UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Parkfield Earthquake Prediction Scenarios and Response Plans

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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 notes 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.

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GEOLOGICAL SURVEY
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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) of the anticipated shock based on observations of precursory phenomena recorded by elements of the prototype earthquake prediction network. The purpose of this report is to define 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 communication (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 <u>must</u> 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 in the near future of the anticipated shock 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 shocks. 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 probablity 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 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. Division of 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 occurrence of an alert and generally is expected to decrease with time to the long-term probability of 10^{-4} - 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 triggering the alert.

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 false alarm rate for individual observational networks (i.e., alerts not followed within 72 hours by the expected magnitude 6 shock). However alerts arise from anomolous conditions on any of the several 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 false alarms are likely, particularly for the lower alert levels. Establishment of more accurate false alarm rates will be based on future analyses of the ongoing Parkfield experiment.

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 $\pm$ 5.2 years, together with the 19+ 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 percent (Bakun and Lindh, 1985).

The evidence supporting the long-term (few years - 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.

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 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 communication (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, reliable 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; (2) to identify geologic and geophysical techniques that would be generally useful in earthquake prediction networks 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. There is not yet sufficient understanding of these newer networks so that they 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. The Parkfield prototype earthquake prediction network then 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 charges and refinements will be described in subsequent updated versions of this report.

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 as 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 mainshock (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 mainshock (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 mainshock. 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 and 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 presently too poorly understood to be of use in predicting the next Parkfield earthquake.

A. Seismic The seismic instrumentation (Figure 4) consists of seismographs of the USGS central California seismic network (CALNET), the borehole seismographs operated by P. Malin of the Univ. of California at Santa Barbara (UCSB), and the strong-motion accelerograph array operated by the Calif. Div. of Mines and Geology (CDMG).

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

	Component(s)	Location relative to Parkfield
Antelope Grade (PAG)	Z	25km SE
Castle Mountain (PCA)	Z	10km E
Curry Mountain (PCR)	Z	22km N
Gold Hill (PGH)	Z	12km SE
Harlan Ranch (PHA)	Z	9km SE
Hog Canyon (PHO)	Z + low-gain 3 comps	5km SW
Hope Ranch (PHP)	Z + 2 horiz. comp.	17km NW
McMillan Canyon (PMC)	Z + low-gain 3 comp.	20km SW
Middle Mountain (PMM)	Z + 2 horiz. comps.	8km NW
Maxie Ranch (PMR)	Z	23km SE
Portuguese Canyon (PPC)	Z + 2 horiz. comps.	15km NW
Parkfield (PPF)	Z	4km SE
Smith Mountain (PSM)	Z	23km NW
Scobie Ranch (PSR)	Z	15km SE
Stockdale Mountain (PST)	Z	8km NW
Turkey Flat (PTF)	Z + 2 horiz. comps.	3km SE
Vineyard Canyon (PVC)	Z + 2 horiz. comps.	9km NW
Work Ranch (PWK)	Z	11km SW

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 $M \geq 1$ foreshocks at Parkfield.

Borehole Seismograph Network. Three 3-component borehole seismometers (Malin, 1985) have been installed with support provided by the USGS external grants program. The borehole seismographs are currently in the test/evaluation phase; they should provide high-gain high frequency seismic information on $M > 0$ shocks in the Parkfield area not obtainable from the CALNET systems.

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 M3.5 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 shock.

B. Creep

There are 8 creepmeters (Schulz et al., 1982) that are located in the Parkfield area (Figure 5). Locations on the fault from the northwest to the southeast: Slack Canyon (XSC1), Middle Mountain (XMM1), Parkfield (XPK1), Taylor Ranch (XTA1), Durham Ranch (XDR2), Work Ranch (WKR1), Carr Ranch (CRR1), and Gold Hill (XGH1). The Middle Mt. creepmeter is located in the epicentral region of past Parkfield main shocks and foreshocks. Six creepmeters (XSC1, XMM1, XPK1, XTA1, XDR2, XGH1) are invar-wire instruments with 0.02 mm resolution, and two (CRR1, WKR1) are invar-rod instruments with 0.05 mm resolution. Creep data is telemetered to Menlo Park every 10 minutes via GOES satellite and telephone telemetry.

C. Continuous Strain

Strainmeters - Two types of strain-measuring devices are currently in use near Parkfield (Figure 6). Sacks-Evertson borehole volumetric dilational strainmeters (dilatometer) (Sacks et al., 1971) are located at two sites along the southern end of the expected rupture zone (Gold Hill One (GHS1) and Gold Hill Two (GHS2). The dilatometers are operated by the USGS in a cooperative effort with the Carnegie Institution of Washington. A single-component, linear strainmeter (extensometer) (Johnston et al., 1977) is sited on the Claussen Ranch (CLS1) near Middle Mt. at the northern end of the rupture zone. The resolution of the dilatometers range from 10^{-2} parts per million (PPM) for signals with periods of several weeks to 10^{-3} PPM for much shorter periods. 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 also transmitted once every 10 minutes with digital telemetry via the GOES satellite or 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 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 - Water level fluctuations in a network of 5 wells (figure 7) near Parkfield are monitored by the USGS Water Resources Division (WRD). 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). These wells record clear earth tides, and have sensitivities at intermediate periods (days) comparable to the dilatometers. Water levels in wells at Gold Hill, Turkey Flat, Joaquin Canyon and Flinge Flat are sampled every 15 minutes, transmitted every 3 hours by GOES satellite to the low frequency data computer in Menlo Park, and also to WRD in Phoenix and then by the WRD data network to a WRD computer in Menlo Park; water level in the well at Vineyard Canyon currently is recorded only at the well head.

Differential Magnetometers - Local magnetic fields are monitored with absolute total field magnetometers (Mueller et al., 1981) at 7 sites [Varian Ranch (VRRM), Lang Canyon (LGCM), Turkey Flat (TFLM), Hog Canyon (HGCM), Gold Hill (GDHM), Antelope Grade (AGDM), and Grant Ranch (GRAM)] in the Parkfield region (Figure 8). The data are synchronized to within 1.0 sec and are transmitted with 16-bit digital telemetry to Menlo Park. The measurement precision in the period range 10 min to tens of days is about 0.2 nT. 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 17 baselines distributed radially around the central instrument site, which is located just south of Parkfield. Under optimal conditions the network can be measured nightly. Typical standard errors of individual line length measurements are 0.5-0.7 mm for 4-6 km long lines.

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 mm to 7 mm for lines 4 km to 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 four lines; a 10-km-long line perpendicular to the fault at Parkfield, a 32-km-long line in the vicinity of Middle Mt., 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/yr in a joint effort with the University of California at Santa Barbara (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. In addition to real-time, or near real-time, processors that respond to predetermined threshold signals by activating radio beeper-paging alert systems, 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 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 judgement to the following probabilities and/or anticipated time interval between alerts:

Alert Level	Probability of shock in next 24 hours	Anticipated Time Interval Between Alerts
d	0.0035 to 0.014	2mo. to 6mo.
c	0.014 to 0.06	6mo. to 18mo.
b	0.059 to 0.22	18mo. to 54mo.
a	> 0.22	>54mo.

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 natural 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.

The anticipated time interval between alerts in the above table emphasizes that use of any set of probabilistic alert criteria implies the occurrence of some false alarms. Whereas the rate of alerts for level d implies 2 to 6 "inhouse" alerts per year for each observation network, the more stringent criteria for level a imply an anticipated alert to OES less frequent than once every 4 to 5 years. Given the Parkfield seismic window of 1988 ± 5.2 years, we expect that the use of the criteria in this report could result in 1 to 2 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 use of the anticipated time interval 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 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 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 Mt. 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, for a total of 25 alerts by 1993.

The probability that an earthquake near Middle Mt. 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 Mt. alert zone.
2) The probability of any one earthquake within the Middle Mt. 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 that the next characteristic Parkfield earthquake will follow an earthquake of magnitude M within the Middle Mt. alert zone is estimated to be

$$P_F = P\left(\begin{array}{c|c}\text{Next Characteristic} & \text{Potential Foreshock} \\ \text{Parkfield Earthquake} & \text{of magnitude M}\end{array}\right) \cong 3.1\times10^{-4} \times 10^{0.62M}$$

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

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

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

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

In addition, for a current estimate of the total probability at any particular time, some estimate of an increase in background probability as times 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 attributable to the long-term recurrence model:

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

where T is years after 1 Jan 1986.

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

$$P = 1/(1+r_o r_1 r_2), \text{ where}$$
$$r_o = (1/P_o) - 1$$
$$r_1 = (1/P_R) - 1$$
$$r_2 = (1/P_F) - 1, \text{ and}$$

P_o (the Poisson probability) $= 1/21.7 \times 1/365$

$= 1.26 \times 10^{-4}$ per day

The resulting total probability estimates for a potential foreshock on 1 Jan 1986 being followed within 24, 48, and 72 hrs 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 (See Figure 10a for alert zone boundaries)	Estimated Prob. of Parkfield Main Shock in first 24	48	72 hrs.	Anticipated Time Interval Between Alerts
d	(1) one M 1.5 shock in the Middle Mt. alert zone (2) two or more M 1.0 shocks in a 72-hour period in the Middle Mt. 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.)	0.0035	0.0056	0.0068	2 - 6 mo.
c	(1) one M 2.5 shock in the Middle Mt. alert zone (2) two or more M 1.5 shocks in a 72-hour period in the Middle Mt. alert zone (3) one M 3.5 shock in the Parkfield alert zone	0.014	0.023	0.028	6 - 18 mo.
b	(1) One M 3.5 shock in the Middle Mt. alert zone (2) two or more M 2.5 shocks in a 72-hour period in the Middle Mt. alert zone	0.059	0.090	0.11	18 - 54 mo.
a	(1) One M 4.5 in the Middle Mt. alert zone (2) two or more M 3.5 shocks in a 72-hour period in the Middle Mt. alert zone	0.22	0.32	0.37	> 54 mo.

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 eight Parkfield creepmeters are sampled every 10 minutes. The automated anomaly detector compares the average creep at each of the 8 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.

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 Figure 11a.) (In the past 2 years, there have been 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; i.e. creep exceeding 0.25 mm within 1 hour with slip velocity decreasing exponentially within 1-2 hours after onset. (See Figure 11b)	< 2 mo.
d	(1) At any one site other than XSC1, a nearly continuous increase in creep (see Figure 11c) that exceeds 0.25 mm within 7 days and continues at a comparable or greater rate over a period greater than 10 days. (This alert has been reached 4 times in the period 1982-1985; XSC1 normally moves 0.25 - 0.5 mm/week).	6 mo.
	(2) At any two sites other than XSC1, nearly simultaneous onset of an almost continuous increase in creep that exceeds 0.2 mm in 24 hours and continues at a comparable or greater rate for more than 2 days. (This alert occurred for the first time in December 1985; XSC1 normally moves 0.25-0.5 mm/week.)	
	(3) At one site, an unusually large creep event (see Figure 11b). For creepmeters northwest of XDR2 (XSC1, XMM1, XPK1, XTA1, and XDR2) events with creep >0.5 mm in the first 30 min. would be unusually large. For creepmeters southeast of XDR2 (WKR1, CRR1, and XGH1), events with creep >0.33 mm in the first 30 minutes would be unusually large.	
c	(1) Nearly simultaneous onset of creep at 2 or more creepmeters that exceeds 0.5 mm in one hour.	6 mo.- 12mo.
	(2) More than 1 mm of creep on the Middle Mt. creepmeter in one hour.	

b	(1)	More than 5 mm of creep in 72 hours on the Middle Mt. creepmeter	>24 mo.
	(2)	More than 5 mm of creep in 72 hours on 2 or more Parkfield area creepmeters.	
a	(1)	Creep rates on multiple instruments (or at Middle Mt. alone) 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. Calculations of the net volumetric strain that would be produced by such aseismic slip show that the moment required to produce observable strains anywhere at the surface is comparable to that of a M 2.5 earthquake located near the surface, and considerably larger for slip at depth. 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 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; such an event might be comparable to a magnitude 5 foreshock.

