record the details of ground motion during the Parkfield main shock and during any M 4.5 or larger foreshocks or aftershocks. The accelerographs are recorded onsite so that data from the strong-motion network will probably not be useful for prediction of the anticipated M=6 main shock.

Force-Balance Accelerometers and Seismometers recorded on GEOS: The seismic instrumentation described above is designed to record the many microearthquakes that occur in the Parkfield area and the S-wave strong motions of the anticipated mainshock and $M_L \geq 4\text{-}1/2$ aftershocks. These systems, however, do not have the capability to adequately record magnitude 3-4 shocks or the complete P-wave motions from larger shocks. For these reasons, an array of GEOS-recorded *(Borcherdt et al., 1985)* FBA and seismometer sensors are installed near Parkfield. Five of these sites are operational; an additional five installations are planned. The GEOS records 6 channels of data at 200 samples/second each channel with 16-bit resolution.

FBA, Seism. on GEOS	Date Installed	Location Relative to Parkfield
Eades	*12/86*	*1.0 km S65°E*
Gold Hill	*8/85*	*10.5 km S48°E*
Antelope Grade	--	*23.4 km S39°E*
Joaquin Canyon	*8/85*	*4.9 km N2°E*
Middle Mtn.	*12/86*	*9.8 km N43°W*
Reason Mtn.	--	*13.3 km N20°W*
Stockdale Mtn.	--	*17.5 km N59°W*
Vineyard Canyon	*8/85*	*10.6 km N42°W*
White Canyon	--	*21.7 km S26°E*
Work Ranch	--	*13.3 km S38°W*

The data recorded on the GEOS system are intended to provide high-resolution recording of the details of significant foreshocks and also provide P-wave signals for the Parkfield main shock. These data will not be available until well after the earthquake and thus are not likely to contribute to any short-term warning.

B. **Creep.** There are 10 creepmeters *(Schulz et al., 1982)* that are located in the Parkfield area (Figure 5).

Creepmeter Site	Date Installed	Location (along fault) Relative to Parkfield
Slack Canyon (XSC1)	*6/05/69*	*25.2 km NW*
Middle Mtn. (XMM1)	*9/26/79*	*9.3 km NW*
Middle Ridge (XMD1)	*7/25/86*	*7.0 km NW*
Parkfield (XPK1)	*9/26/79*	*1.0 km NW*
Taylor Ranch (XTA1)	*10/04/85*	*1.0 km SE*
Durham Ranch (XDR2)	*7/15/69*	*1.8 km SE*
Work Ranch (WKR1)	*9/24/76*	*5.9 km SE*
Carr Ranch (CRR1)	*7/04/66*	*10.2 km SE*
Gold Hill (XGH1)	*7/15/69*	*11.0 km SE*
Hwy. 46 South (X461)	*8/22/86*	*24.6 km SE*

The Middle Mtn. creepmeter is located in the epicentral region of past Parkfield main shocks and foreshocks. Eight creepmeters *(XSC1, XMM1, XMD1, XPK1, XTA1, XDR2, XGH1, X461)* are invar-wire instruments with *0.02 mm* resolution, and two *(CRR1, WKR1)* are invar-rod instruments with *0.05 mm* resolution. Creep data are telemetered to Menlo Park every 10 minutes via GOES satellite and telephone telemetry.

C. Continuous Strain.

Dilational Strainmeters. There are 8 Sacks-Evertson borehole volumetric strainmeters (dilatometers) *(Sacks et al., 1971)* located near Parkfield (Figure 6).

Dilatometer Site	Date Installed	Location Relative to Parkfield	Depth
Donnalee	*11/18/86*	*5.0 km N10°E*	*578 ft*
Eades	*7/06/84*	*1.0 km S65°E*	*886 ft*
Froelich	*12/06/86*	*6.0 km N42°W*	*1056 ft*
Gold Hill 1 (GHS1)	*6/06/83*	*10.5 km S48°E*	*385 ft*
Gold Hill 2 (GHS2)	*7/08/83*	*10.5 km S48°E*	*582 ft*
Jack Canyon	*1/18/87*	*28.8 km S43°E*	*552 ft*
Red Hills	*1/19/87*	*34.3 km S32°E*	*751 ft*
Vineyard Canyon	*11/24/86*	*10.6 km N42°W*	*668 ft*

The dilatometers are operated by the USGS in a cooperative effort with the Carnegie Institution of Washington. The resolution of the dilatometers range from 10^{-2} parts per million (PPM) for signals with periods of several weeks to 10^{-5} PPM for much shorter periods. The data are recorded on-site by GEOS at 2 gain levels and also are transmitted once every 10 minutes with digital telemetry via the GOES satellite and on telephone circuits to the low-frequency data computer in Menlo Park.

Tensor Strainmeters. There are 3 tensor strainmeters *(Gladwin, 1984)* operated by the USGS near Parkfield (Figure 6) in a cooperative program with the Physics Department of the University of Queensland. The resolution of the instruments is similar to that of the dilatometers; however, these instruments have the powerful advantage of allowing determination of principal strains, shear strain, directions of maximum shear, areal strain, and various other strain parameters. The data are transmitted with digital telemetry through the GOES satellite to the low frequency data computer in Menlo Park and are also recorded at each field site on a digital printer.

Tensor Strainmeter Site	**Date Installed**	**Location Relative to Parkfield**	**Depth**
Donnalee	*11/08/86*	*5.0 km N10°E*	*570 ft*
Eades	*11/13/86*	*1.0 km S65°E*	*889 ft*
Froelich	*12/07/86*	*6.0 km N42°W*	*777 ft*

Extensometer. A single-component, linear strainmeter *(extensometer) (Johnston et al., 1977)* is sited on the Claussen Ranch *(CLS1)* near Middle Mtn. at the northern end of the rupture zone (Figure 6). Resolution of the extensometer is 0.5 PPM at short periods, unless severe meteorological conditions cause an increase in the noise level. The data are recorded on-site and are also transmitted once every 10 minutes with digital telemetry via the GOES satellite and telephone circuits to the low frequency data computer in Menlo Park.

Tiltmeters. A network of 4 closely-spaced shallow borehole tiltmeters *(Mortensen et al., 1977)* is operated at Gold Hill (Figure 6). These data are also recorded on-site and transmitted every 10 minutes with digital telemetry through the GOES satellite to the low-frequency data computer in Menlo Park. Although the tilts due to earth tides are coherent between sites, the long-term tilts are not and reflect long-term instability in the near surface materials. The tilt resolution is of the order of 0.1-1 microradians at periods of days and 0.01-0.1 microradians at periods of hours.

Water Wells. Fluctuations in ground-water levels in a network of wells near Parkfield (Figure 7) are being monitored by the USGS Water Resources Division (WRD). In December 1986, 17 wells had been installed at 12 sites. Thirteen wells are completed in relatively deep, confined aquifers, and 4 monitor shallow water-table aquifers. At Middle Mtn. and Joaquin Canyon dual-completion wells monitor 2 separate, confined or semi-confined intervals at each site. In addition, 2 unused stock wells in Hog Canyon are equipped with analog recorders. At sites indicated in the table below with asterisks, water levels are sampled every 15 minutes and accumulated data are transmitted every 4 hours via GOES satellite to the low- frequency data computer in Menlo Park. Data are also transmitted to a WRD computer in Menlo Park via a receiver site in Phoenix. Satellite telemetry from 5 additional sites will be put into operation as rapidly as circumstances permit (probably by 6/87). At periods of 2 weeks or shorter, water levels respond to the local volume strain, so that water level changes can be directly compared to dilatometer data *(Roeloffs and Bredehoeft, 1985).* All of the wells on satellite telemetry record clear earth tides, indicating that their sensitivities at periods on the order of days are at least 0.01 PPM.

Water Well Sites	Location Relative to Parkfield	Depth Intervals Monitored (feet)
**Bourdieu Vly (2 wells)*	*27.6 km N36°W*	*94-97; 918-924*
Cholame Hills	*11.2 km S15°E*	*874-880*
**Flinge Flat*	*9.1 km N67°W*	*300±40-400*
**Gold Hill*	*10.7 km S45°E*	*60-290*
Hog Canyon (2 wells)	*8.8 km S46°W*	*<100*
**Joaquin Canyon (2 wells)*	*2.4 km N3°W*	*35-36; 482-502; 900-906*
**Middle Mtn*	*9.8 km N43°W*	*270-276; 772-810*
Pine Canyon (2 wells)	*8.8 km N29°W*	*584-590; 953-959*
Stockdale Mtn	*9.1 km N67°W*	*938-944; 960-966*
Stone Corral	*16.6 km S53°E*	*784-790; 898-904*
**Turkey Flat (2 wells)*	*5.3 km S80°E*	*101-104; 500-580*
**Vineyard Canyon (2 wells)*	*9.6 km N84°W*	*150-151; 528-548*
White Canyon	*21.7 km S26°E*	*782-788*

Differential Magnetometers. Local magnetic fields are monitored with absolute total field magnetometers *(Mueller et al., 1981)* at 7 sites in the Parkfield region (Figure 8).

Magnetometer Sites	Installation Date	Location Relative to Parkfield
Varian Ranch (VRRM)	*6/85*	*11.2 km N34°W*
Hog Canyon (HGCM)	*6/85*	*7.1 km N39°W*
Lang Canyon (LGCM)	*7/76*	*4.0 km N86°W*
Turkey Flat (TFLM)	*6/85*	*5.8 km S44°E*
Gold Hill (GDHM)	*7/76*	*11.8 km S39°E*
Antelope Grade (AGDM)	*7/76*	*23.4 km S39°E*
Grant Ranch (GRAM)	*3/80*	*41.0 km S35°E*

The data are synchronized to within 1.0 second and are transmitted with 16-bit digital telemetry through the GOES satellite to Menlo Park. The measurement precision in the period range 10 minutes to tens of days is about 0.2 to 0.7 nT, respectively. Changes of 1.0 nT corresponding to stress changes of several bars, according to current models, can be detected with the present instrumentation at periods greater than a day.

D. **Geodetic Survey.** There are several dense geodetic networks, both trilateration and leveling, in the Parkfield region.

Two-Color Laser Geodimeter Network: A distance-ranging network employing an observatory-based two-color geodimeter (Figure 9) was deployed in 1984 by the Cooperative Institution for Research in the Environmental Sciences (CIRES) of the University of Colorado and is operated through a joint USGS/CIRES program *(Slater and Burford, 1985).* The network currently consists of 18 baselines distributed radially around the central instrument site, which is located at Car Hill just south of Parkfield. Under optimal conditions the network can be measured nightly but is typically measured 2-3 times/week, weather conditions permitting. Typical standard errors of individual line length measurements are 0.5-0.7 mm for 4-6 km long lines.

Eleven of the lines (marked by * in the following table) were installed and the lengths measured by October 1984. The full 18-line network was completed with installation of station *BUCK* on July 31, 1986.

Permanent Two-Color Reflector Sites	Measurements Started	Location Relative to Car Hill Laser Source	Average Extension Rate mm/yr
**CAN*	*10/09/84*	*5.7 km N03°W*	*-10.06±0.07*
NORM	*11/14/85*	*1.1 km N45°E*	*-2.45±0.08*
**TABLE*	*10/09/84*	*6.2 km N69°E*	*+9.26±0.08*
HUNT	*07/28/85*	*2.7 km S72°E*	*+6.17±0.07*
**MEL-S*	*10/14/84*	*5.4 km S68°E*	*+7.02±0.08*
FLAT	*09/25/85*	*1.8 km S60°E*	*+8.00±0.08*
GOLD	*04/18/86*	*9.2 km S49°E*	*+8.07±0.47*
**CREEK*	*06/27/84*	*5.7 km S36°E*	*+0.51±0.06*
**MASONW*	*06/26/84*	*6.3 km S11°W*	*-0.93±0.06*
TODD	*08/07/85*	*3.7 km S15°W*	*+1.22±0.12*
**HOG-S*	*07/25/84*	*5.0 km S62°W*	*+1.93±0.05*
**LANG*	*07/25/84*	*4.1 km N72°W*	*+2.32±0.05*
POMO	*04/29/86*	*5.6 km N51°W*	*+10.60±0.30*
**PITT*	*10/09/84*	*5.7 km N47°W*	*-0.17±0.14*
**MID*	*08/23/84*	*5.0 km N43°W*	*-0.61±0.06*
**MID-E*	*08/21/84*	*4.5 km N35°W*	*-12.61±0.05*
BUCK	*07/31/86*	*3.1 km N32°W*	*-15.25±0.35*
**BARE*	*10/09/84*	*4.8 km N12°W*	*-11.59±0.06*

Portable Two-Color Laser Geodimeter Network: A distance-ranging network consisting of 20 baselines (Figure 9) that span the Middle Mtn. section of the San Andreas fault is now resurveyed periodically. Precision of these measurements is 0.2 PPM of the baseline length. Measurements commenced in late August 1986 and are expected to be repeated 3-4 times per year, weather permitting. Data from this network provide a measure of surface and shallow slip near the preparation zone. The network features two instrument stations: *LIME* which is located on Middle Mtn. just east of the active fault trace, and *PIG* which is located 2.5 km northeast of the San Andreas fault.

Geodolite Network: A network of 80 geodolite lines *(Segall et al., 1985)* spans the Parkfield region. Standard errors of individual line-length measurements range from 3-7 mm for lines 4-33 km in length. It is anticipated that at least part of the network will be measured annually. Four *monitor* lines near the southern end of the rupture zone will be surveyed quarterly.

Small Aperture Networks. Three small aperture trilateration networks *(Segall et al., 1985)* span the Parkfield section of the San Andreas fault. Standard errors for individual measurements are 4 mm. Thirty-one near-fault lines are scheduled to be surveyed quarterly.

Leveling Network. A network of leveling lines *(Segall et al., 1985)* in the Parkfield region has been periodically resurveyed since 1979. The network consists of 4 lines: a-10-km-long line perpendicular to the fault at Parkfield, a 32-km-long line in the vicinity of Middle Mtn., a 17-km-long line perpendicular to the fault at the southern end of the rupture zone, and a 24-km-long line parallel to the fault line. Short (~ 1 km) sections of these long lines are surveyed 3-4 times/year in a joint effort with UCSB.

V. ALERT THRESHOLDS.

Based on analyses of the historic seismicity at Parkfield, the probability of a characteristic Parkfield earthquake is about 10^{-4} /day. Anomalous signals result in short-term increases in our estimate of the probability and are used to initiate a series of alerts: *e.g., notification of the Parkfield Working Group and other personnel responsible for the operation and maintenance of the data collection systems.* Real-time, or near real-time, processors that respond to predetermined threshold signals activate radio beeper-paging alert systems. In addition, data from all of the monitoring networks described in this report are reviewed frequently so that anomalous signals that are not specified in the design of the beeper alert algorithms might be detected and evaluated.

From reported anomalies before historic Parkfield shocks, it is possible to define conditions that would cause a reassessment of the short-term earthquake potential in the Parkfield region. Observations of foreshocks before the 1934 and the 1966 shocks permit approximate *(i.e., order of magnitude)* estimates of the probability that a given earthquake is a foreshock to a characteristic Parkfield earthquake. Data from the other (non-seismic) networks which have been recently established can only be analyzed in terms of the expected occurrence interval of a range of anomalous signals. Consequently these probabilities are assigned subjectively. There is no sound statistical basis for determining the probabilities that these anomalous conditions would be followed by a characteristic Parkfield earthquake. We attempt to define alert levels that correspond in our best judgment to the following probabilities and/or anticipated time intervals between alerts:

Alert Level	Probability of Shock in Next 24 Hours	Anticipated Time Interval Between Alerts
D	*0.0035 to 0.014*	*2 mo to 6 mo*
C	*0.014 to 0.06*	*6 mo to 18 mo*
B	*0.059 to 0.22*	*18 mo to 54 mo*
A	*>0.22*	*>54 mo.*

The occurrence of anomalous conditions intuitively increases our estimate of the earthquake probability for some short time period. Unless the anomaly continues, or unless other anomalous conditions occur, our estimate of earthquake probability decreases with time back to the pre-anomaly level. That is, the level of concern implicit in the alert has a finite lifetime. Although there is not sufficient data to define these lifetimes empirically, the 67-hour duration of foreshock activity before the 1934 shock *(Wilson, 1936)* suggests that a 3-day (72-hour) lifetime is appropriate. Thus, all alerts revert to the normal N level 72 hours after the last anomalous signal triggering the alert.

The anticipated time interval between alerts in the above table emphasizes that use of any set of probabilistic alert criteria implies the occurrence of alerts not followed by the anticipated Parkfield earthquake. Whereas the rate of alerts for **level D** implies 2 to 6 *inhouse* alerts per year for each criteria for each observation network, the more stringent criteria for **level A** imply a **geologic hazards warning** to OES less frequent than once every 4 to 5 years. Given the Parkfield window of *1988 ±5.2 years*, we expect that the use of the criteria in this report could result in 1 to 2 **geologic hazards warnings** to OES without a magnitude 6 shock if the anticipated shock occurs at the end of the prediction window *(1993)*.

Care should be taken in the use of the anticipated time intervals between alerts. Data are not sufficient to reliably estimate the time interval between alerts for several of the observational networks. Furthermore, the stated anticipated time intervals refer to each criterion for an individual observation network so that the total alert frequency is likely to be significantly greater than indicated, particularly for the lower alert levels.

A. **Seismic.** Seismic signals from the CALNET stations are telemetered to Menlo Park and processed by computer in real time to provide estimates of earthquake locations and magnitudes within 3-5 minutes of their occurrence *(Allen, 1978)*. Alert thresholds that signal unusual Parkfield seismicity activate paging systems that alert the seismologists responsible for surveillance of seismic data at Parkfield. Two criteria are used to define an anomalous seismic condition: *(1) a magnitude 2.5 or larger shock in the Parkfield area* *alert zone, and (2) either a magnitude 1.5 shock, or two magnitude 1.0 shocks within a 72-hour period, in a restricted Middle Mtn. zone that includes the Parkfield preparation zone (Figure 10).* Occurrence of a magnitude 3.5 or larger shock anywhere in central California also activates the beeper-paging system. Based on recent seismicity rates, we expect the automated seismicity alert system to be triggered 3-5 times per year by earthquakes at Parkfield.

The probability that an earthquake near Middle Mtn. will be a foreshock to the characteristic Parkfield earthquake has been calculated based on the following assumptions:

1) The next characteristic Parkfield earthquake is assumed to have a 0.5 chance of having some foreshocks, magnitude unspecified, within the Middle Mtn. alert zone;

2) The probability of any one earthquake within the Middle Mtn. alert zone being the *foreshock, is inversely proportional to the number of such earthquakes that occur per 21.7 year recurrence cycle.*

The resulting conditional probability P_F that the next characteristic Parkfield earthquake will follow an earthquake of magnitude M within the Middle Mtn. alert zone is estimated to be:

$$P_F = P\ [(next\ characteristic\ Parkfield\ eqk)\ |\ (potential\ foreshock\ of\ mag\ M)]$$
$$= 3.1x\,10^{-4}x\,10^{0.62M}$$

P_F is an estimate of the probability of a Parkfield earthquake occurring within the first few days following a potential foreshock of magnitude M.

If we wish to apply this estimate to a specific time interval following a potential foreshock, we must have an estimate of how this probability decays with time. Lindh and Jones *(1985)* showed that probability density functions of the form e^{-at} provided a reasonable fit to the foreshock data of Jones *(1985)* for southern California. Based on this, we have used

$$f(t) = e^{-0.021t}$$

where t is in hours after the potential foreshock. Thus, the probability of a Parkfield main shock occurring between time t_1 and t_2 after a potential foreshock *(given that it has not already occurred by time t_1) is*

$$P_{F,T} = P_F \ x \ (-0.021) \int_{t_1}^{t_2} e^{-0.021t} dt$$

For $t_1 = 0$ and $t_2 = 24$, 48 or 72 hours following a potential foreshock, the integral equals 0.41, 0.65 and 0.79 respectively. Thus, the probability of a characteristic Parkfield earthquake in the 24 hours following a potential foreshock of magnitude M is

$$P_{F,24} = P_F \ x \ 0.41 = 1.27 x 10^{-4} \ x \ 10^{0.62M}$$

In addition, for a current estimate of the total probability at any particular time, some estimate of an increase in background probability as time passes is necessary, as it seems intuitively compelling that the probability increases with time as one approaches or passes the mean recurrence time. Combining the estimate of Bakun and Lindh *(1985)* of 1988.0 ± 5.2 for the next Parkfield event with the long-term conditional probability formulation of Lindh *(1983)*, we obtain an estimate of the daily probability P_R attributable to the long term recurrence model:

$$P_R = 4.1 \ x \ 10^{-4} \ x \ 10^{0.12T}$$

where T is years *after* 1 January 1986.

These numbers can be combined to give a single probability estimate P using the formulation of Utsu *(1979)*:

$$P = \frac{1}{\left[1 + r_o^{-1} r_1 r_2\right]} , \quad where$$

$$r_o = \frac{1}{P_o} - 1,$$

$$r_1 = \frac{1}{P_R} - 1,$$

$$r_2 = \frac{1}{P_F} - 1, \text{ and}$$

$$P_o \text{ (the poisson probability)} = \left[\frac{1}{21.7}\right] x \left[\frac{1}{365}\right] = 1.26x\,10^{-4} \text{ per day.}$$

The resulting total probability estimate for a potential foreshock on 1 January 1986 being followed within 24, 48, and 72 hours by a characteristic Parkfield earthquake are listed below. The total probability for T =24 hours is plotted in Figure 10b as a function of M, the magnitude of the potential foreshock. While these probabilities are quoted to 2 significant figures, they are approximate and somewhat subjective, and are best treated as order of magnitude estimates.

Seismic Alert Level	Seismicity	Estimated Probability of Parkfield Main Shock in First 24 hrs	48 hrs	72 hrs	Anticipated Time Interval Between Alerts
D	*1) One M 1.5 shock in the Middle Mtn. alert zone*	*0.0035*	*0.0056*	*0.0068*	*2-6 mo*
	2) Two or more M 1.0 shocks in a 72-hour period in the Middle Mtn. alert zone				
	3) One M 2.5 shock in the Parkfield alert zone				
	4) One M 3.5 shock in the Parkfield area (San Ardo, Coalinga, etc.)				
C	*1) One M 2.5 shock in the Middle Mtn. alert zone*	*0.014*	*0.023*	*0.028*	*6-18 mo*
	2) Two or more M 1.5 shocks in a 72-hour period in the Middle Mtn. alert zone				
	3) One M 3.5 shock in the Parkfield alert zone				
B	*1) One M 3.5 shock in the Middle Mtn. alert zone*	*0.059*	*0.090*	*0.11*	*18-54 mo*
	2) Two or more M 2.5 shocks in a 72-hour period in the Middle Mtn. alert zone				
A	*1) One M 4.5 in the Middle Mtn. alert zone*	*0.22*	*0.32*	*0.37*	*> 54 mo*
	2) Two or more M 3.5 shocks in a 72-hour period in the Middle Mtn. alert zone				

B. **Creep:** Parkfield-area creepmeters exhibit long-term average creep rates ranging from 23 mm/yr at Slack Canyon to 4 mm/yr at Gold Hill *(Schulz et al., 1982)*. Data from the Parkfield creepmeters are sampled every 10 minutes. The automated anomaly detector compares the average creep at each of the sites in the past hour with the average level in the preceding 23 hours. A change of 0.25 mm or greater activates the paging device. In 1985, 16 beeper-paging alarms were triggered by creep events. Surface measurements of strain are sometimes affected by meteorological conditions so that we anticipate more creep alerts during the rainy season *(October to April)* than during the dry season.

Creep Alert Level	Creep Observations (in the absence of M 3.5 or larger shocks)	Anticipated Time Interval Between Alerts
E	*1) At one site, a right- or left-lateral creep step of >0.25 mm within one 10-minute telemetry sample period. (See Fig. 10a) (In 1984 and 1985 there were at least 6 of these alerts, all due to battery, telemetry, and/or telephone transmission failures).*	*< 4 mo*
	2) At one site, a small right- or left-lateral CREEP EVENT; ie., creep exceeding 0.25 mm within one hour with slip velocity decreasing exponentially within 1-2 hours after onset (See Fig 11b).	*< 2 mo*
D	*1) At any one site other than XSC1, a nearly continuous increase in creep (see Fig 11c) that exceeds 1 mm within 7 days and continues at a comparable or greater rate over a period greater than 10 days. (XSC1 normally moves 0.25-0.5 mm/wk.)*	*< 6 mo*
	2) At any two adjacent sites other than XSC1, nearly simultaneous onset of an almost continuous increase in creep that exceeds 0.5 mm in 24 hours.	
	3) At one site, an unusually large creep event (See Fig 11b). For creepmeters northwest of XDR2 (XSC1, XMM1, XMD1, XPK1, XTA1 and XDR2) events with creep >0.5 mm in the first 30 minutes would be unusually large. For creepmeters southeast of XDR2 (WKR1, CRR1, XGH1 and X461) events with creep >0.33 mm in the first 30 minutes would be unusually large.	
	4) At any one site, a series of closely spaced creep events, with continuous movement greater than 1.5 mm in 3 hours.	
C	*1) Nearly simultaneous onset of creep at two or more creepmeters that exceeds 0.5 mm in one hour.*	*6 mo to 12 mo*
	2) More than 1 mm of creep on the Middle Mtn. creepmeter in one hour.	
B	*1) More than 5 mm of creep in 72 hours on the Middle Mtn. creepmeter with confirming signals of tectonic origin on another network.*	*> 24 mo.*
	2) More than 5 mm of creep in 72 hours on two or more Parkfield area creepmeters.	
A	*1) Creep rates on multiple instruments (or at Middle Mtn. alone with confirming signals of tectonic origin on another network) in excess of 0.5 mm/hour sustained for 6-10 hours or cumulative creep in excess of 5 mm in a shorter period.*	*> 24 mo.*

C. **Continuous Strain:** The sizes of strain anomalies that might precede a Parkfield earthquake can be estimated on the assumption that these anomalies would be produced by aseismic slip on a vertical fault. For example, calculations of the net volumetric strain that would be produced by 5 cm of strike slip over a 100 m-by-100 m area of such a fault show that the maximum volume strain at the surface would be 3.5, 0.03, 2.3×10^{-4}, or 3×10^{-5} PPM if the event were centered at depth of 0.2, 1.0, 5.0, or 10.0 km, respectively. In addition to *strainmeters* specifically designed to measure crustal strain, water levels are classified on an experimental basis as continuous strain instruments.