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 onsite 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 (longer 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. Longer-term strain changes are detected by an algorithm that identifies changes in strain rate normalized by estimates of noise in the data.

Although only two borehole strainmeters now operate in the Parkfield region, during the past two years (Nov. 83-Nov. 85) four longer-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 Mt. All four longer-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 hr period on one dilatometer. These may occur because of phone line, telemetry, or instrument malfunctions, and generally triggers maintenence response.
d	(1)	Changes of 0.1 PPM per week on two dilatometers
	(2)	changes of 0.1 PPM within a 24 hour period on one dilatometer with indications of a simultaneous signal on a second dilatometer.
c	(1)	Changes of 0.2 PPM per week on two or more independent dilatometers
	(2)	changes of 0.2 PPM within a 24 hour period on one dilatometer with indications of a simultaneous signal on a second dilatometer.

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 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. 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 decreased with lengthening event time scale. For example, seasonal water level changes will 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 will require more time to detect.

Water level data are examined daily, and filtered and plotted two times per week. In addition, as water level data are received (every three 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 amplitudes 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 long 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.

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 attributed 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 at 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. Differential magnetic field data are sampled automatically every 10 minutes and transmitted to Menlo Park where they are monitored frequently and plotted weekly. Changes of ~1 nT within a day, or at longer periods, in the averaged data are considered anomalous. This has happened only once during 10 years of monitoring and occurred during the few months following the May 1983 Coalinga earthquake.

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 five 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 five 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 two-color observations are more appropriate for a more slowly developing scenario than has been 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 history of line length changes is obtained.

Anomalous Line length Alert Level	Line-Length Changes Between Successive Measurements
d	(1) Short-term changes. Three or more lines with distance changes (absolute value) of $\geq$ 3.0 mm each within a single event window of 25 days or less, with at least one line changing by $\geq$ 4.0 mm. Changes on each line must exceed the 2 σ level of significance where $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$, and σ_1 and σ_2 are the std. error of the lengths measured before and after the changes. (In the case of oscillatory changes, at least two independent, consecutive measurements, made 15 or more hours apart within the same event window identified for other lines, must deviate by more than 2 σ from the mean of the final 3 independent values obtained just before the beginning of the event window.) Two such periods of change have been documented in the Parkfield 2-color geodimeter network since October, 1984, the first from April 22 to May 8, and the second from July 28 to August 20, 1985. These examples are presented in Figures 14 and 15. (2) Trend changes. Three or more lines showing changes in rate of extension (or contraction) of $\geq$ 0.04 mm/day (15 mm/yr), as determined by least-squares analysis. The times of the three line changes must fall within one event window of 30 days or less. The change on each line must exceed the 2 σ level of significance.
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	Network 1		Network 2		Network 3		Network 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 networks 1, 2, 3, and 4. 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 - i.e., a warning to OES.

VI. RESPONSE

Project Chief. The responsibility for recognizing the anomalous condition 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 preceding section.
3) Immediately alert the Chief Scientist and the Chief of the Seismology Branch or Tectonophysics Branch of all a, b, c, or d level alerts.
4) Train and maintain an alternate capable of assuming the above r -ponsibilities.
5) Delegate these responsiblities 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 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 Branch and Tectonophysics Branch of the status of the alert levels.

2) After consultation 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 a c, b, or a alert level is reached.

3) For an a alert level, the Chief Scientist is responsible for notifying the Office of the Director of OES (See Appendix B).

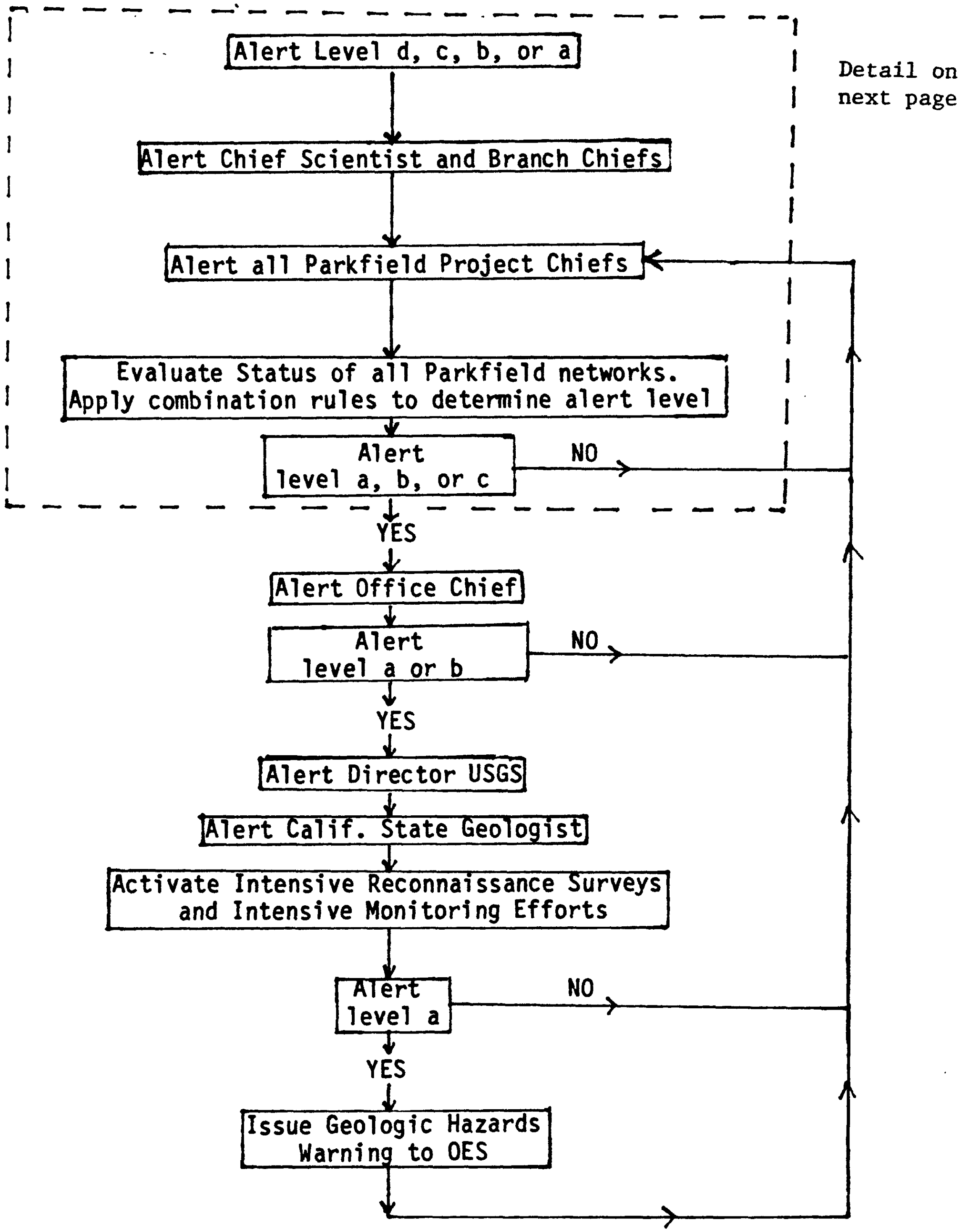
Chiefs, Seismology and Tectonophysics Branches. The branch chiefs have the responsibility for maintaining the personnel and resources within their branches that are necessary to maintain and operate the real-time surveillance and prediction capabilities described in this report. The branch chiefs have 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 a replacement for the Chief Scientist in fulfilling the Chief Scientist's responsibilities that are described above.
5) Serve as a replacement for the Office Chief in fulfilling the Office Chief's responsibilities that are described below.

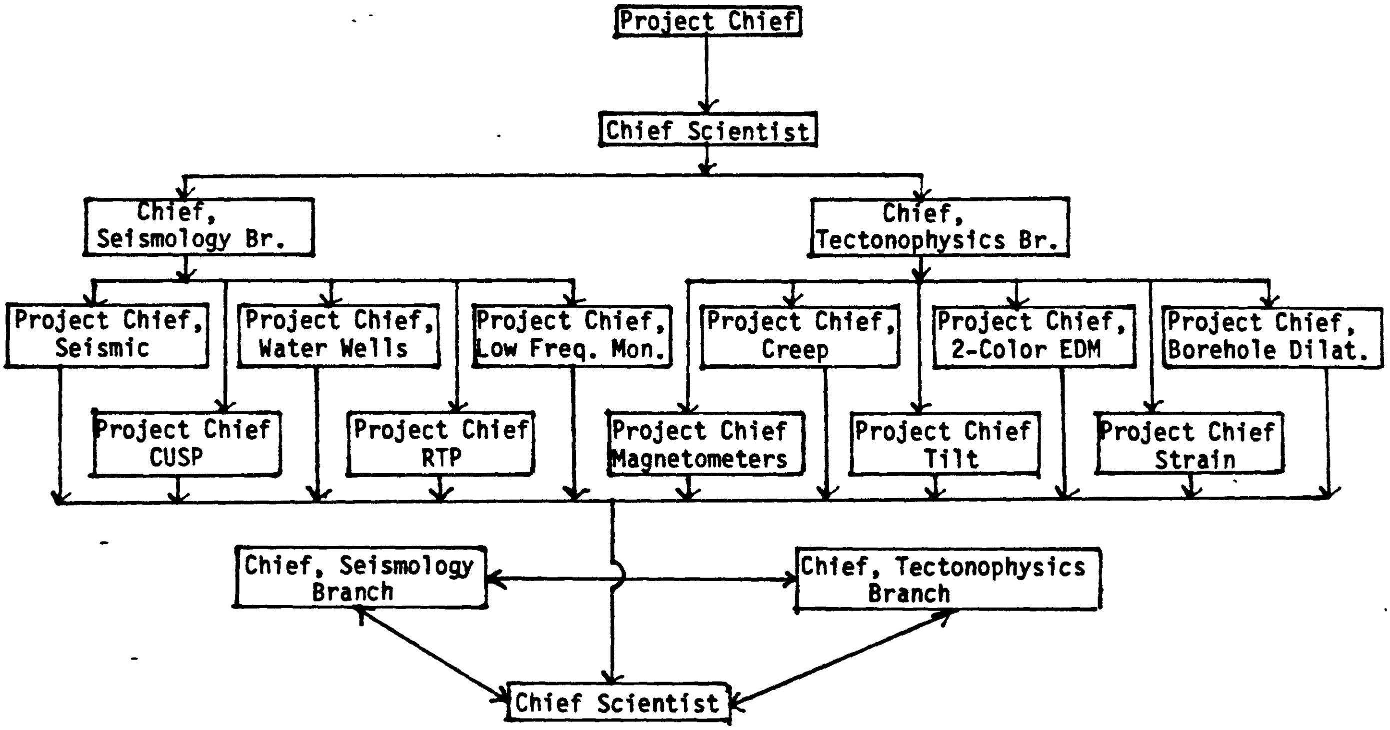
Chief, Office of Earthquakes, Volcanoes, and Engineering (OEVE). The Office Chief is responsible for communicating the alert level status to non-USGS OEVE personnel. The Office Chief has the following specific responsibility:

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 USGS and the Calif. state geologist, CDMG.