1. *Strainmeters*. Data from the Parkfield strainmeters are sampled automatically every 10 minutes and the data are transmitted to Menlo Park. For the dilational strain data, average strain for the last 60 minutes is computed. Earth tides and atmospheric pressure loading, determined from a theoretical earth tide model and an on-site pressure transducer, respectively, are removed from the data. Provided the instruments and telemetry are operating correctly, changes in strain of 0.2 PPM over several days *(long term)* or 0.1 PPM at periods less than a day *(short term)* can be clearly detected. Short-term strain changes are detected by an algorithm that identifies strain changes of more than 0.05 PPM in a 24 hour period. Long-term strain changes are detected by an algorithm that identifies changes in strain rate normalized by estimates of noise in the data.

Four long-term alerts have been triggered for strain rate increases of about 0.03 PPM/day for periods of about a week. One of these strain perturbations occurred on a dilatometer at the same time as minor seismicity and a creep event at Middle Mtn. All four long-term strain perturbations were independently recorded and identified in water level data in a well at Gold Hill.

Strainmeter Alert Level	Changes in Strain
E	*Changes of 0.05 PPM or greater within a 24 hour period on one dilatometer. These may occur because of phone line, telemetry, or instrument malfunctions, and generally triggers maintenance response.*
D	*1) Changes of 0.1 PPM/week on 2 dilatometers* *2) Changes of 0.1 PPM within a 24-hour period on 1 dilatometer with indications of simultaneous signal on a second dilatometer*
C	*1) Changes of 0.2 PPM/week on 2 or more independent dilatometers* *2) Changes of 0.2 PPM within a 24-hour period on 1 dilatometer with indications of a simultaneous signal on a second dilatometer*
B	*Give the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant warnings to the Directors of the USGS and CDMG.*
A	*Given the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant a warning to OES.*

2. *Water Wells.* In order to define the network alert levels, the sensitivity of each well is determined based on observed water level change per unit strain associated with the M2 semidiurnal tide. Although sensitivities and noise levels vary among the wells, a value of 0.03 PPM is the smallest dilatation that could be observed if it took place over a few hours. Figures 12a and 12b are contour maps of volumetric strain for slip events having moments of 10^{25} dyne-cm centered at 5 and 10 km depth, respectively. The deeper event is comparable in moment and depth to the 1966 characteristic Parkfield earthquake. Assuming a detection threshold of 0.03 PPM , such an event would have been observable over almost all of the area shown in the contour maps. The area within which an event with ten times smaller moment would have been observed is somewhat reduced; the moment of such an event might be comparable to that of a magnitude 5 foreshock.

Water level changes can be observed in response to dilatational strains imposed with time scales ranging from a few seconds to a few weeks, but the observability of strain events generally decreases with lengthening event time scale. For example, seasonal water level changes mask strain events of amplitude less than about 0.20 PPM that take place over a period of a week. In addition, slow strain events require more time to detect.

Plots of raw and filtered water level data are examined daily. In addition, as water level data are received (every four hours), each water level observation is corrected for barometric pressure variation and compared with a projected water level, which is equal to the previous day's mean water level plus variation due to earth tides. If, at any time, observed and projected water levels differ by an amount representing strain of more than 0.05 PPM, a message is sent alerting personnel to examine the data in order to determine whether an alert should be issued. No alert is issued if visual inspection indicates that the event generating the message is attributable to barometric or rainfall disturbances, or to instrument, telemetry, or software malfunction.

An anomaly could escape detection by the real-time scanner either because it is smaller than the threshold level at which the scanner is set, or because it does not rise to the threshold amplitude within one day, which is the time period after which the reference level for the projected water level is reset. Numerical experiments have delineated a curve of event amplitude versus rise-time constant within which water level events having exponential forms (similar to creep events) could be perceived by visual inspection of filtered data. This curve, which is labeled *detectable* in Figure 13, shows that for events with rise times longer than 2 days, the minimum amplitude that can be detected increases with increasing rise time. Although any event with an amplitude of 0.05 PPM or greater can represent significant slip at depth, only those events in the region indicated in Figure 13 have a high probability of being identified. These events are the ones that will generate alarms, provided they are not ascribable to rainfall, barometer, or equipment problems.

A group of wells located within a 250 m radius of the same point or measurements at two or more depths in the same well, will be considered as a *cluster* that will be treated as a single site for alert purposes. For example, once a water level change at a single well reaches the D **level alert** threshold, anomalies at additional wells in the same cluster would not raise the D **level alert** to a C **level alert**. When a water level change occurs at one well in a cluster, its absence at other sufficiently sensitive wells in the same cluster may constitute evidence that the anomaly is not of tectonic origin, in which case the water level change would not generate an alert.

Water Well Alert Level	Changes in Strain
E	*Event of amplitude greater than 0.05 PPM at one well (See above description of the water well 'real-time' detection algorithm.)*
D	*1) Unexplained event of amplitude greater than 0.05 PPM at one well with rise time less than 24 hours (corresponds to an E level alert that cannot be attributable to rainfall, barometric disturbances, etc.)* *2) Unexplained event at one well with rise time greater than 24 hours and clearly detectable amplitudes (i.e., amplitudes to the right of the 'detectable' curve in Figure 13)*
C	*1) Unexplained events of amplitude greater than 0.05 PPM at two wells, each with rise time less than 24 hours* *2) Unexplained events at two wells with rise time greater than 24 hours and clearly detectable amplitudes (i.e., amplitudes to the right of the 'detectable' curve in Figure 13)*
B	*Given the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant warnings to the Directors of USGS and CDMG.*
A	*Given the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant a warning to OES.*

3. *Differential Magnetic Field.* Magnetic field data are sampled automatically every 10 minutes and transmitted to Menlo Park where they are processed and monitored. To isolate local magnetic field changes, data from adjacent stations are differenced and smoothed by averaging differences over a 3-day window centered on the sample. These averaged, differential magnetic field data are monitored daily and plotted weekly to identify anomalies. Changes greater than 1 nT (nanotesla), at periods greater than a day, are considered anomalous. This has happened only once during 10 years of monitoring and occurred during the months following the May 1983 Coalinga earthquake. Specific alert criteria for levels B and A are not yet available.

Continuous Magnetic Field Alert Level	Changes in Magnetic Field
E	*Changes of 1 nT or greater between station pairs over time periods less than 24 hours. This may occur because of instrument malfunction and/or clock syncronization failure and generally triggers maintenance.*
D	*Changes of 1 nT or more in a day or longer between two instruments. This has occurred only once during the past 5 years in the Parkfield region.*
C	*Changes of 1 nT or greater in a day or longer on two independent instrument pairs. This has not occurred during the past 5 years in the Parkfield region.*
B	*Given the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant warnings to the Directors of USGS and CDMG.*
A	*Given the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant a warning to OES.*

D. *Geodetic Survey.* Distance measurements using the two-color geodimeter are collected 2-3 times/week, weather conditions permitting, so that the resulting data are appropriate for a more slowly developing scenario than that considered in this report. Nevertheless, it is possible to identify some circumstances under which these relatively infrequent discrete measurements would contribute to a rapid reassessment of the Parkfield earthquake hazard. Sufficient data now exist to define specific criteria for alert level **D**; specific criteria for alert levels **A**, **B**, and **C** must be developed as a more complete history of line length changes is obtained. All two-color geodimeter alert criteria are based on apparent length changes that exceed $\pm 2\sigma$, where $\sigma^2 = \sigma_1^2 + \sigma_2^2$ and σ_1 and σ_2 are standard deviations of lengths measured before and after the potential alert. For criteria D(2) and D(3), a *flagged length change* for any line is one that equals or exceeds $\pm 2\sigma$ within the appropriate window length (eg., 2 or more data points) for that line. Appropriate window dimensions (length and height) are determined line-by-line so that the percentage of flagged length changes over the history of length changes for each line falls within a specified range. If the number of flagged length changes exceeded 10% of the total comparisons in the initial test of a particular line, the change threshold (i.e., the window height) was increased for that line to reduce the percentage of flagged data to 10% or less. If less than 2-1/2% of the total comparisons were flagged, the window length (i.e., the number of data points included in the window) was increased so that the percentage of flagged data was at least 2-1/2%. The status for alert criteria D(2) and D(3) is then determined by the total number of flagged length changes that occurred within each possible 4-day-long window for a particular network of lines being tested, as indicated in the accompanying table.

Anom. Line Length Alert Level	Line Length Changes Between Successive Measurements	Anticipated Alert Freq. (time between alerts)
D	*1) Three or more lines with length changes (absolute value) of 3.5 mm each within a time span of 25 days or less, with at least one line changing by 4.0 mm.*	*6-12 mo*
	2) Four or more flagged length changes in a 4-day time span on the 11-line network in operation on 10/14/84 (lines CAN, TABLE, MEL-S, CREEK, MASON-W, HOG-S, LANG, PITT, MID, MID-E, BARE).	*3 mo*
	3) Five or more flagged length changes in a 4-day time span on a 17-line network (all lines except PITT).	*1-2 mo*
C	*Not yet defined.*	
B	*Given the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant warnings to the Directors of USGS and CDMG.*	
A	*Given the lack of experience at Parkfield, at this time there are no clear criteria for anomalies that in the absence of other anomalies would warrant a warning to OES.*	

E. *Alert Thresholds on Multiple Instrument Networks.* Clearly anomalous conditions detected on several networks would increase our concern that a Parkfield earthquake is imminent. Simultaneous alarms can combine to establish a level of concern appropriate to a higher alert threshold. We propose that a set of simple *alert level combination rules* be applied to the alert levels for the individual network groups:

STATUS OF NETWORK ALERT LEVELS *

Rule	Net 1	Net 2	Net 3	Net 4		Combined Alert Level
1)	D	+ N	+ N	+ N	⟶	D
2)	D	+ D	+ D or N	+ D or N	⟶	C
3)	C	+ D or N	+ D or N	+ D or N	⟶	C
4)	C	+ C	+ C,D or N	+ C,D or N	⟶	B
5)	B	+ C,D or N	+ C,D or N	+ C,D or N	⟶	B
6)	B	+ B	+ B,C,D or N	+ B,C,D or N	⟶	A
7)	A	+ A,B,C,D or N	+ A,B,C,D or N	+ A,B,C,D or N	⟶	A

* N = normal condition

To apply these rules, rank the four network groups in decreasing order of current alert level status. For example, if the seismic, creep, continuous strain, and geodetic survey alert levels were C, B, C and D respectively, then creep, seismic, continuous strain, and geodetic survey would be labelled nets 1, 2, 3, and 4, respectively. That is, the networks alert level status would be B, C, C, D, corresponding to combination rule 5. Rule 5 states that one level B, two level C, and one level D alert are *not* sufficient to warrant an alert level A response.

VI. RESPONSE

Project Chief. The responsibility for recognizing the anomalous conditions described in this report resides with the project chiefs of the individual Parkfield earthquake prediction networks. Each project chief has the following specific responsibilities:

1. Maintain a monitor system for the data collected by the project.
2. Maintain an effective detector system capable of detecting the anomalous conditions defined in the previous section.
3. Immediately alert the Chief Scientist and the Chief of the Seismology Branch or Tectonophysics Branch of the USGS of all **A, B, C,** or **D level alerts.**
4. Train and maintain an alternate capable of assuming the above responsibilities.
5. Delegate these responsibilities to the alternate whenever the project chief cannot adequately perform these responsibilities. The Chief Scientist and the appropriate branch chief (Seismology or Tectonophysics) must be notified of this delegation of responsibility.

Chief Scientist. The responsibility for coordinating earthquake prediction efforts at Parkfield resides with the Chief Scientist. The Chief Scientist has the following specific responsibilities.

1. Once alerted by a project chief or their alternate that a **D, C, B,** or **A alert level** has been recognized, the Chief Scientist has the responsibility of notifying the Chiefs of the Seismology and Tectonophysics Branches of the status of the alert levels.
2. After consulting with these branch chiefs and determining the alert level, the Chief Scientist is responsible for notifying the Chief of the Office of Earthquakes, Volcanoes and Engineering whenever an **A, B,** or **C alert level** is reached.
3. For an **A, B,** or **C level alert** the Chief Scientist is responsible for notifying the Office of the Director of OES *(see Appendix B)*

Chiefs, Seismology and Tectonophysics Branches. The branch chiefs have the responsibility for maintaining the personnel and resources within their branches that are necessary to maintain and operate the real-time surveillance and prediction capabilities described in this report. The branch chiefs have the following specific responsibilities:

1 Advise the Chief Scientist regarding the status of alert levels for the 4 network groups whenever a D, C, B, or A **alert level** is recognized by a project chief.

2. For a D, C, B, or A **level alert** notify the appropriate project chiefs of the alert status. The project chiefs to be notified by each branch chief are indicated on the detailed decision flow diagram that follows.

3. For a B or A **level alert**, coordinate the intensive reconnaissance and monitoring efforts described in Appendix A.

4. Serve as an alternate for the Chief Scientist in fulfilling the Chief Scientist's reponsibilities that are described above.

5. Serve as an alternate for the Office Chief in fulfilling the Office Chief's responsibilities that are described below.

Chief, Office of Earthquakes, Volcanoes, and Engineering (OEVE). The Office Chief is responsible for communicating the alert level status to non-USGS OEVE personnel. The Office Chief has the following specific responsibility:

1. Once alerted by the Chief Scientist that a B or A **level alert** has been reached, the Office Chief has the responsibility to notify the Director of the U. S. Geological Survey and the California State Geologist (CDMG).

APPENDIX A.

INTENSIVE MONITORING-RECONNAISSANCE EFFORTS

In the event that a high-level (A or B) alert is initiated, additional efforts at Parkfield are necessary so that the maximum information regarding the generation process of Parkfield earthquakes and information relevant to the imminent occurrence of a large shock on the San Andreas fault can be obtained. Current plans are to undertake the following steps:

1. Alert Chief, Branch of Engineering Seismology and Geology
2. Alert CDMG Manager of strong-motion network at Parkfield
3. Remeasure geodetic baselines established along the San Andreas fault in the Parkfield area and to southeast of the Parkfield section
4. Alert cooperating agencies (University of California at Berkeley, University of California at Santa Barbara, University of Colorado, Carnegie Institute)
5. Verify that telemetry (phone, radio, microwave and satellite) are functional
6. Institute nightly measurements on the two-color geodolite network
7. Measure alignment array networks in the Parkfield region
8. Perform reconnaissance of highways that cross the active traces of the San Andreas fault within and southeast of the rupture zone of the characteristic Parkfield earthquake
9. Establish temporary seismic networks in Parkfield area. (Eg., Install high-gain seismographs at GEOS and strong-motion sites where necessary.)

APPENDIX B.

SAMPLE WARNING MESSAGE

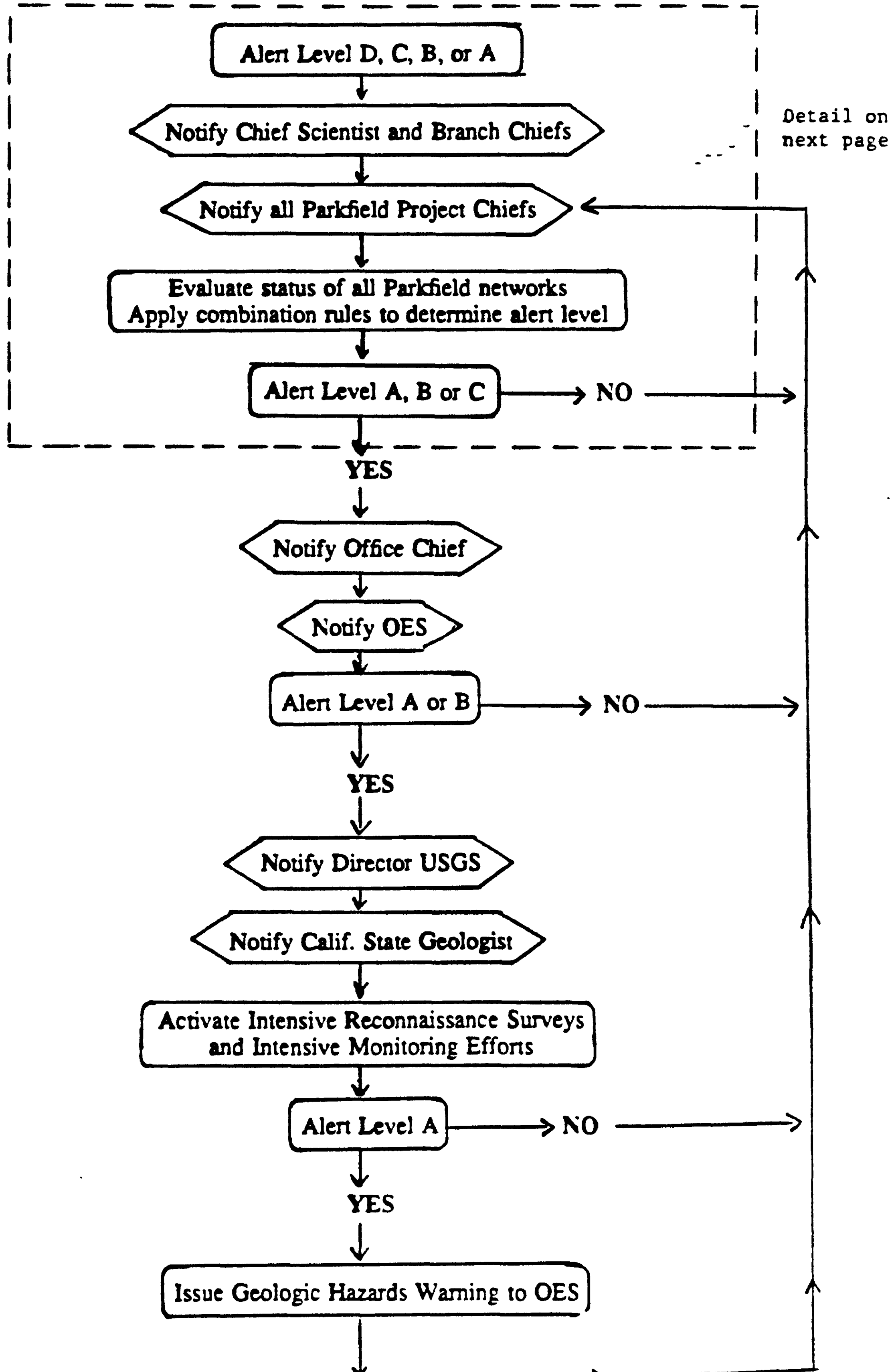
Experience in other fields where public safety is an issue has consistently shown the necessity of clear, complete, unambiguous communication of information to agencies responsible for disseminating warnings to the public and to news media. Agreement by the USGS and OES on the content and format of warnings to OES from the USGS guarantee that the USGS estimates of immediate geologic hazards due to Parkfield earthquakes will be quickly understood and acted upon by OES. When an **A, B,** or **C level alert** is reached, the Chief Scientist will inform by telephone the duty office of the OES communication center in Sacramento that the **alert** *is in force*. In the event of an **A level alert,** the following message will be sent by overnight mail to the director of OES.

> *Recent observations by the U.S. Geological Survey (USGS) along the 25-km-long Parkfield section of the San Andreas fault, midway between San Francisco and Los Angeles, suggest that there is about a 1 in 2 chance that a moderate-size earthquake of about magnitude 6 will occur near Parkfield in the next 72 hours. This warning is based on anomalous signals recorded on geophysical instrument networks operated by the USGS near Parkfield. This period of high likelihood for a magnitude 6 Parkfield earthquake is expected to last 72 hours. Additional anomalous signals recorded in the Parkfield area could extend the warning time period. Any extension of this alert period, and the end of the alert period, will be communicated by the USGS to the Office of Emergency Services.*
>
> *An earthquake of magnitude 6 is of moderate size, at the threshold of being able to cause modest damage to some structures that have not been designed for earthquake resistance. The last magnitude 6 Parkfield earthquake occurred on June 28, 1966 and caused only minor damage to wood frame houses in the region. The potential exists for a shock of about magnitude 7 that would rupture southeast into the adjacent 25-mile section of the San Andreas fault; this larger shock is sufficiently plausible geologically to warrant consideration in emergency planning and response.*

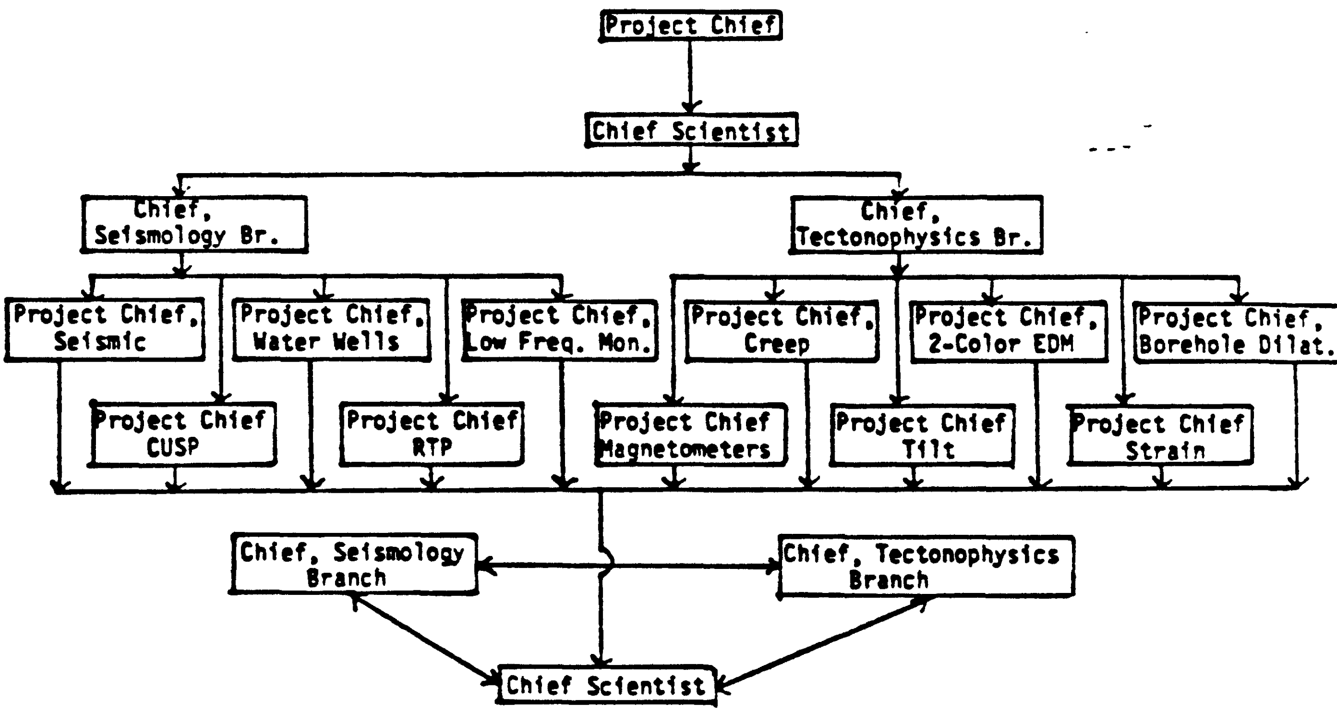
Note that OES has reviewed this message and has used it (and this report) to compose warning messages that will be transmitted at an **A level alert** over OES communication channels to the responsible county and local officials. OES is developing plans to optimize the response of state, county and local governments to the Parkfield earthquake prediction.

Although the USGS will notify OES of B and C alert levels, these notifications and alerts do not constitute an earthquake prediction so that no public warning will be issued and no written warning will be sent to the director of OES.