DECISION FLOW DIAGRAM



DETAIL OF DECISION FLOW DIAGRAM



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 if the maximum information regarding the generation process of Parkfield earthquakes is to be obtained and information relevant to the imminent occurrence of a large shock on the San Andreas fault southeast of the Parkfield section is to be available. Although these efforts have not yet been fully planned, it is clear that the following steps should be undertaken.

1) Alert Chief, Branch of Strong Ground Motion and Faulting
2) Alert CDMG manager of strong-motion network at Parkfield.
3) Remeasure geodetic baselines estabished 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 networks in the Parkfield region.
8) 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.

APPENDIX B. SAMPLE WARNING MESSAGE

Experience in other fields where public safety is at 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. Prior agreement by the USGS and OES on the content and format of warnings to OES from the USGS are essential if the USGS estimates of immediate geologic hazards due to Parkfield earthquakes is to be quickly understood and acted upon by OES. Thus, we propose to communicate the geologic hazards warning to OES in the following message:

"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 magnitude 6 earthquake 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.

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 larger than the 1966 shock and for the fault to rupture southeast into the adjacent 25-mile section of the San Andreas fault."

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FIGURE CAPTIONS

Figure 1. Map of earthquake epicenters (1975-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 $M \geq 2.3$ earthquakes are shown, except for the very many $M \geq 3$ 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, $M \geq 2$ shocks for 28 Jan 1966 - 30 June 1966 are shown.

Figure 3. Location of geophysical instrumentation relative to the preparation zone and the rupture zone of the characteristic Parkfield earthquake.

Figure 4. Seismic instrumentation near Parkfield. See caption for Figure 3. The letter code designation corresponds to the list given in the text. Borehole seismographs exist at PGD, PJQ, and PVC (located within about 50 m of the CALNET sensor at PVC.) The location of the strong-motion sensors operated by CDMG are shown in McJunkin and Shakal (1983).

Figure 5. Creepmeters located near Parkfield. See caption for Figure 3. The creepmeter at Slack Canyon (SLC1) is located on the trace of the San Andreas fault just off the top of the map.

Figure 6. Strainmeters (borehole dilatometers, tiltmeters, and linear strainmeter) located near Parkfield. See caption for Figure 3.

Figure 7. Water wells located near Parkfield. See caption for Figure 3.

Figure 8. Magnetometers located near Parkfield. See caption for Figure 3. Magnetometer sites at Antelope Grade (AGDM) and at Grant Ranch (GRAM) are near the trace of the San Andreas fault off the map to the south.

Figure 9. Two-color geodolite reflector sites located near Parkfield. See caption for Figure 3.

Figure 10. (a) Seismic alert zones near Parkfield. The Middle Mt. alert zone includes shocks with epicenters within the small figure centered on Middle Mt. and with focal depths $\geq$ 6.5 km. The Parkfield area alert zone extends along the San Andreas fault trace from the creeping section northwest of Middle Mt. to the Simmler section southeast of Cholame.
(b) Probability of a characteristic Parkfield earthquake in the 24 hours following the occurrence of a potential foreshock of magnitude M.

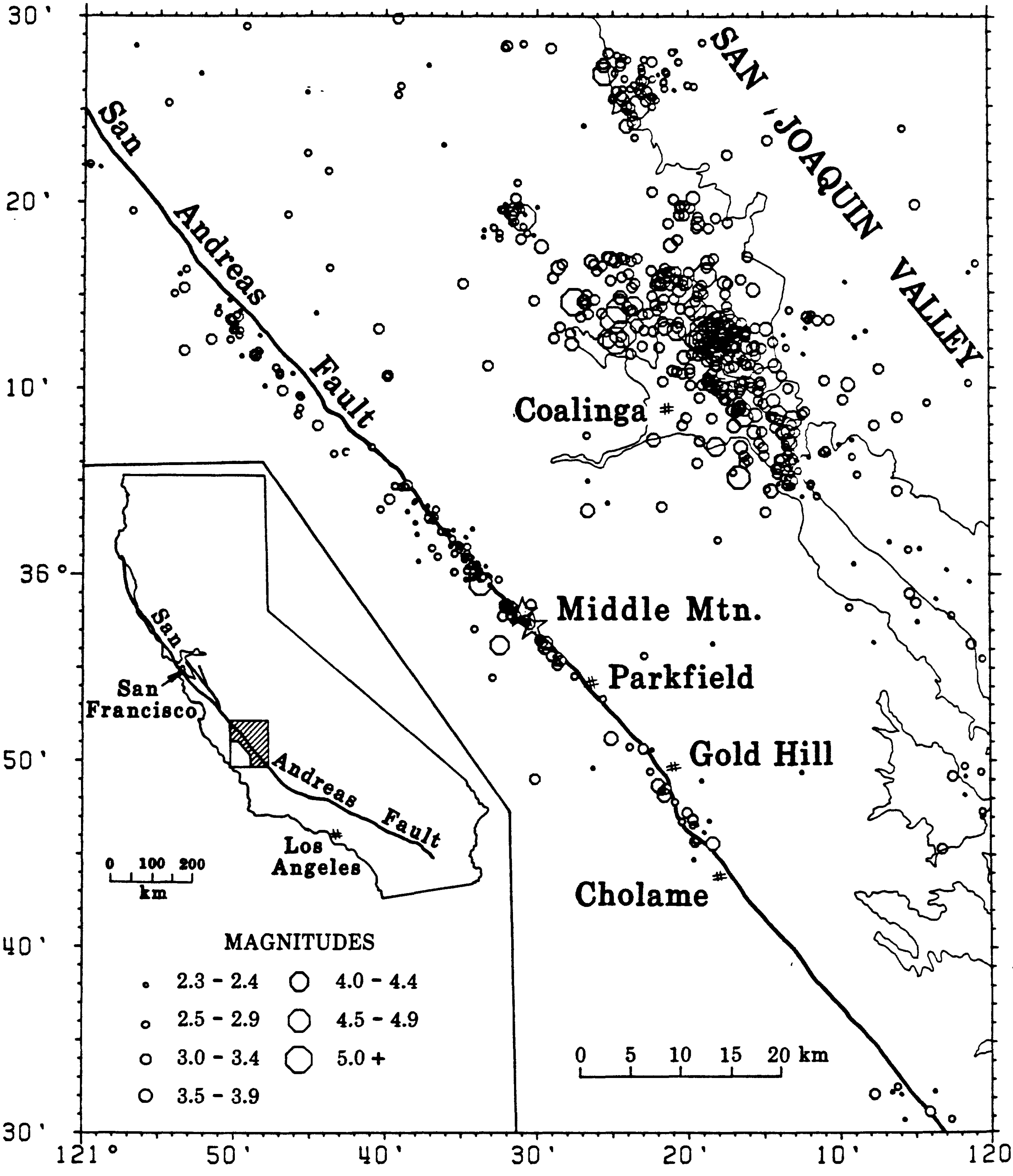
Figure 11. (a) A creep step recorded at XMM1, caused by telemetry problems. This signal triggered the beeper-paging system (an e alert level). (b) A creep event recorded at XMM1. Although not large enough for a d level alarm, it did trigger the beeper-paging system (an e alert level). (c) Sustained rapid 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.

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 the 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.

Figure 14. Distance readings to 11 reflector sites in the Parkfield 2-color geodimeter network recorded between April 18 and June 12, 1985 (error bars represent +/-1 standard deviation). Measurements to stations TODD and HUNT were not begun until late July. Distances to TABLE, MIDE, BARE, and CAN changed by 3 mm or more during the 17 days between April 22 and May 8 (pairs of vertical dashed lines). The change to station MIDE reached the 4-mm minimum required for one of the lines, according to the criteria for alert level d (1) (-4.9 +/-0.8 mm if the event window is extended to May 16, a full 25 days).

Figure 15. Distance readings to 12 reflector sites in the Parkfield 2-color geodimeter network recorded between July 3 and September 29, 1985 (error bars represent +/-1 standard deviation). As for distance changes to MASON, records for station TODD show no length changes meeting the alert level d criteria and are omitted. Distances to MELV, TABLE, MIDE, and HUNT changed 3 mm or more during the 24 days between July 28 and August 20 (pairs of dashed vertical lines). Distance changes to stations TABLE and MIDE exceeded the 4-mm minimum required for at least one line, according to the criteria for alert level d (1).



30'
20'
10'
36°
50'
40'
30'
121°
50'
40'
30'
20'
10'
120°
San Andreas Fault
SAN JOAQUIN VALLEY
Coalinga
Middle Mtn.
Parkfield
Gold Hill
Cholame
San
San Francisco
Andreas Fault
Los Angeles
0 100 200
km
MAGNITUDES
2.3 - 2.4
2.5 - 2.9
3.0 - 3.4
3.5 - 3.9
4.0 - 4.4
4.5 - 4.9
5.0 +
0 5 10 15 20 km