DECISION FLOW DIAGRAM



DETAIL OF DECISION FLOW DIAGRAM



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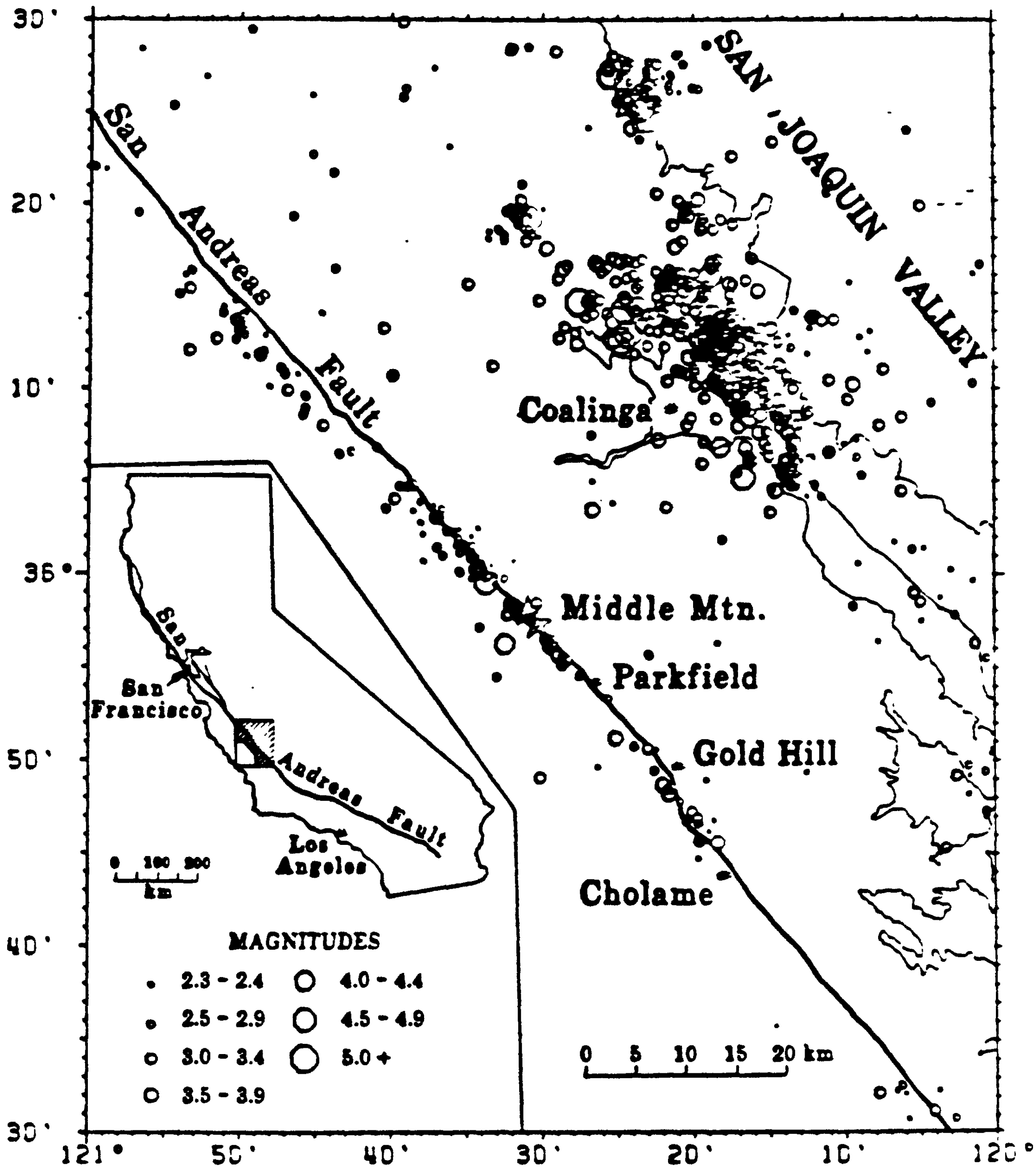


Figure 1. Map of earthquake epicenters (1975 to June 1985) relative to the trace of the San Andreas fault (bold line) and the epicenters of the M=5.1 foreshock and the main shock in 1966 shown as small and large stars respectively. Epicenter clusters near the western edge (faint line) of the San Joaquin Valley are aftershocks of the 1975 Cantua Creek, 1976 Avenal, 1982 New Idria, and 1983 Coalinga earthquakes. Epicenters for all M≥2.3 earthquakes are shown, except for the very many M≥3 aftershocks of the 1983 Coalinga earthquake, which cover the Coalinga area when plotted.

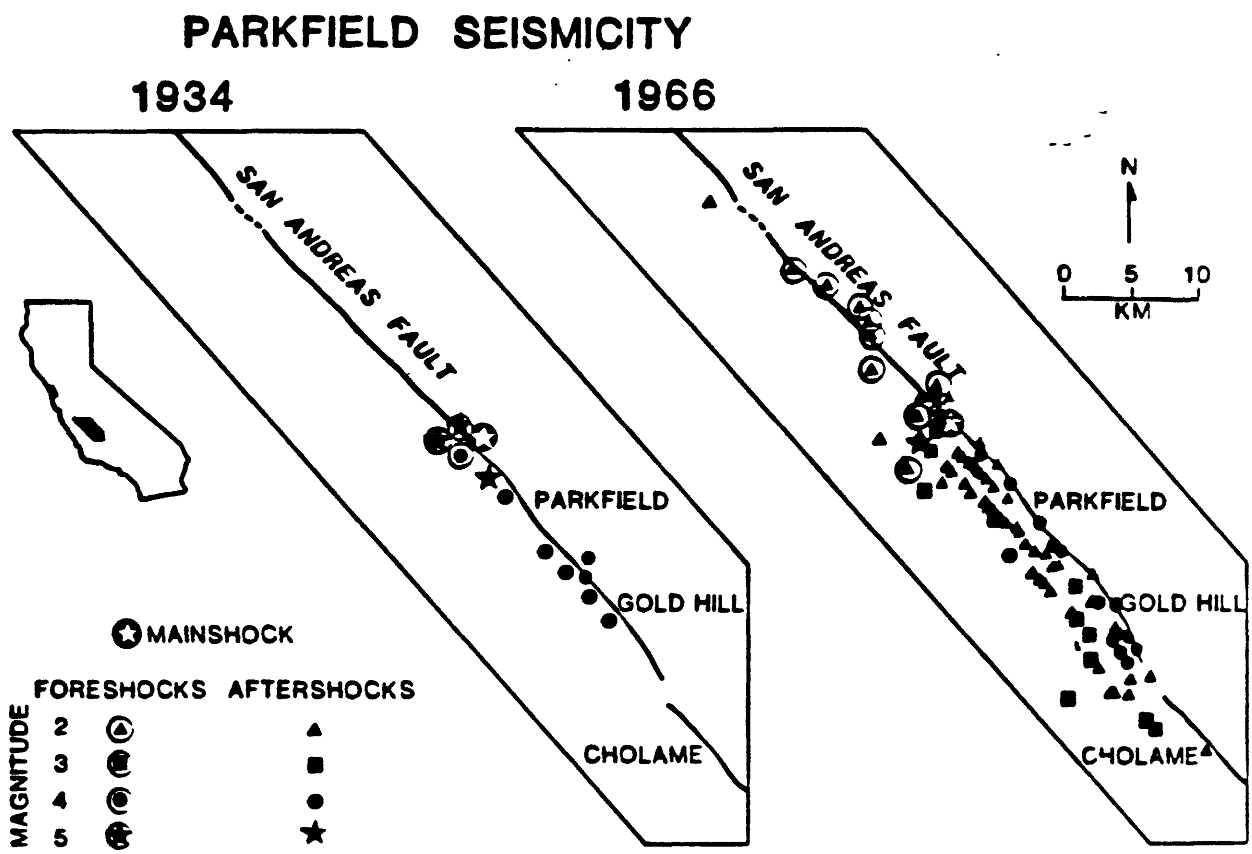


Figure 2. Map of the Parkfield area showing epicenters of earthquakes associated with the 1934 (left) and the 1966 (right) characteristic Parkfield earthquakes. In 1934, only M > 4 shocks can be accurately located; in 1966, M≥2 shocks for 28 January 1966 to 30 June 1966 are shown.

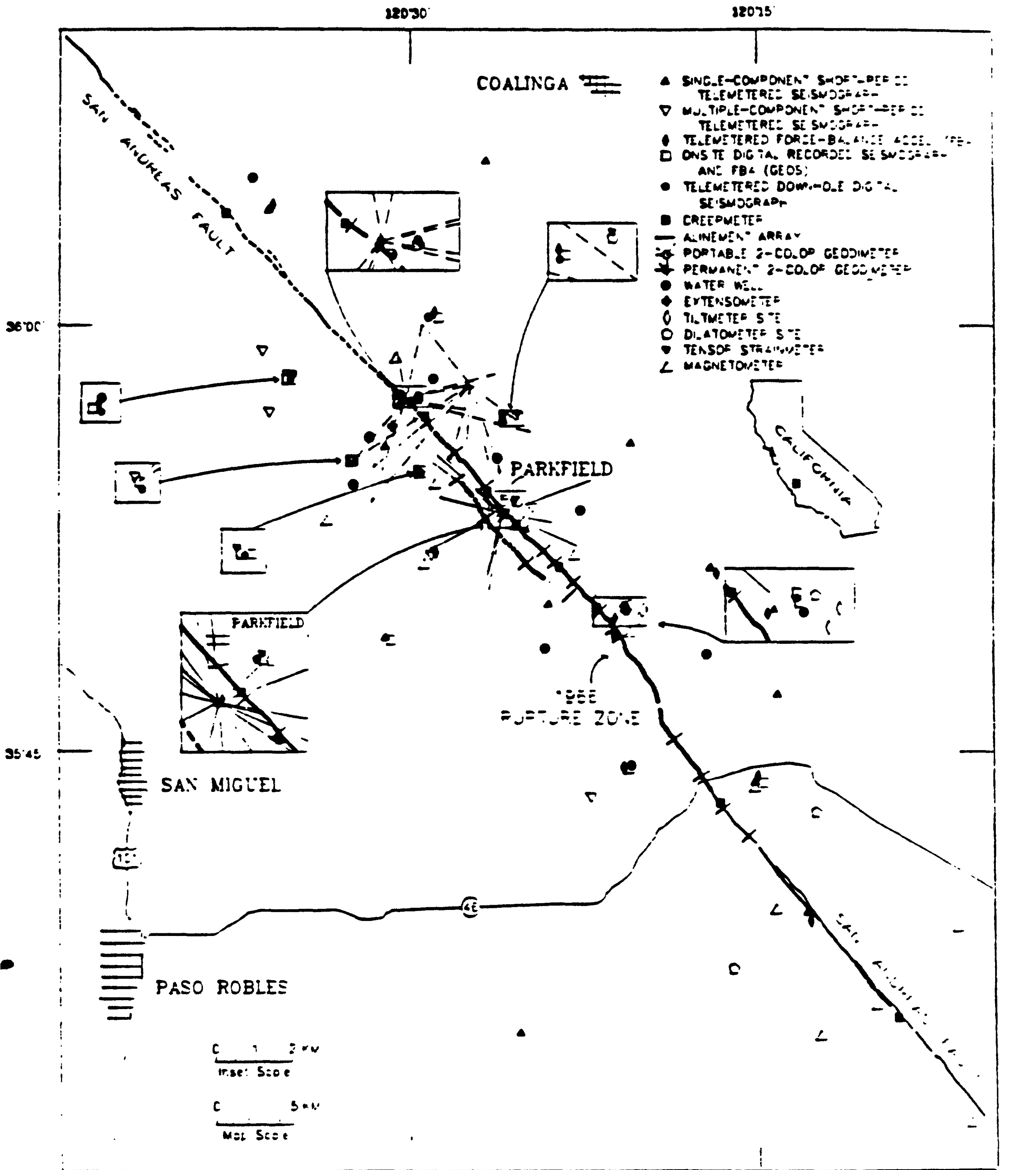


Figure 3. Location of geophysical instrumentation relative to the rupture zone of the characteristic Parkfield earthquake in 1966.

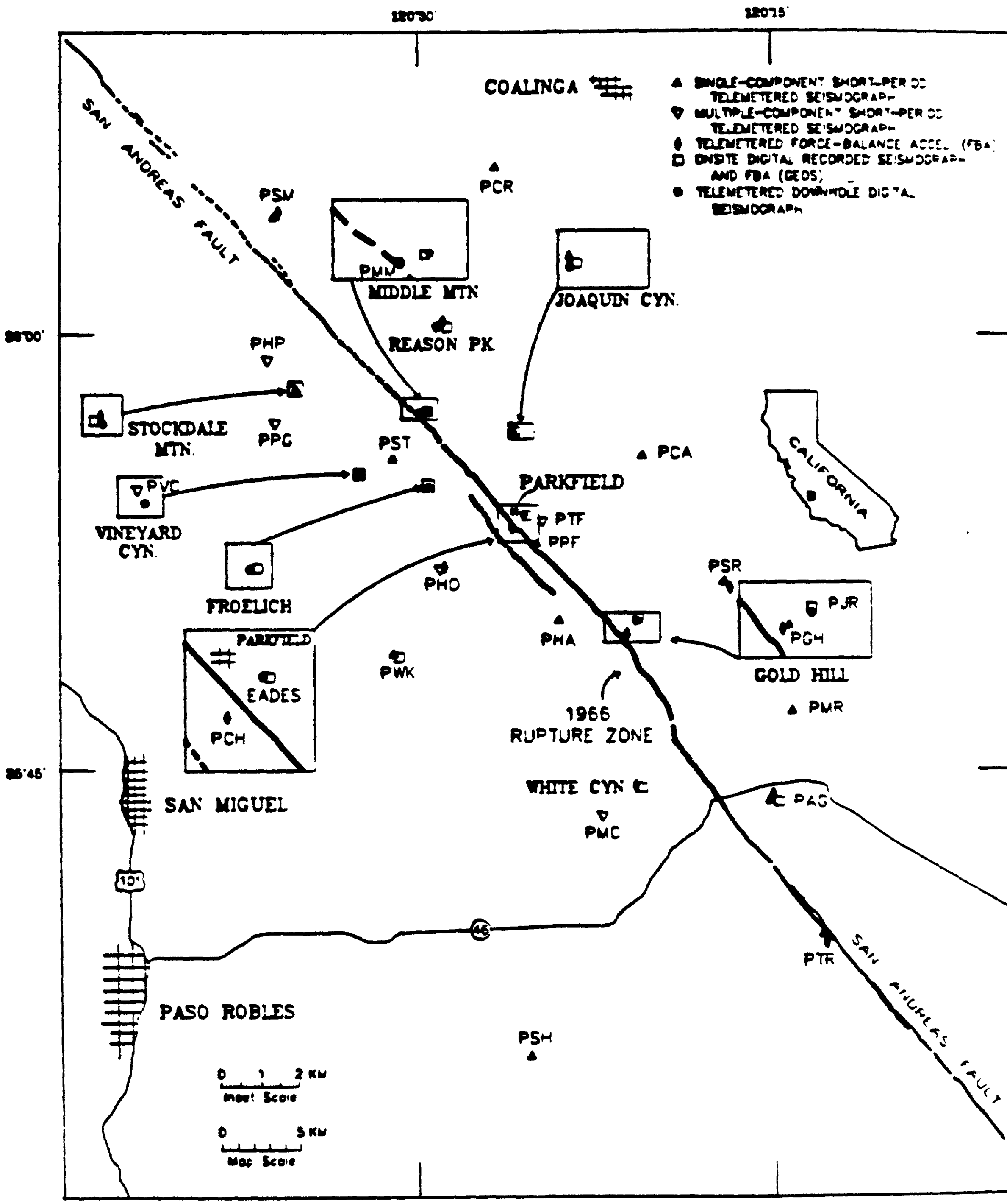


Figure 4. Seismic instrumentation relative to the rupture zone of the characteristic Parkfield earthquake in 1966. The location of strong-motion sensors operated by CDMG are shown in McJunkin and Shakal (1983).