Figure 1

PARKFIELD SEISMICITY

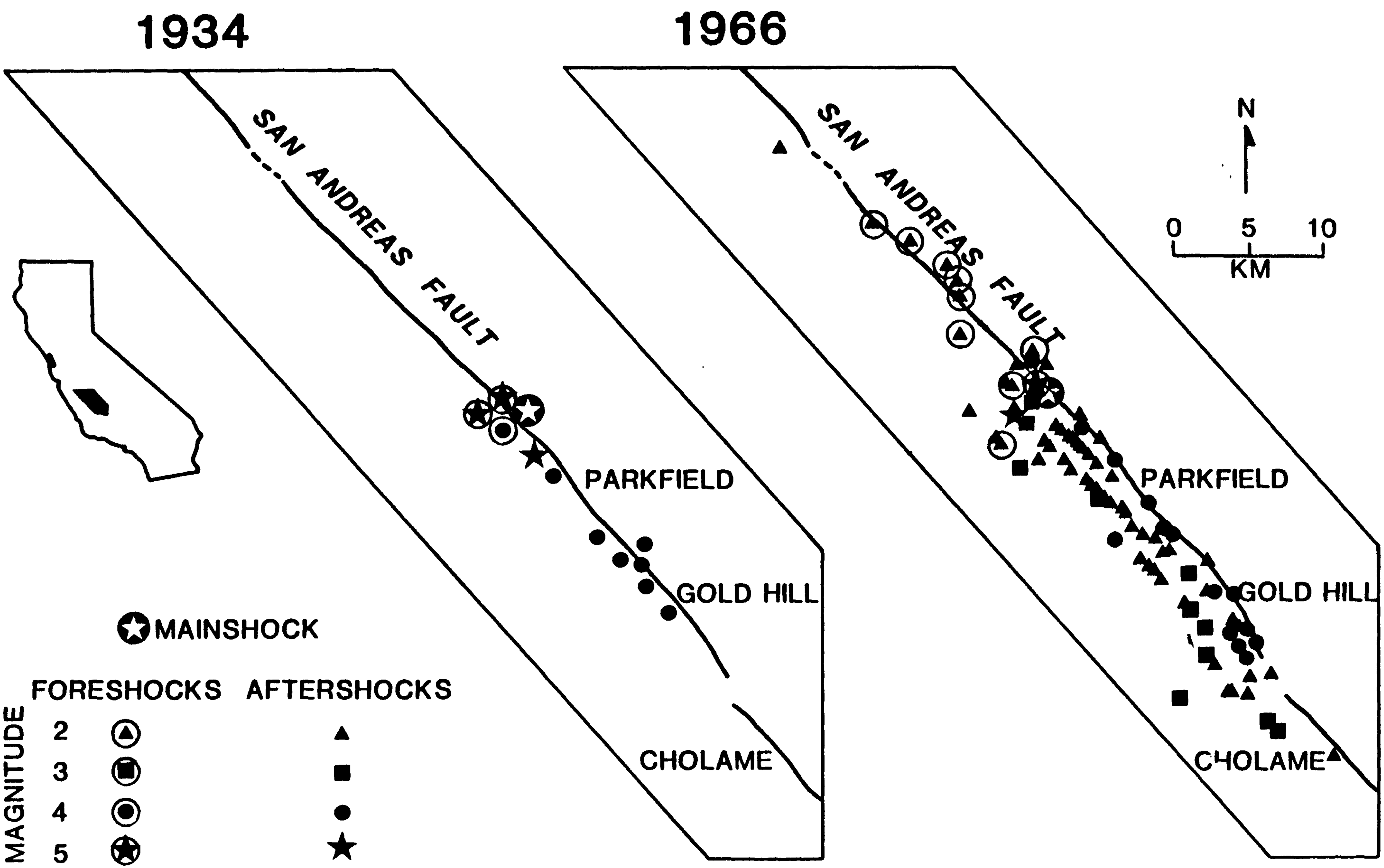


Figure 2

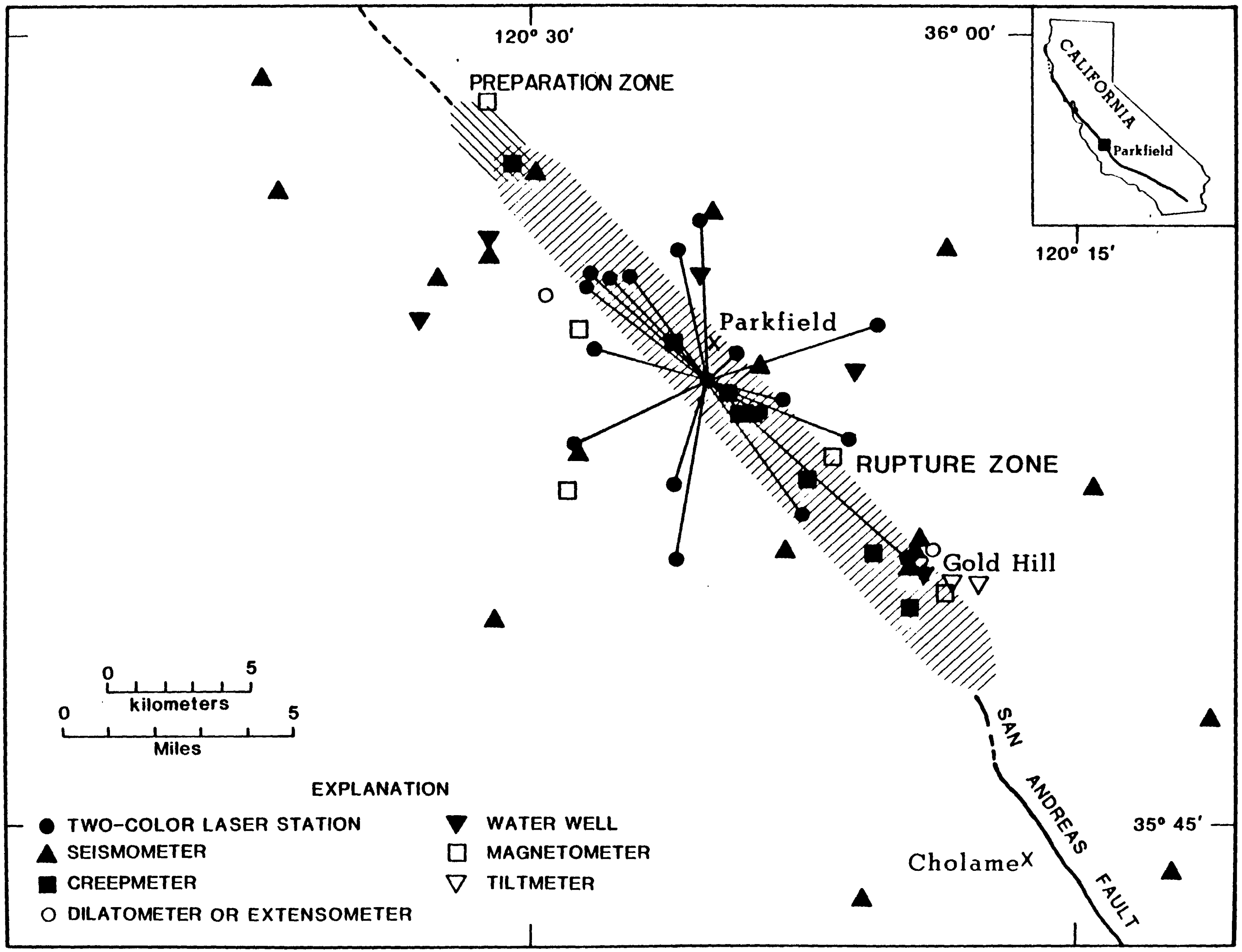

120° 30′
36° 00′
120° 15′
35° 45′
CALIFORNIA
Parkfield
PREPARATION ZONE
Parkfield
RUPTURE ZONE
Gold Hill
SAN ANDREAS FAULT
Cholame
0 5 kilometers
0 5 Miles
EXPLANATION
TWO-COLOR LASER STATION
SEISMOMETER
CREEPMETER
DILATOMETER OR EXTENSOMETER
WATER WELL
MAGNETOMETER
TILTMETER

Figure 3

SEISMOMETERS

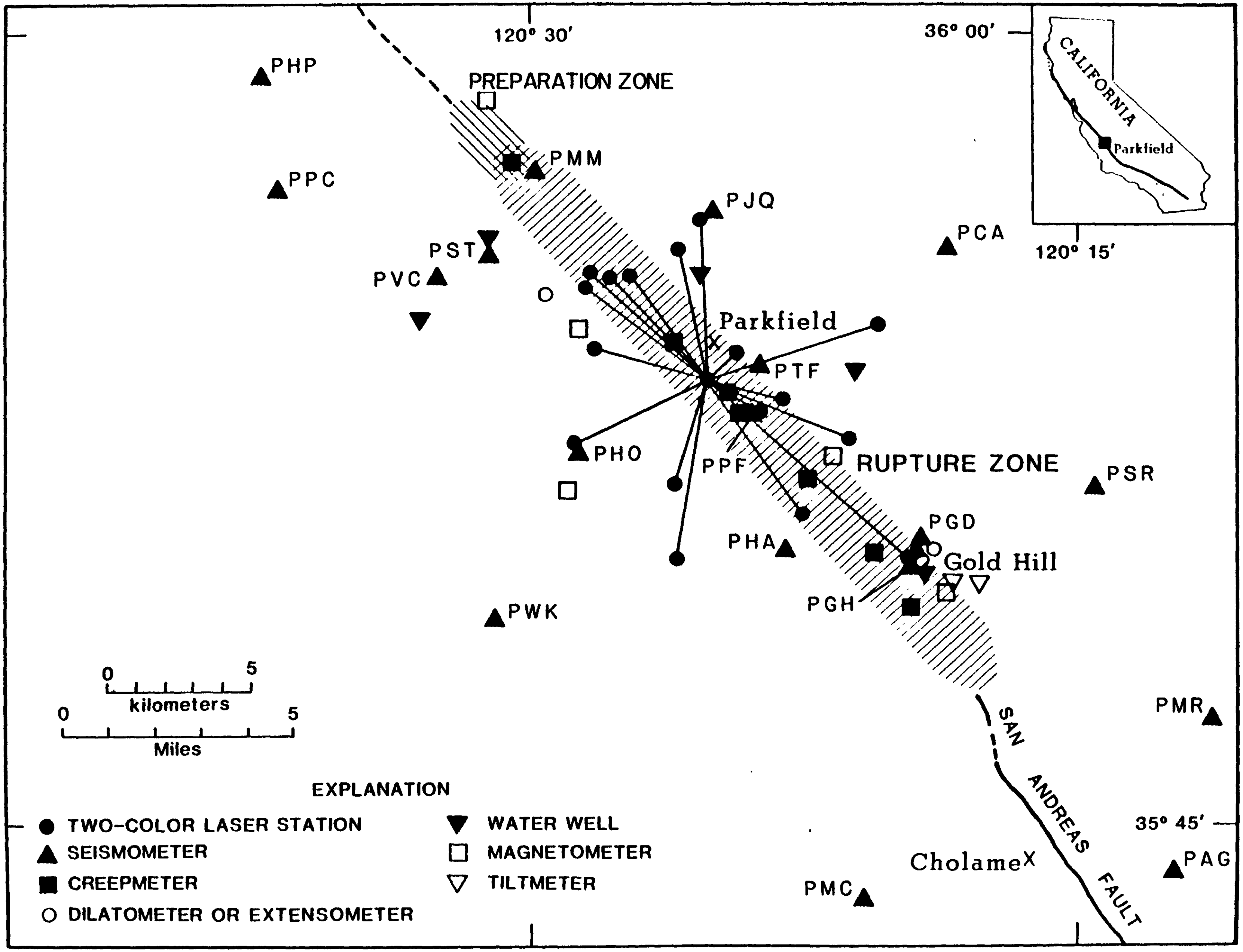


Figure 4

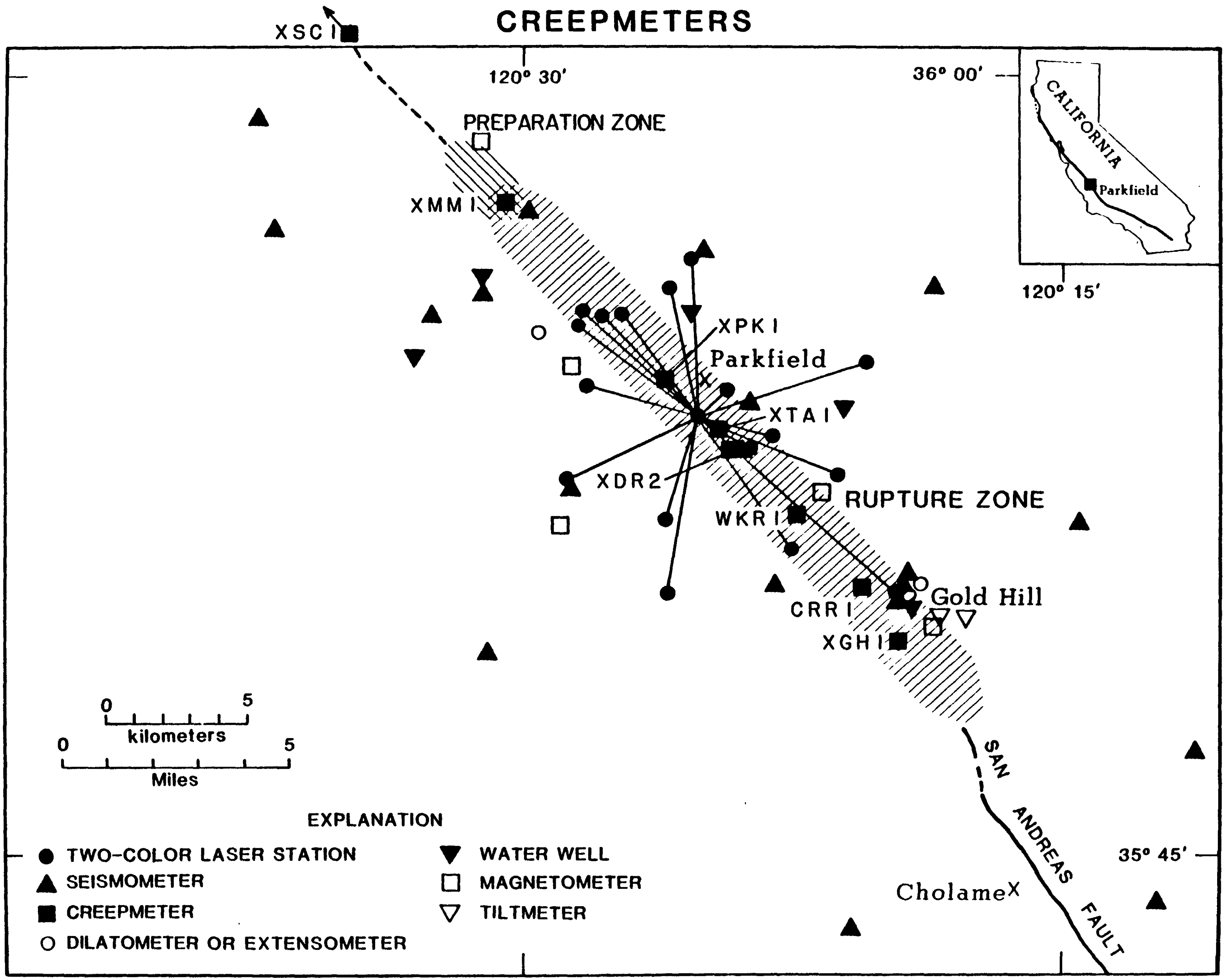

CREEPMETERS
XSC I
120° 30'
36° 00'
CALIFORNIA
Parkfield
120° 15'
PREPARATION ZONE
XMM I
XPK I
Parkfield
XTA I
XDR2
RUPTURE ZONE
WKR I
Gold Hill
CRR I
XGH I
0
5
kilometers
0
5
Miles
SAN ANDREAS FAULT
35° 45'
Cholame
EXPLANATION
TWO-COLOR LASER STATION
SEISMOMETER
CREEPMETER
DILATOMETER OR EXTENSOMETER
WATER WELL
MAGNETOMETER
TILTMETER