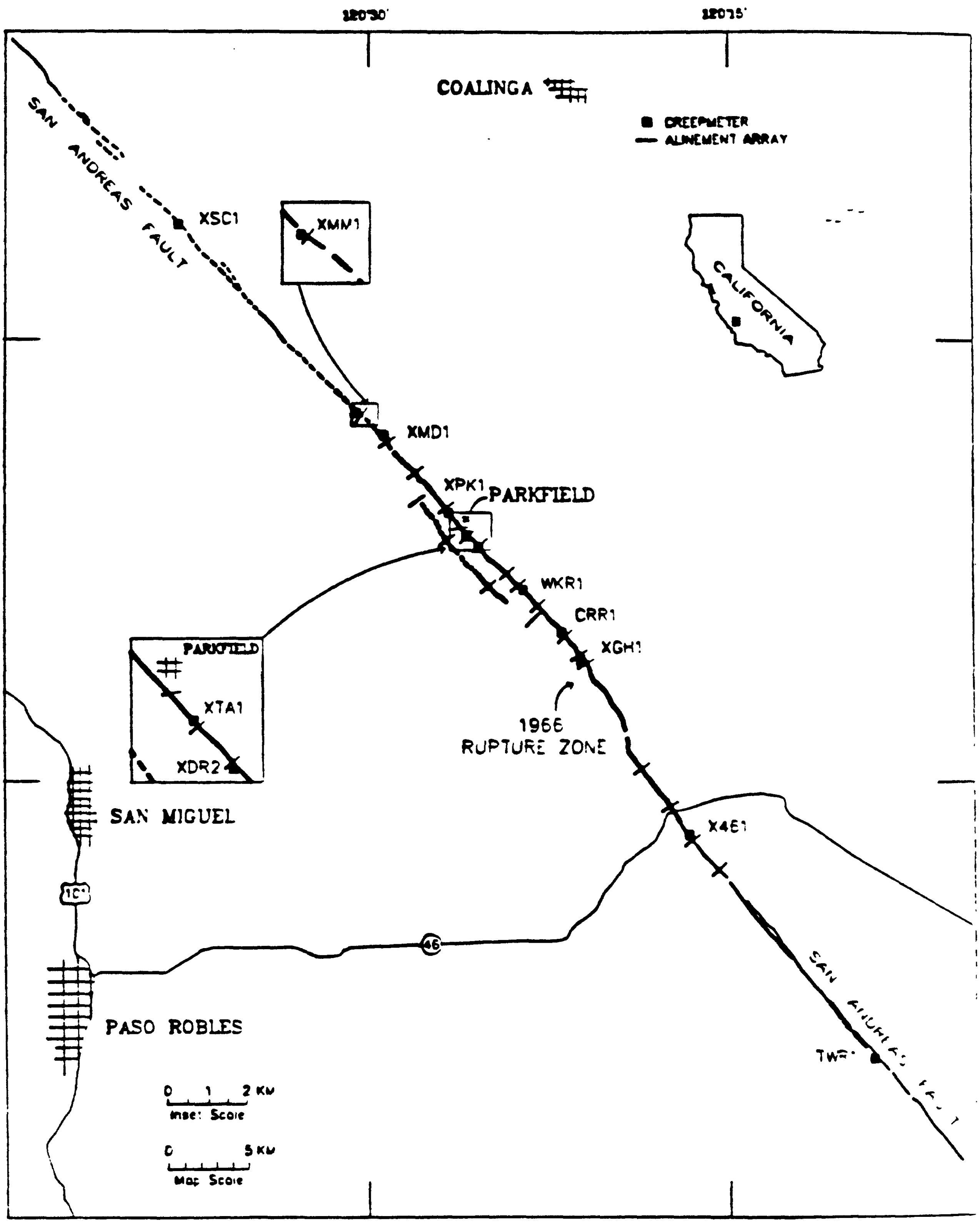


Figure 5. Creepmeter locations relative to the rupture zone of the characteristic Parkfield earthquake in 1966.

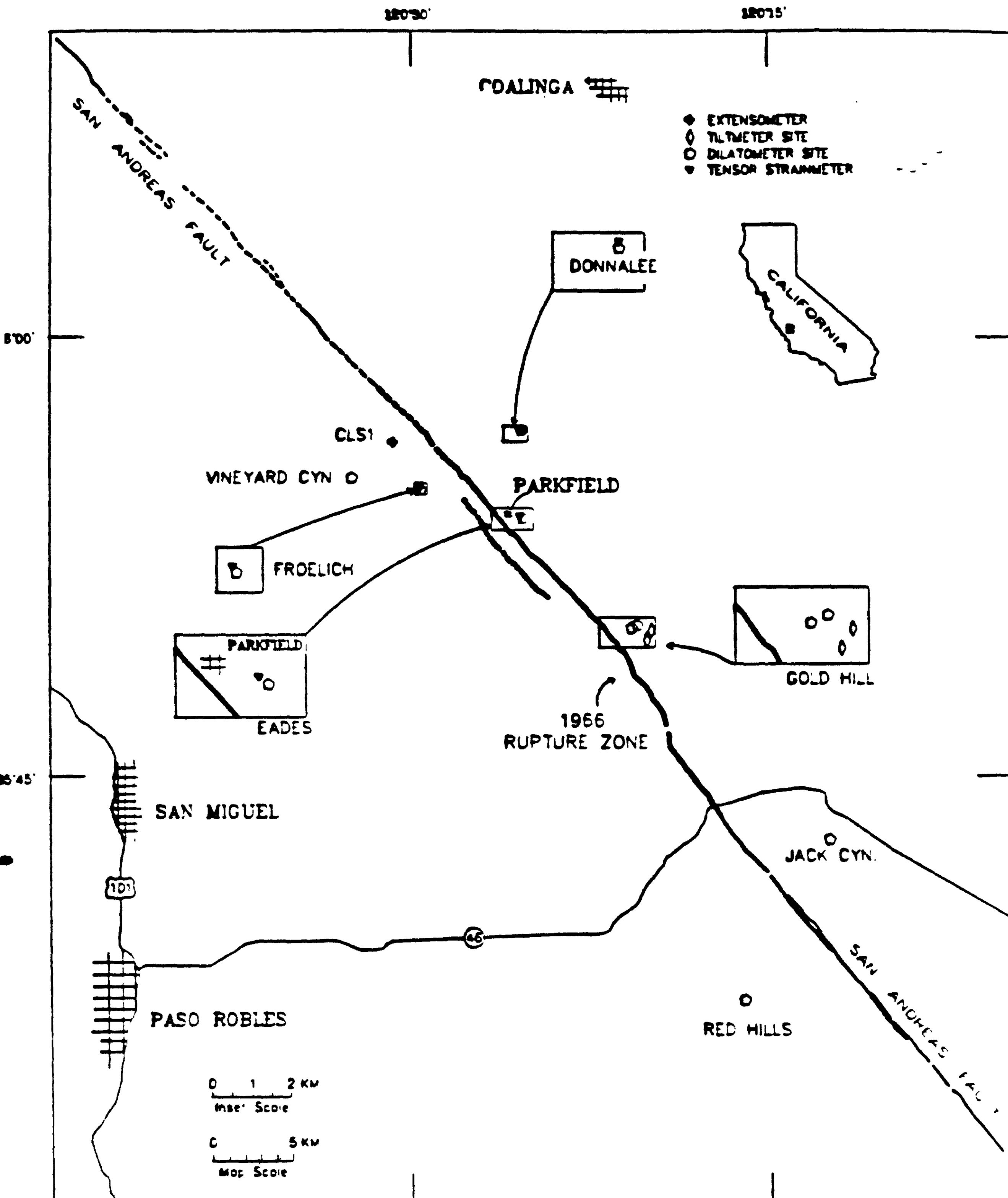


Figure 6. Strainmeter (borehole dilatometers, tiltmeters, and linear strainmeter) locations relative to the rupture zone of the characteristic Parkfield earthquake in 1966.

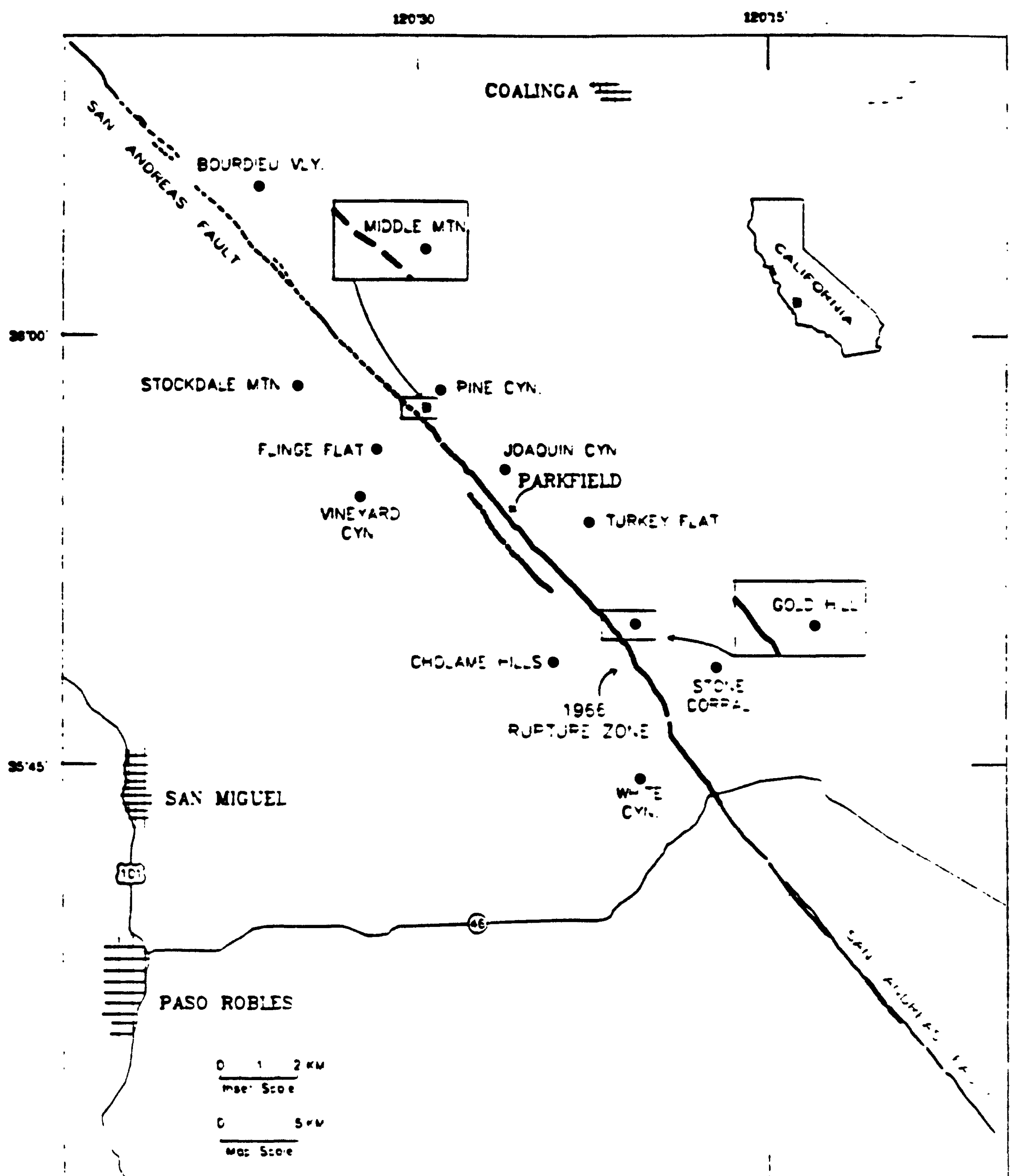


Figure 7. Water well locations relative to the rupture zone of the characteristic Parkfield earthquake in 1966.