Figure 5

DILATOMETERS, EXTENSOMETERS, AND TILTMETERS

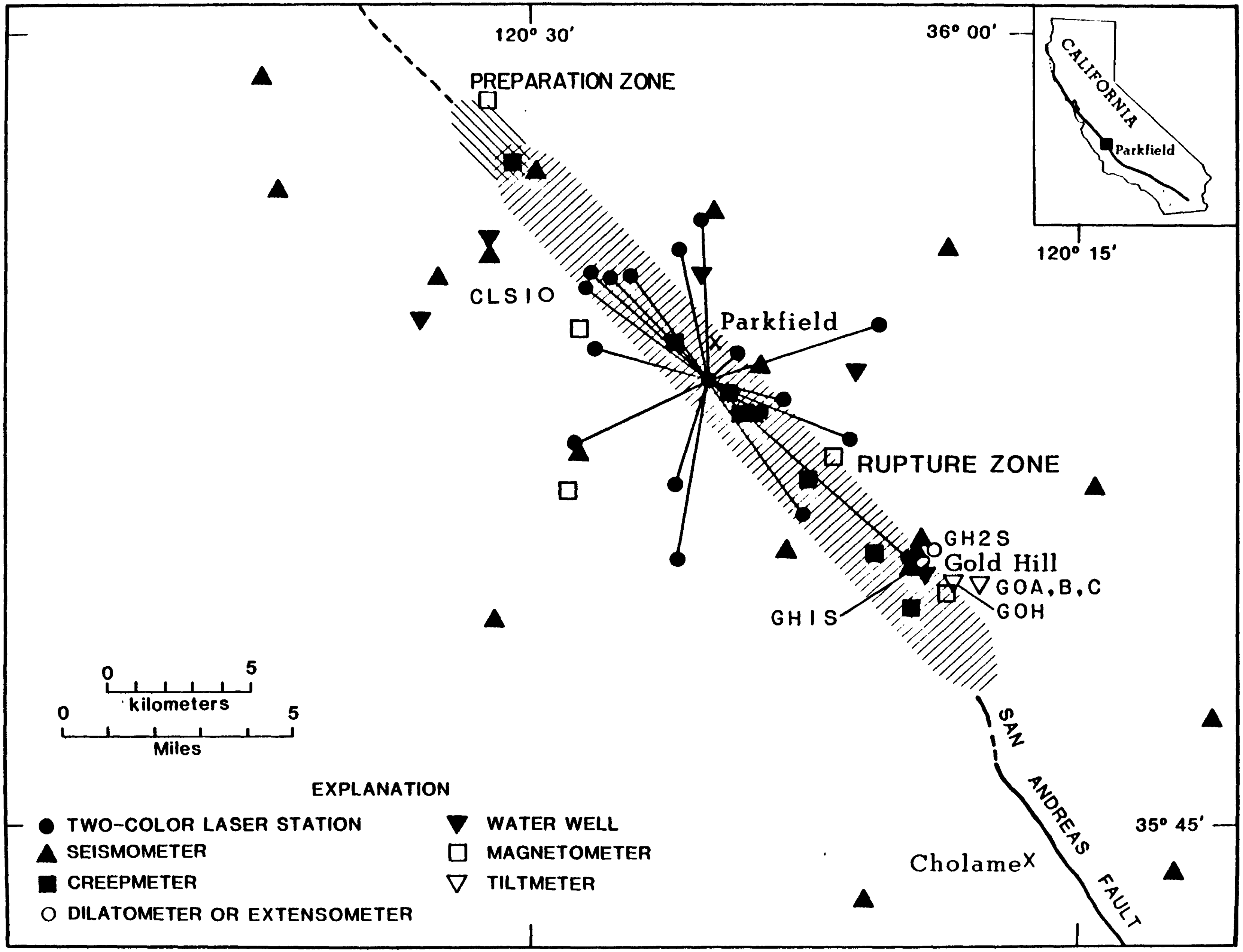


Figure 6

WATER WELLS

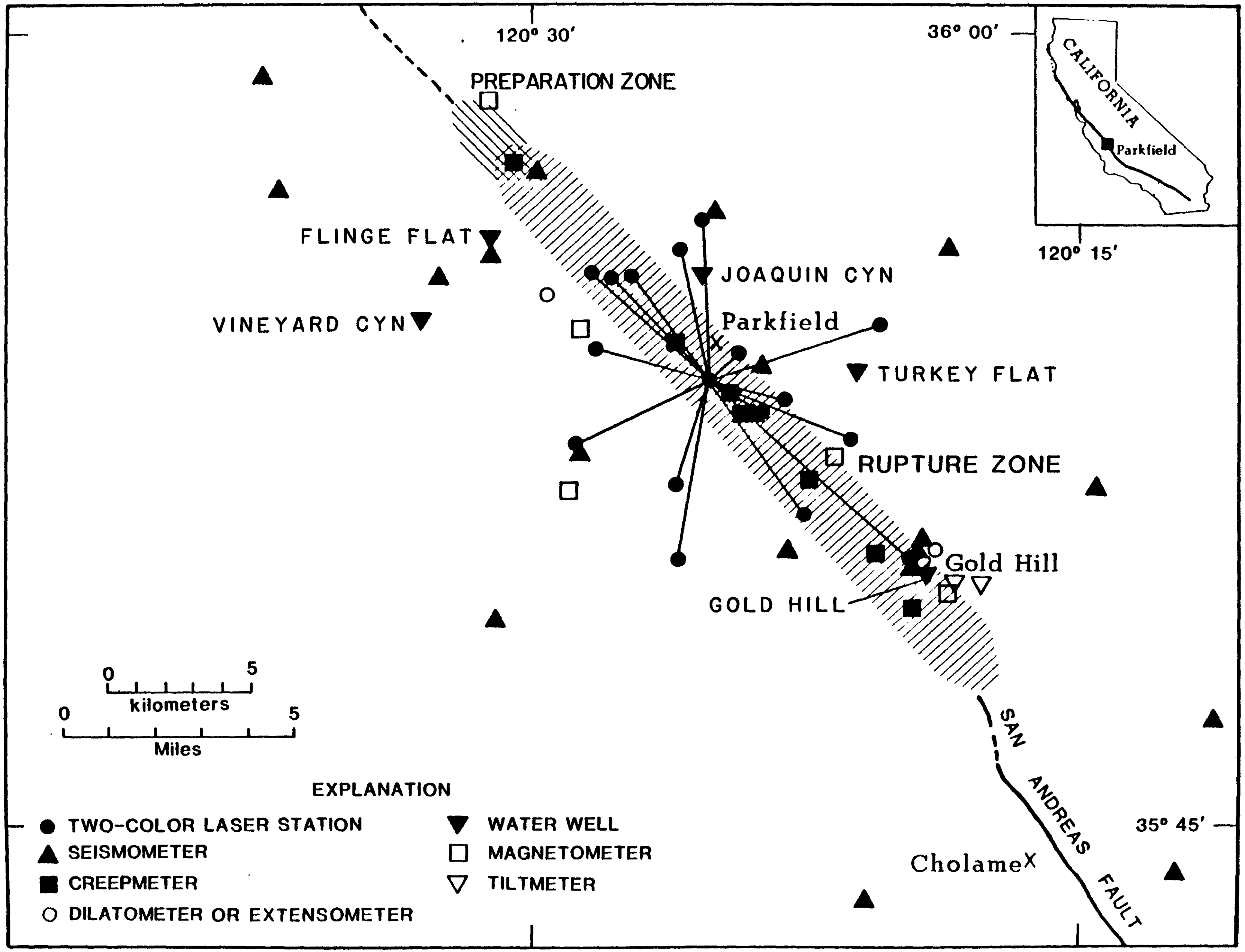


Figure 7

MAGNETOMETERS

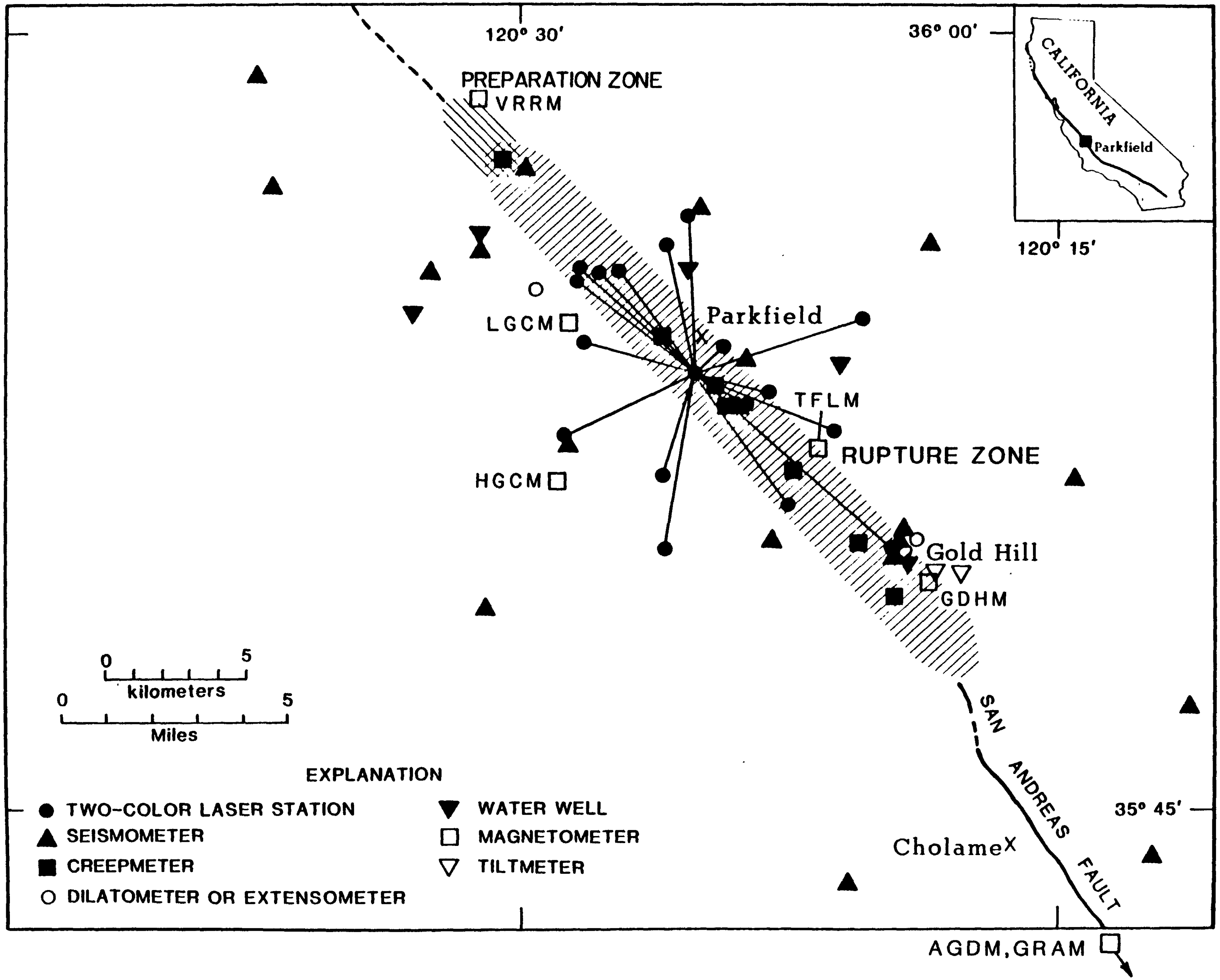


Figure 8

TWO-COLOR LASER STATIONS

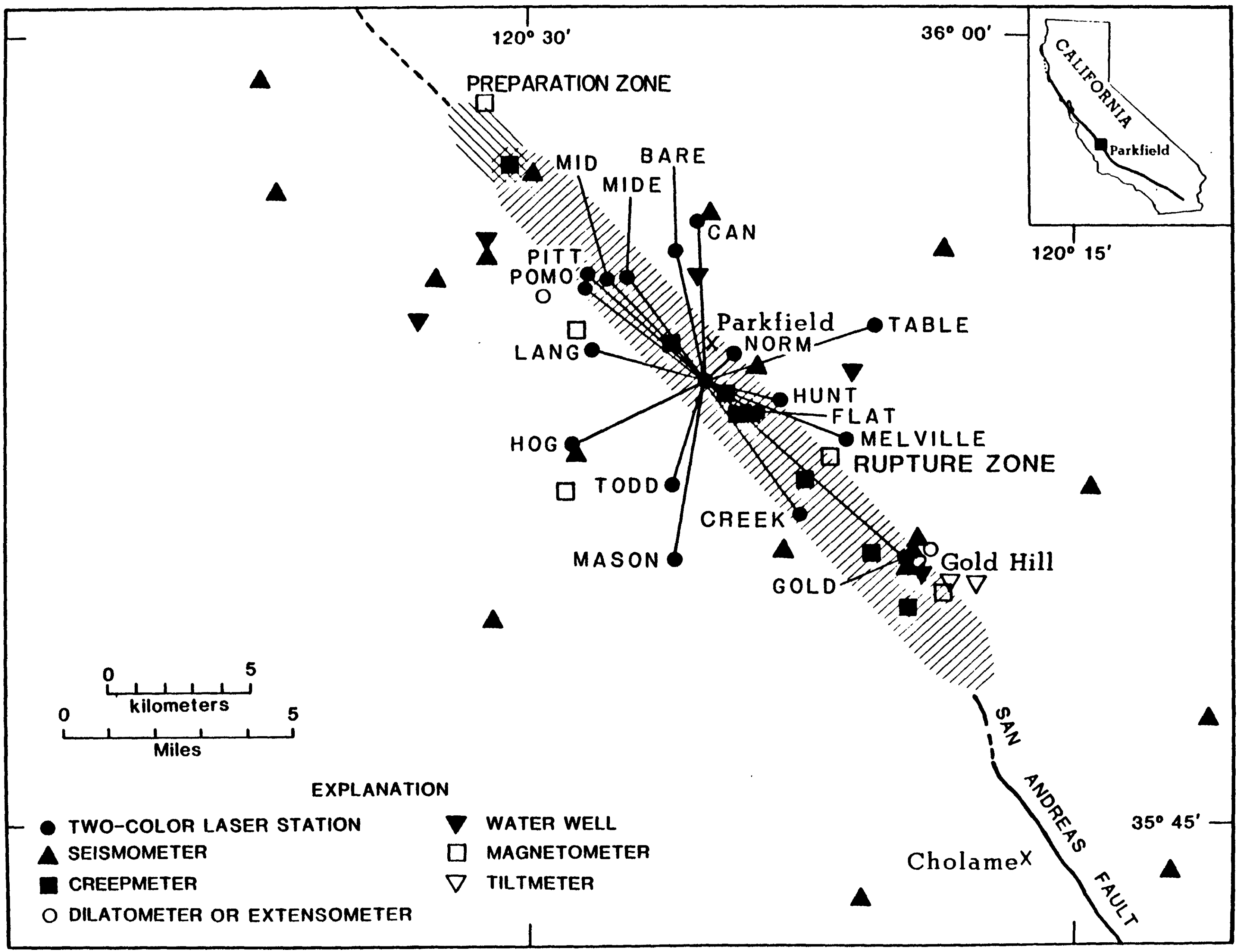


Figure 9

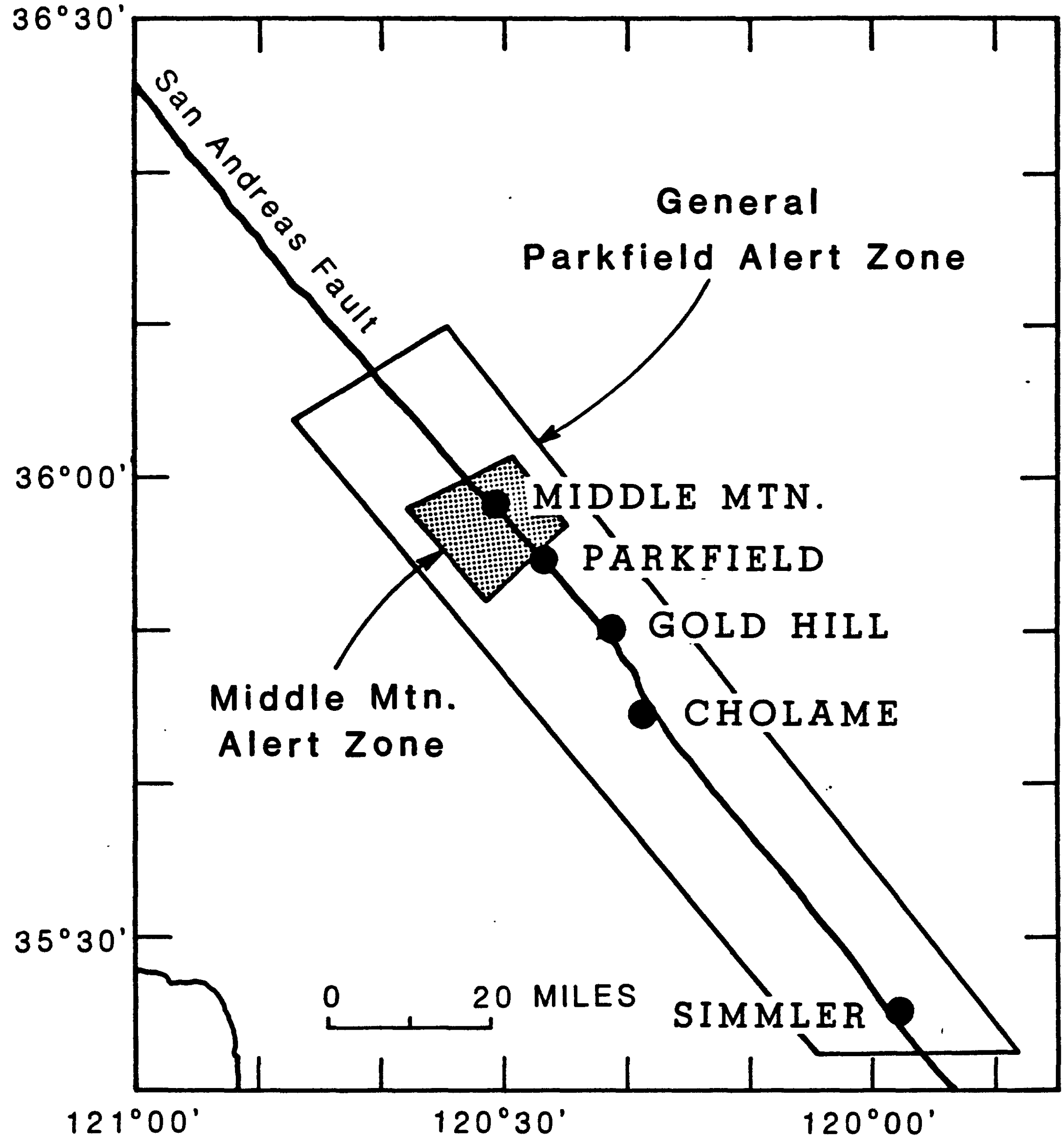

36°30'
36°00'
35°30'
121°00'
120°30'
120°00'
San Andreas Fault
General
Parkfield Alert Zone
MIDDLE MTN.
PARKFIELD
GOLD HILL
CHOLAME
Middle Mtn.
Alert Zone
0
20 MILES
SIMMLER