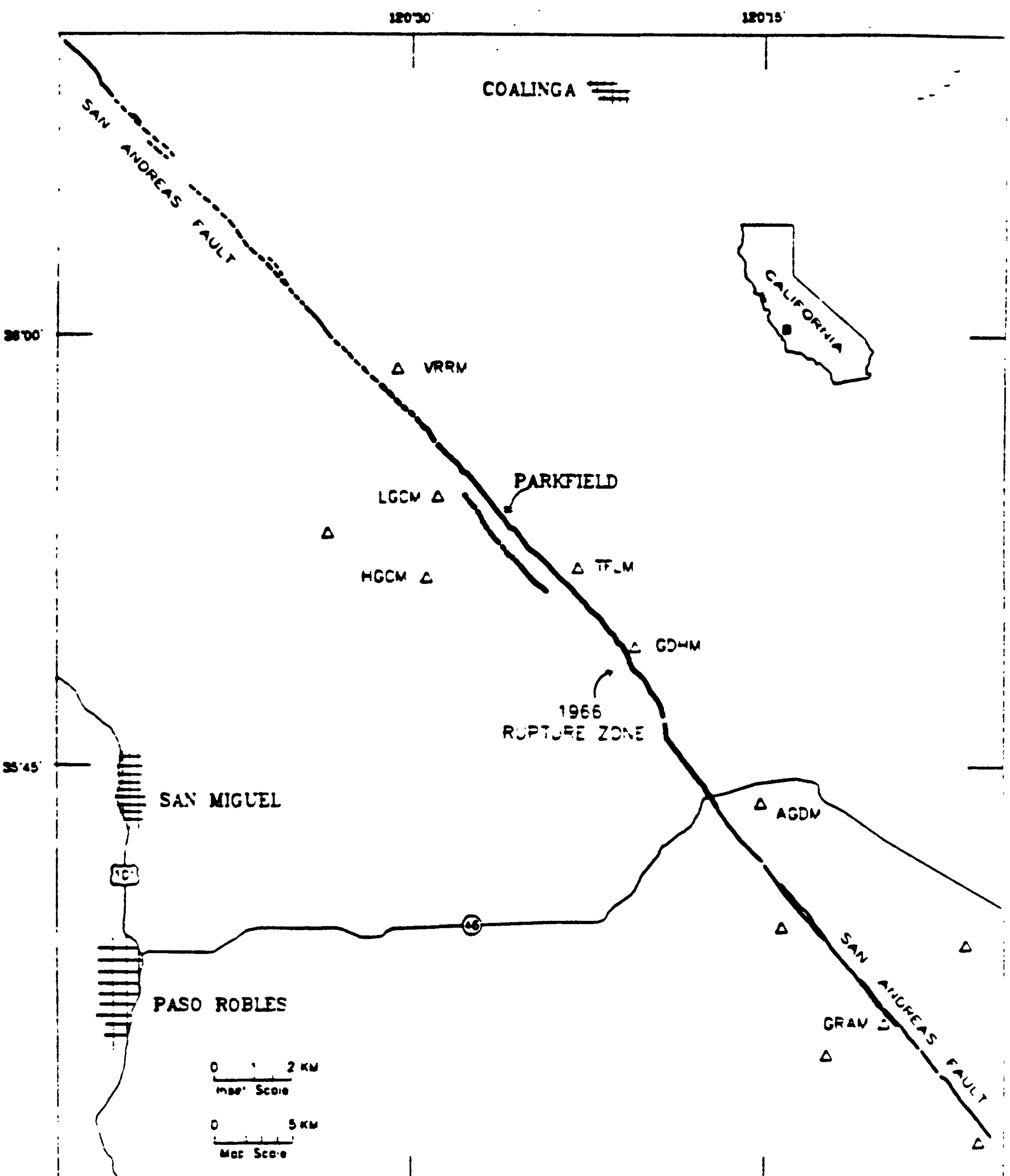


Figure 8. Magnetometer locations relative to the rupture zone of the characteristic Parkfield earthquake in 1966. Sites not labeled are not continuously operated magnetometer locations.

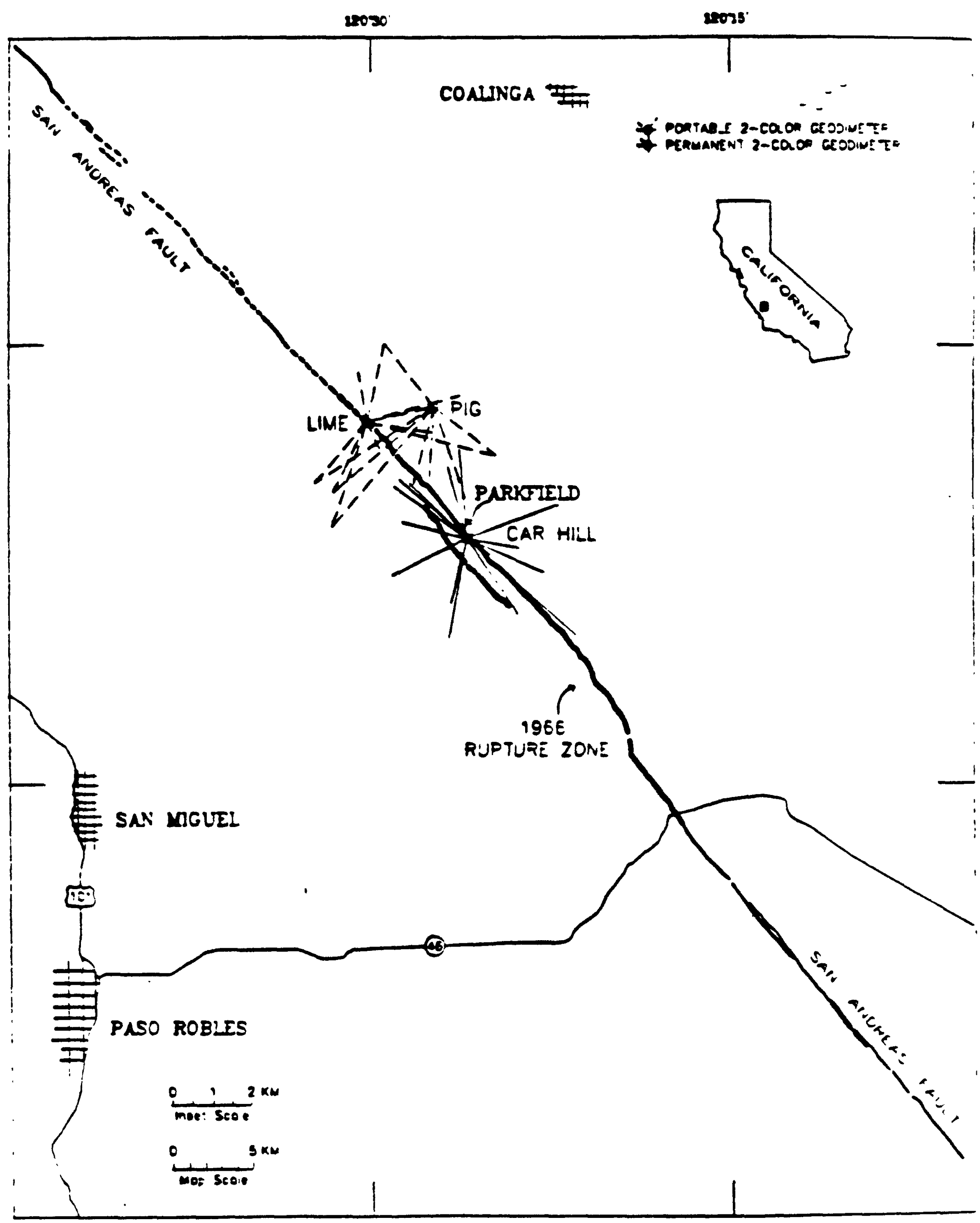


Figure 9. Two-color geodolite reflector sites relative to the rupture zone of the characteristic Parkfield earthquake in 1966.

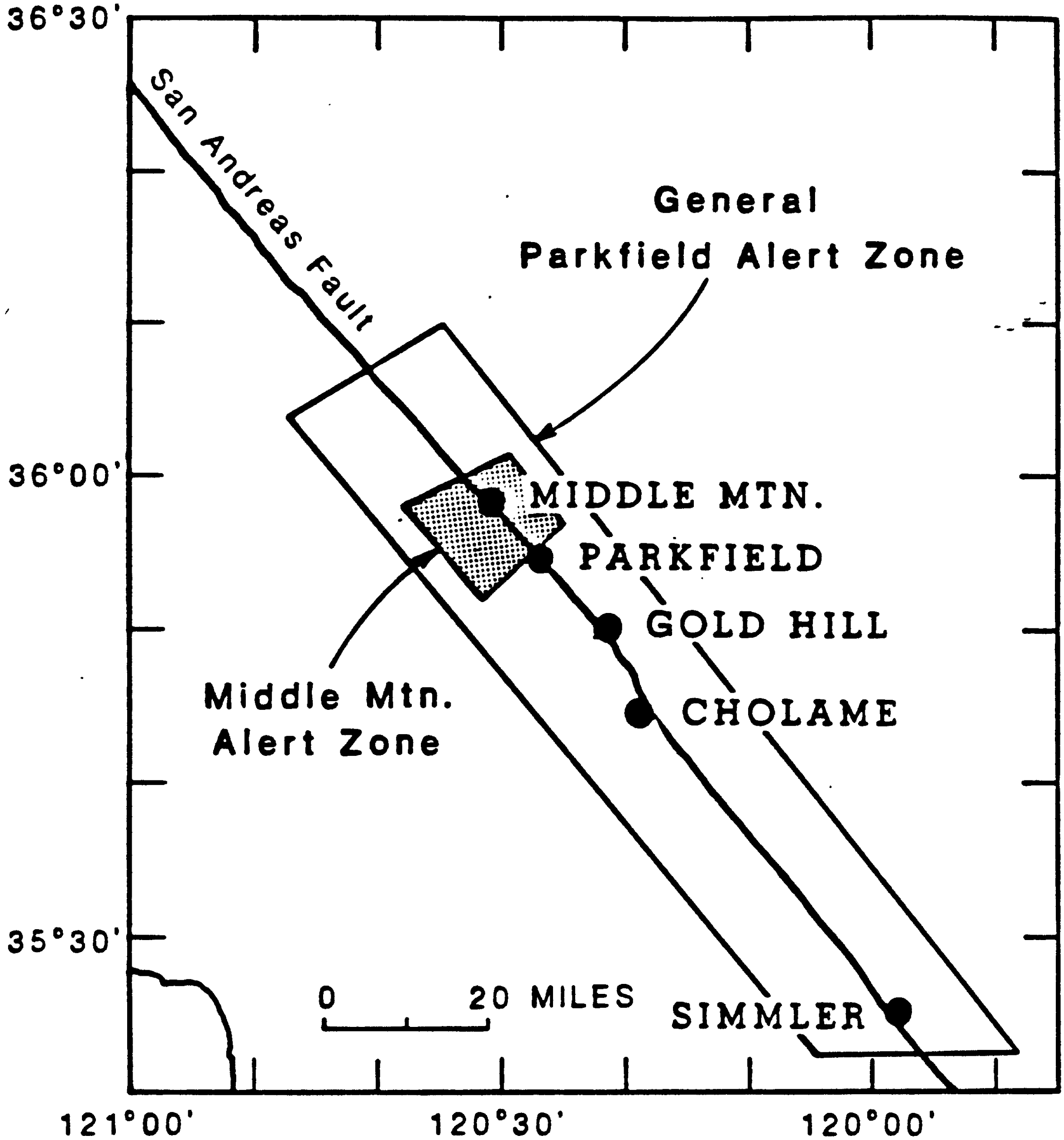


Figure 10a. Seismic alert zones near Parkfield. The Middle Mtn. alert zone includes shocks with epicenters within the small figure centered on Middle Mtn. and with focal depths ≥6.5 km. The Parkfield area alert zone extends along the San Andreas fault trace from the creeping section northwest of Middle Mtn. to the Simmler section southeast of Cholame.