Figure 10a

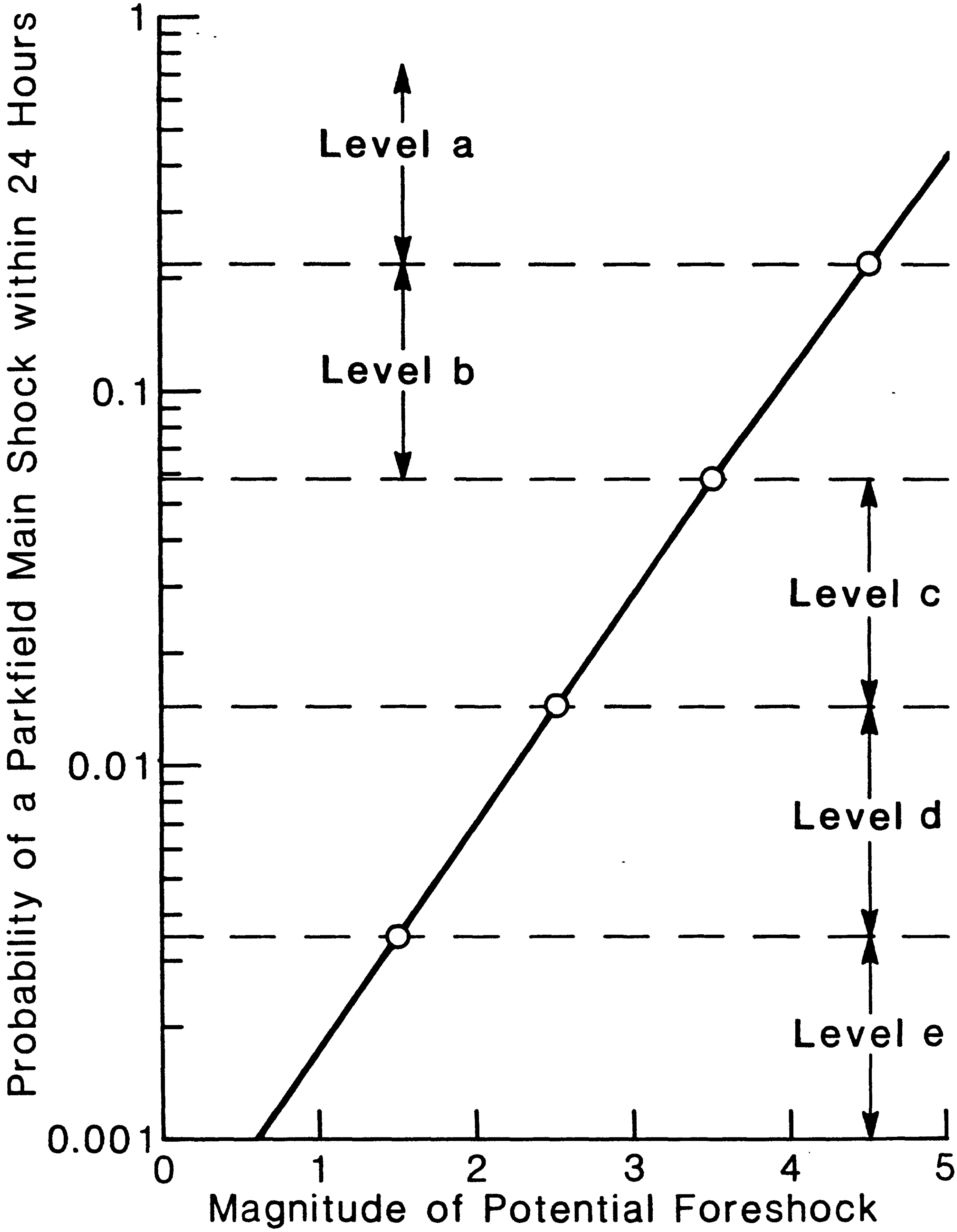

Probability of a Parkfield Main Shock within 24 Hours
1
0.1
0.01
0.001
Level a
Level b
Level c
Level d
Level e
0
1
2
3
4
5
Magnitude of Potential Foreshock

Figure 10b

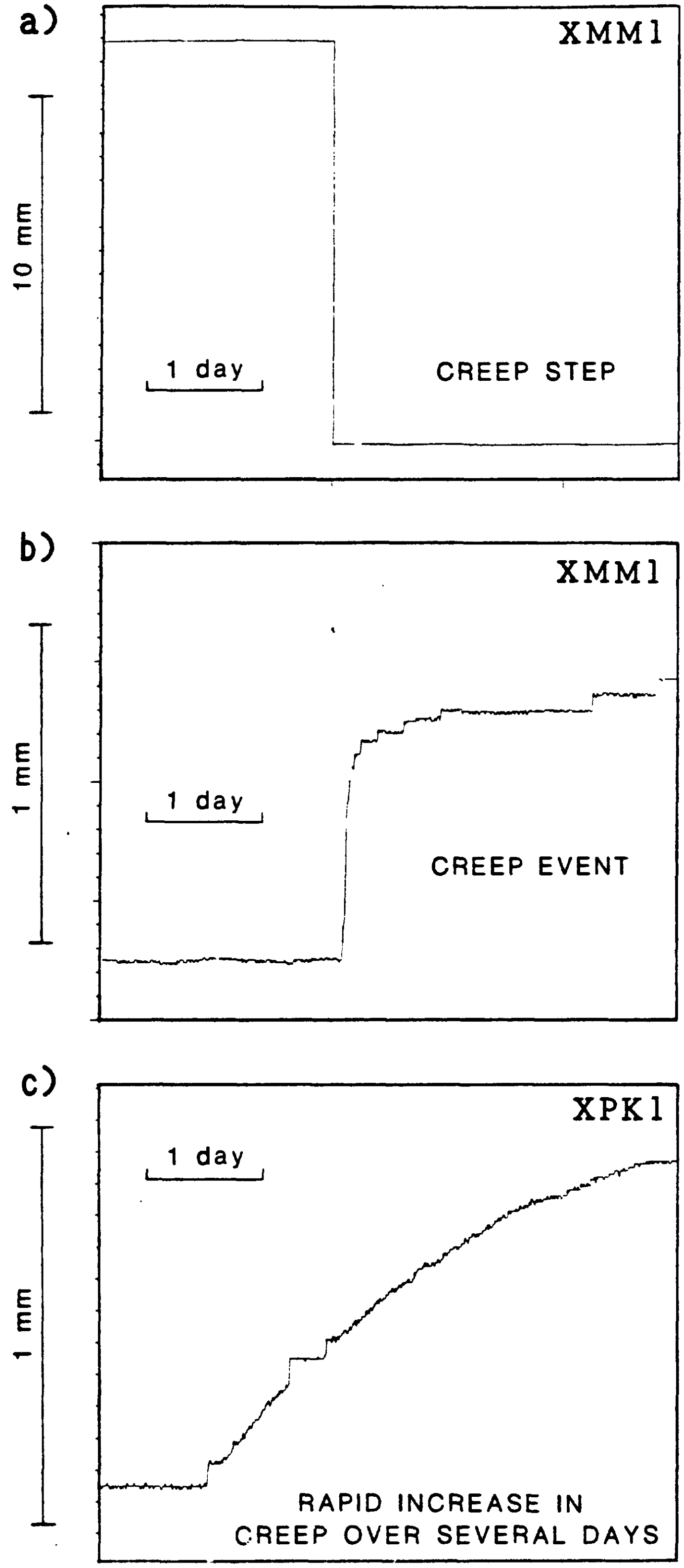
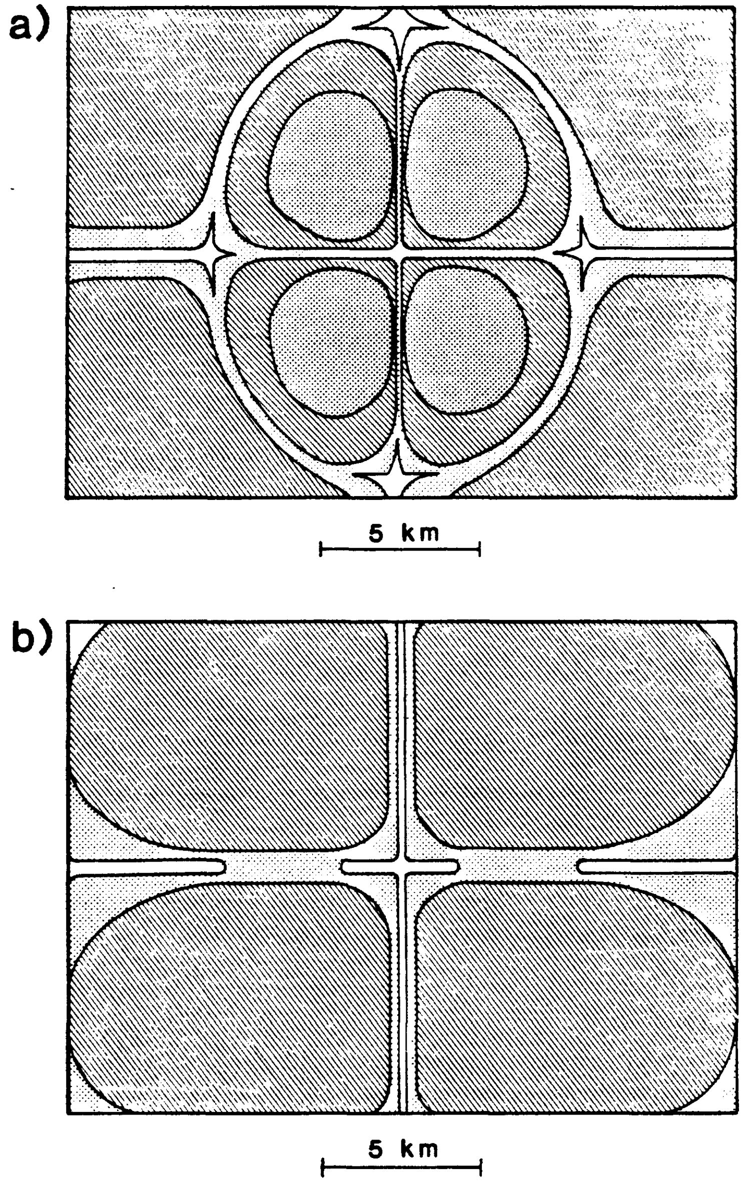

a)
XMM1
10 mm
1 day
CREEP STEP
b)
XMM1
1 mm
1 day
CREEP EVENT
c)
XPK1
1 day
1 mm
RAPID INCREASE IN
CREEP OVER SEVERAL DAYS

Figure 11



Moment, dyne-cm

	10^{25}	10^{24}	10^{23}
	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

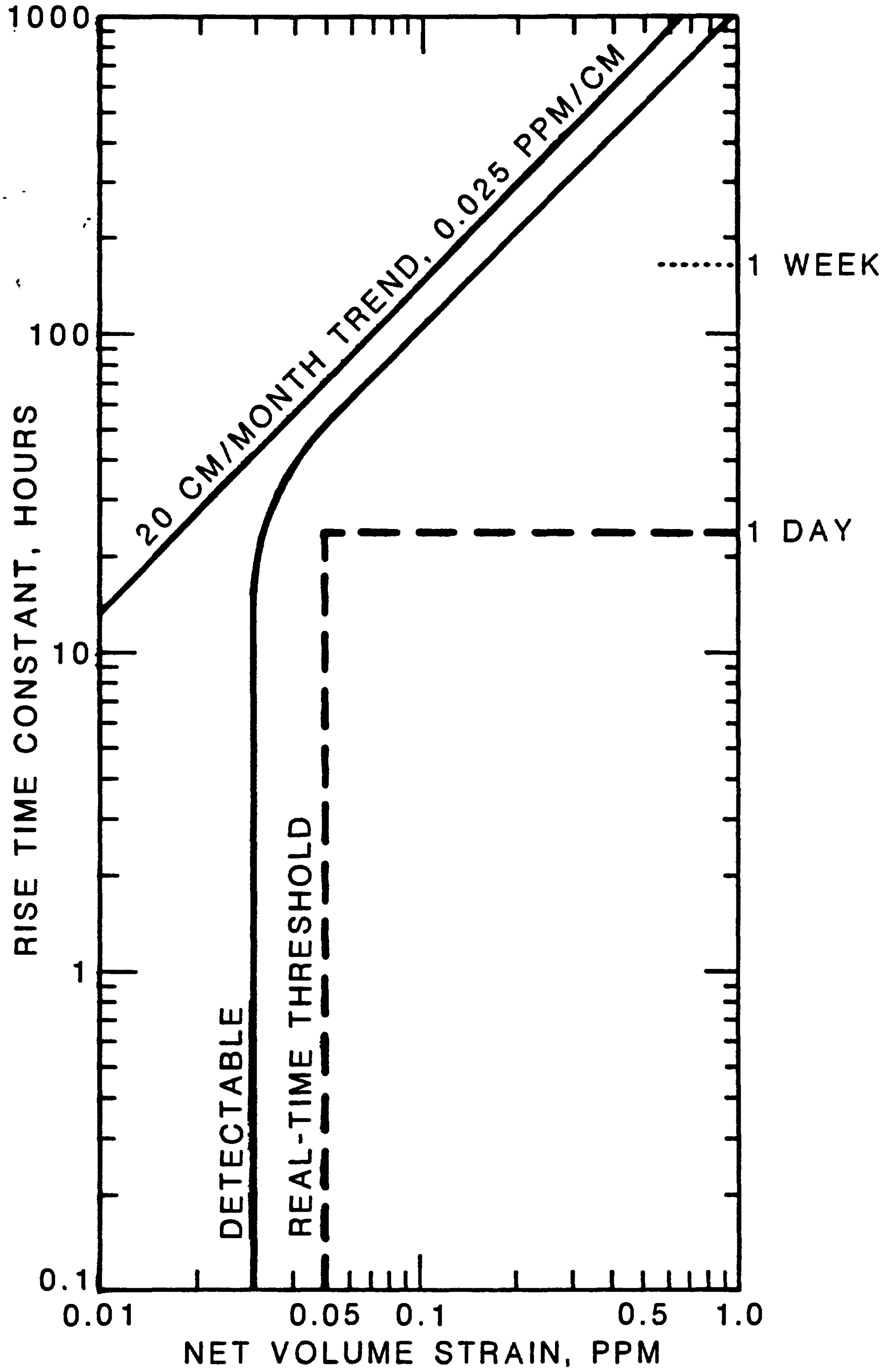

1000
100
10
1
0.1
RISE TIME CONSTANT, HOURS
20 CM/MONTH TREND, 0.025 PPM/CM
1 WEEK
1 DAY
DETECTABLE
REAL-TIME THRESHOLD
0.01
0.05
0.1
0.5
1.0
NET VOLUME STRAIN, PPM

Figure 13

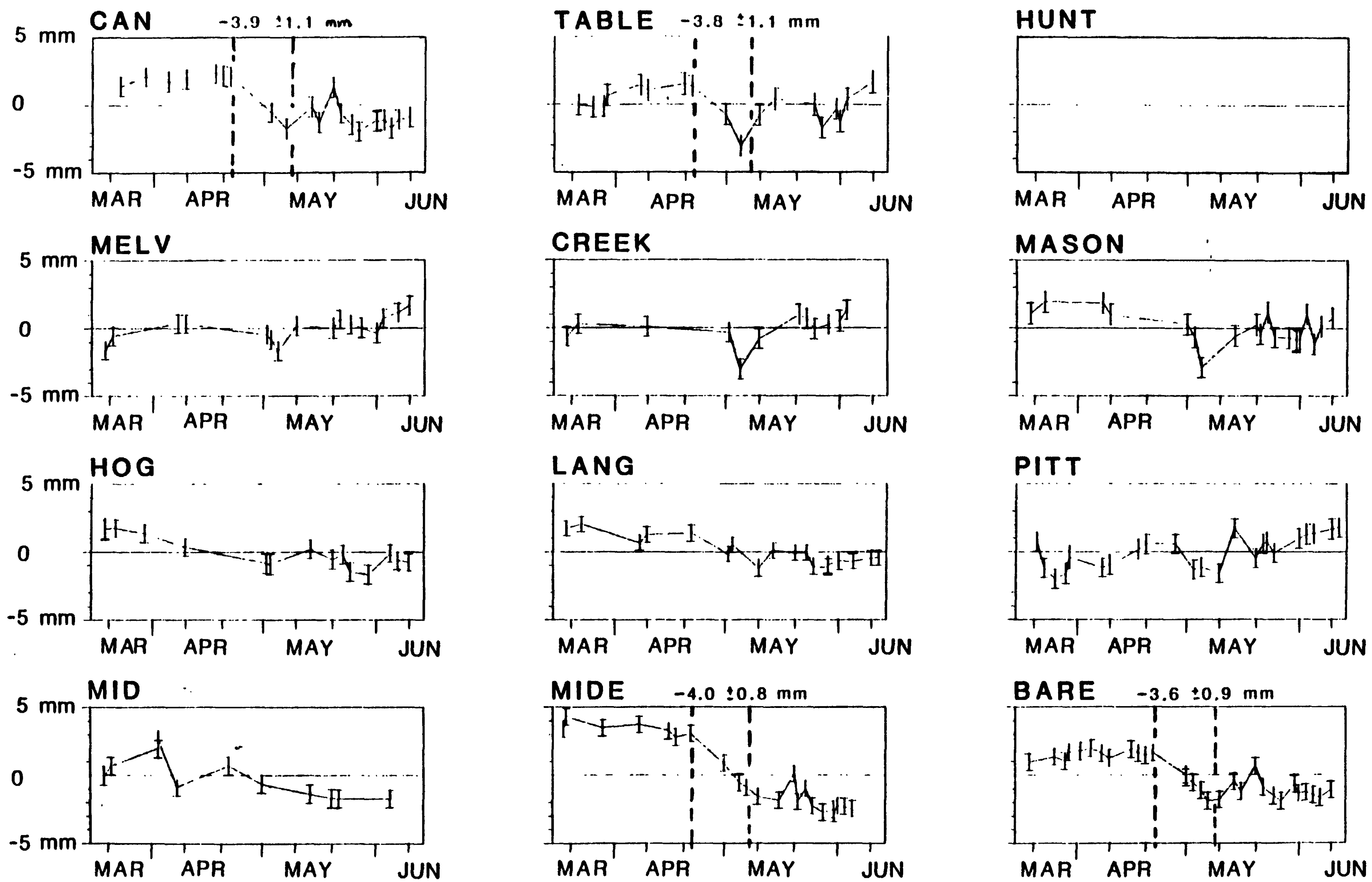

CAN
-3.9 ±1.1 mm
TABLE
-3.8 ±1.1 mm
HUNT
MELV
CREEK
MASON
HOG
LANG
PITT
MID
MIDE
-4.0 ±0.8 mm
BARE
-3.6 ±0.9 mm
5 mm
0
-5 mm
MAR
APR
MAY
JUN

Figure 14

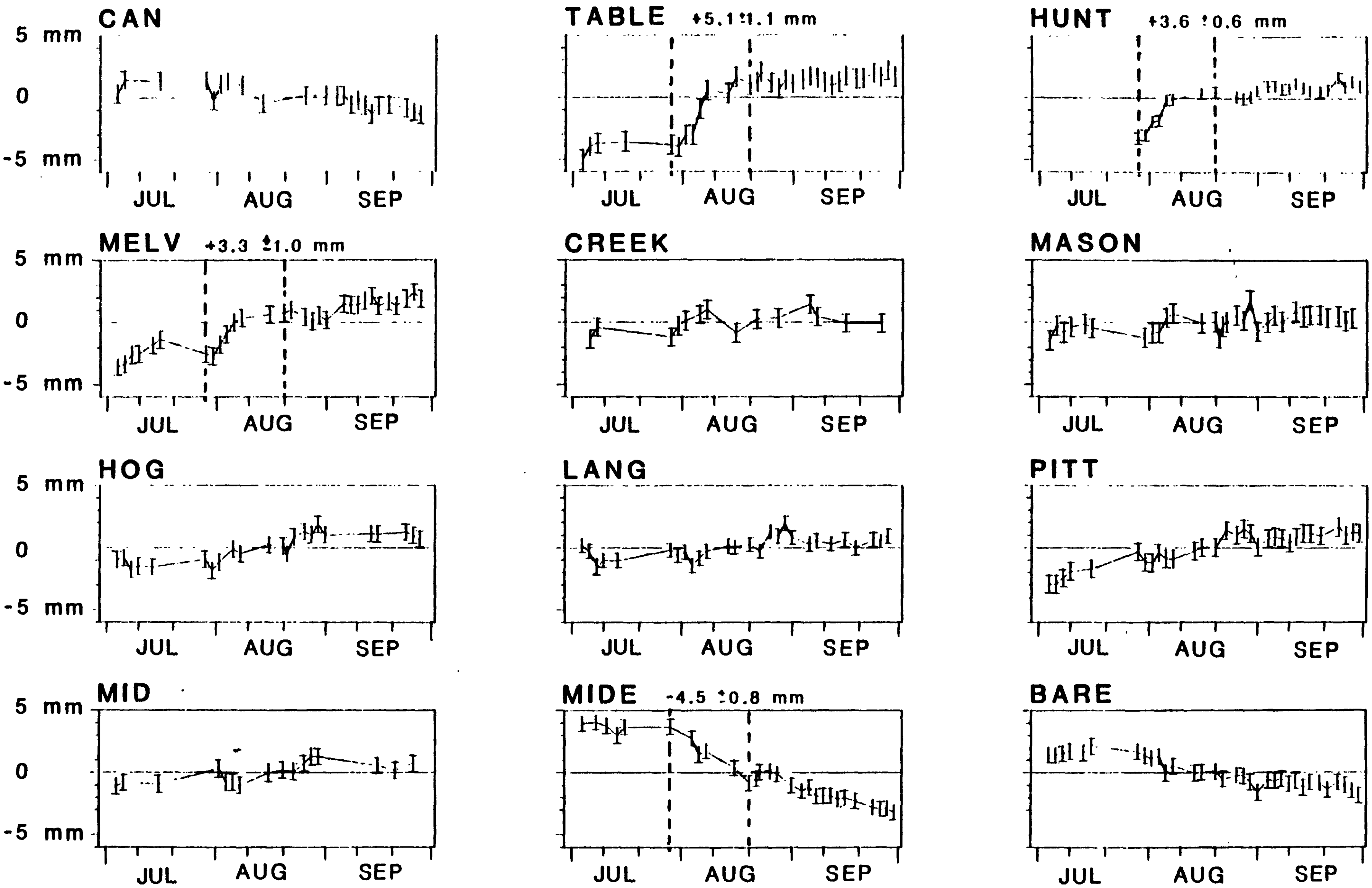

CAN
TABLE +5.1 ±1.1 mm
HUNT +3.6 ±0.6 mm
MELV +3.3 ±1.0 mm
CREEK
MASON
HOG
LANG
PITT
MID
MIDE -4.5 ±0.8 mm
BARE
5 mm
0
-5 mm
JUL
AUG
SEP

Figure 15