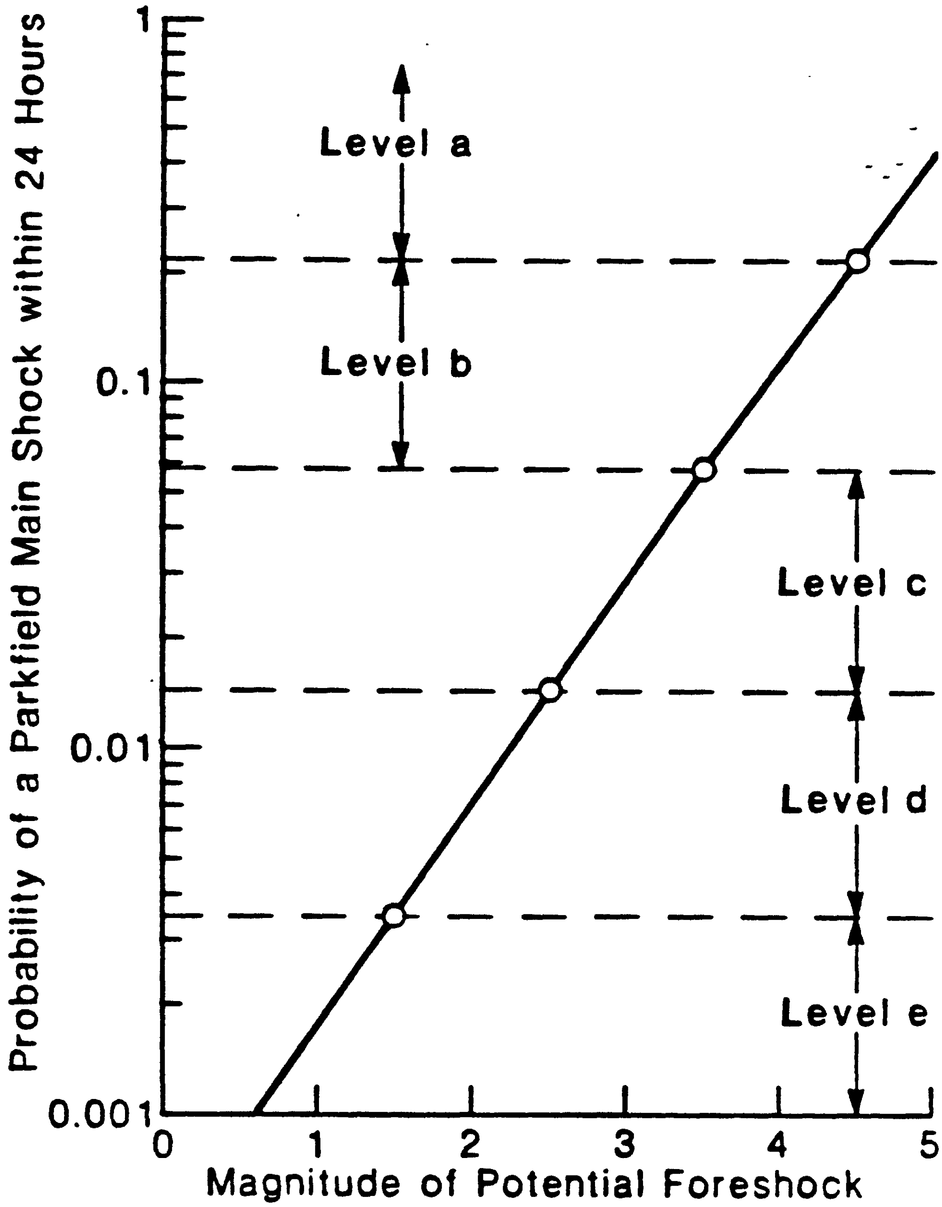


Figure 10b. Probability of a characteristic Parkfield earthquake in the 24 hours following the occurrence of a potential foreshock of magnitude M.

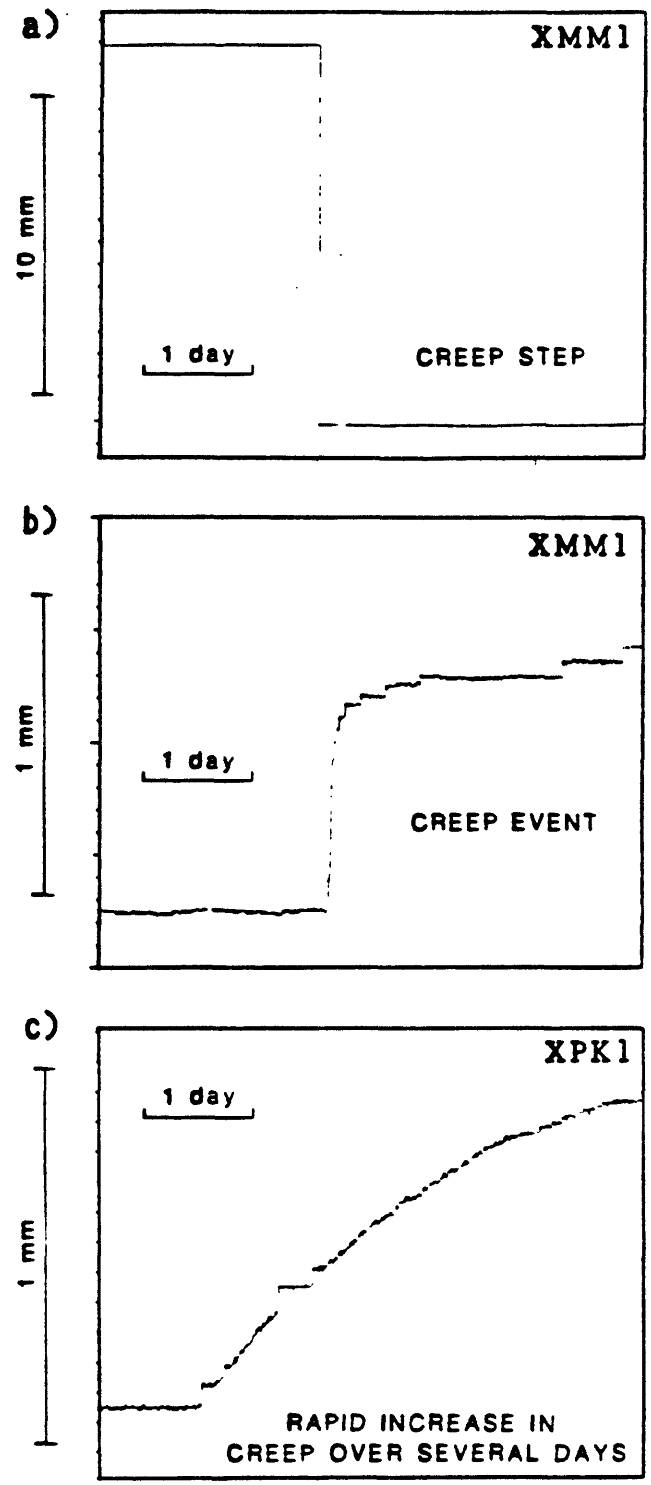
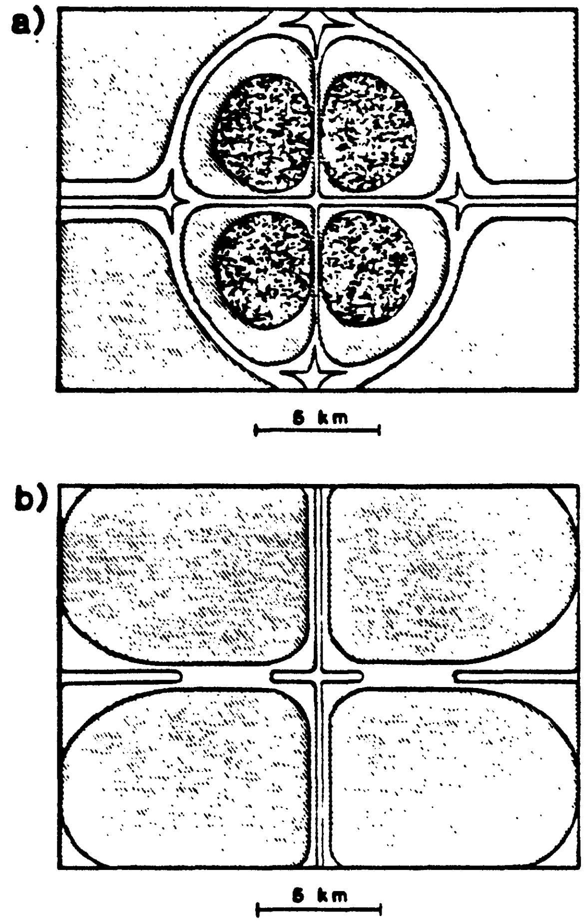


Figure 11a. A creep step recorded at XMM1, caused by telemetry problems. This signal triggered the beeper-paging system (an **E alert level**).

Figure 11b. A creep event recorded at XMM1. Although not large enough for a **D level alarm** it did trigger the beeper-paging system (an **E alert level**).

Figure 11c. Sustained rapid creep at XPK1. This kind of signal does not trigger the beeper-paging system, but would constitute a **D level alert** if sustained for a few more days.



Moment, dyne-cm

Key	10^{25}	10^{24}	10^{23}
(dark stipple)	100 to 1000	10 to 100	1 to 10
	10 to 100	1 to 10	not detectable
	1 to 10	not detectable	not detectable
	not detectable	not detectable	not detectable

Units in table are in multiples of detectability threshold.

Figure 12. Contour maps of volumetric strain produced at the surface by strike-slip over a 5 km x 5 km section of vertical fault. (a) Hypocenter at 5 km depth. (b) Hypocenter at 10 km depth. The key assumes a detectability threshold of 0.03 PPM, which is appropriate for water level detection of events having rise times shorter than 1 day.

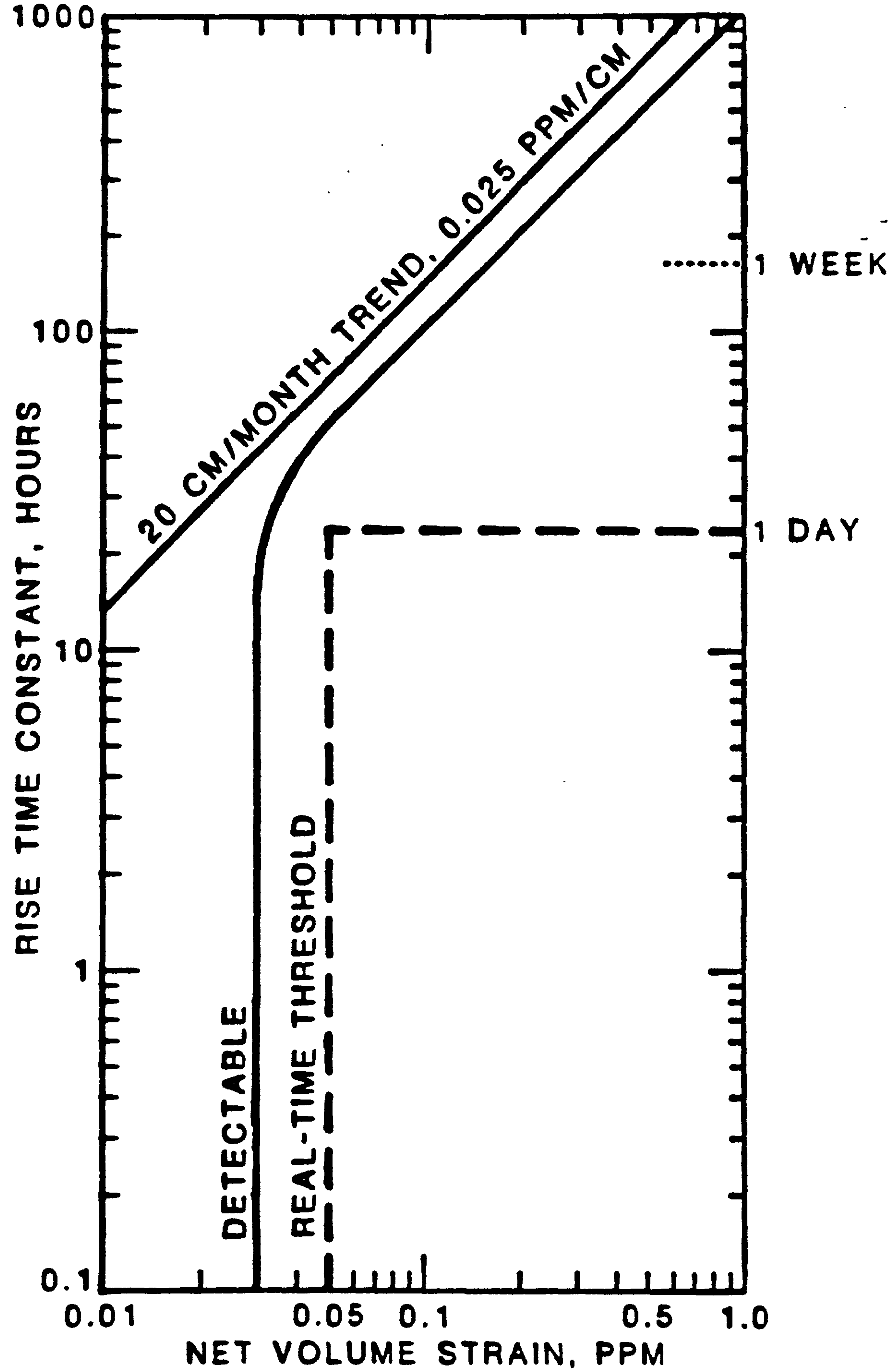


Figure 13. Minimum amplitude strain event that can be detected as a water level change, as a function of event rise time. Events below and to the right of curve can be distinguished from noise and environmental effects. Effects within the dashed box should be detected by the real-time processing system. The diagonal line at the top and left is the threshold above which events would be masked in a well with a sensitivity of 0.025 PPM/cm and with seasonal water level trends of 20 cm/month.