DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

MINUTES OF THE NATIONAL EARTHQUAKE PREDICTION EVALUATION COUNCIL NOVEMBER 16-17, 1984 Menlo Park, California

by
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Open File Report 85-201

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PREFACE

The National Earthquake Prediction Evaluation Council (NEPEC) was established in 1979 pursuant to the Earthquake Hazards Reduction Act of 1977 to advise the Director of the U.S. Geological Survey (USGS) in issuing any formal predictions or other information pertinent to the potential for the occurrence of a significant earthquake. It is the Director of the USGS who is responsible for the decision whether and when to issue such a prediction or information.

NEPEC, also referred to in this document as the Council, according to its charter is comprised of a Chairman, Vice Chairman, and from 8 to 12 other members appointed by the Director of the USGS. The Chairman shall not be a USGS employee, and at least one-half of the membership shall be other than USGS employees.

The USGS has not published the minutes of earlier meetings of NEPEC. This open-file report is the first in an anticipated series of routinely published proceedings of the Council.

NATIONAL EARTHQUAKE PREDICITION EVALUATION COUNCIL

Friday, 16. November, 1984 Menlo Park, California

Council Members Present

Dr. Lynn R. Sykes, Chairman, Lamont-Doherty Geological Observatory Columbia University
Dr. John R. Filson, Vice-Chairman, Chief, Office of Earthquakes, Volcanoes, and Engineering, USGS
Dr. Clem Shearer, Executive Secretary, USGS
Dr. John Davies, Alaska Department of Natural Resources
Dr. Thomas McEvilly, University of California, Berkeley
Dr. Mark Zoback, Stanford University
Dr. Keiiti Aki, University of Southern California
Dr. James H. Dieterich, USGS
Dr. William Ellsworth, USGS
Dr. Wayne Thatcher, USGS
Dr. Robert E. Wallace, USGS

Observers Present

Paul Seigel, USGS
Al Lindh, USGS
George Gryc, USGS
John Healy, USGS
William J. Kockelman, USGS
Cynthia Ramseyer, USGS (recording secretary)
Kerry Sieh, USGS
Robert Page, USGS
Teresa Rodriguez, USGS
Sandra Schulz, USGS
Wanda Seiders, USGS
Edna King, USGS

Opening Remarks

Chairman Sykes opened the meeting by reviewing several goals he would like to see the NEPEC pursue: to meet several times a year for on-going reviews of high-risk areas; to advise the Director of the USGS of earthquake hazards and earthquake potential at specific sites; to take a more active role in earthquake prediction; and to publish quickly information (scientific papers and data bases) reviewed by NEPEC regarding earthquake potential and predicition.

Filson observed that this meeting could be an historic moment for the NEPEC if it should chose to take a more active role. He suggested that NEPEC can "do more than respond to other people's prediction" and that the NEPEC could set a pace that would enable it to present to the country a "systematic review of the situation in seismic areas."

Filson also noted that there is a polarization of opinion about long-term and short-term prediction, and that an issue before NEPEC is how to determine criteria for prediction and for advising the USGS Director of earthquake potential and hazard.

Sykes reviewed briefly the history of the NEPEC, which was chartered under the 1978 National Earthquake Hazards Reduction Program, and outlined some of the responsibilities and issues NEPEC might pursue:

- need for a mechanism for quick publication of data,
- relationship with the media and press,
- relationship (reciprocity) with the California Earthquake Prediction Evaluation Council,
- short-term responses to rapidly changing conditions,
- review of critical seismic areas, and
- determination of language for issuing earthquake hazard warnings.

Concerns not on this meeting's agenda, but which nevertheless should be addressed:

- A review of the legal status of the NEPEC, especially the personal and professional liability of individuals, in both the Federal and private sectors, who serve on the NEPEC; Council may ask for Dept. of the Interior solicitor's review and advice.
- How to minimize or avoid misrepresentations to the public.
- Ongoing communication within NEPEC by means of small working groups that might meet or teleconfer on a regular basis.
- Guidelines for NEPEC repsonse to predictions that are presented to NEPEC.
- Recommendation that NEPEC continue to follow its previous policy of not making any reviews of foreign predictions unless specifically asked by the USGS Director.

AGENDA ITEM: NEPEC's ROLE

Wallace agreed that NEPEC should be more active. Also, he stated that earthquake predictions will not be made by individuals but by groups and will evolve with the accumulation and analysis of data. He further noted that the ongoing monthly prediction meetings at the USGS reflect such an evolutionary process, in that it is a group effort between the USGS and private contractors that relies on a redundancy of data. Wallace also noted that raw data and preliminary interpretations of the monthly USGS meetings are on record and printed quickly.

Dieterich spoke to NEPEC taking a more active role in long-term forecasting, and the need to identify pre-agreed upon "triggers" that would enable NEPEC to respond quickly in making short-term predictions. He recommended regular reviews of long-term forecasting by the Council as a way to focus the long-and short-term purposes of the NEPEC.

Davies spoke to a change of emphasis for NEPEC towards long-term prediction. By so doing, NEPEC could lend credence to the idea that certain circumstances promote further investigation of earthquake potential.

Aki, in referring to the Japanese model of earthquake predicition, voiced some concern about the time demands and logistics of calling the NEPEC together on a more frequent or regular basis.

McEvilly pointed out that earthquake probability maps and the Parkfield experiment have been developed since the last NEPEC meetings (1/81 and 6/82).

Filson pointed out that California earthquake probability maps have not been brought before the NEPEC and have not been formally transferred to the State of California; and that the USGS has previously issued several formal statements regarding earthquake hazards to the State of California and that these statements should be reviewed and either updated or cancelled.

Sykes referred to the Japanese model for earthquake prediction and felt that there was a problem with the council in Japan being too large and too formal to make it directly applicable to the United States. The ongoing monthly review at Menlo Park (USGS) could in part suffice as an informal, ongoing mode of earthquake prediction communication and information.

Sykes/Filson suggested that specialists be asked to be present at NEPEC meetings to present their data or make evaluations. NEPEC should also be receptive to persons coming before the Council with earthquake predictions; it needs to respond quickly to data that is put before it.

Dieterich stated that long-term prediction is necessary: NEPEC must be aware of data on long-term predictions, so as to make an informed judgement about short-term predictions.

Ellsworth recommended a NEPEC base of long-term potential data, and a systematic and ongoing review of long-term prediction data by NEPEC, so that if NEPEC is forced to (or decides to) make short-term predictions, the Council has information available on potential long-term behavior.

Sykes mentioned that three groups (USGS, Lamont, and Caltech) have produced earthquake probability maps that are essentially in agreement with one another: NEPEC should review these yearly or every other year.

Zoback mentioned short-term problems confronting NEPEC:

1. NEPEC hasn't yet acquired the background (data) to make judgements about specific sites, and

2. NEPEC needs to familiarize itself with instruments and data related to specific sites. Suggested that the NEPEC needs a system to gather, synthesize, and evaluate data.

Sykes responded with a suggestion that to make sure data gets shared quickly and accurately, perhaps data could be kept simultaneously in several locations and be available to qualified users by a dial-up phone capability.

Wallace brought up the "Ridgecrest Affair" wherein politics entered into a scientific/technical problem -- this is an issue when the use and application of scientific data comes under political purview and pressure.

Thatcher suggested that formal decisions need to be made in a logical sequence: identify areas that need concentrated attention and bring regular updates to NEPEC.

Filson felt it was necessary to identify and limit areas of study to specific sites; otherwise NEPEC will be forced into taking a merely responsive rather than active role in earthquake prediction.

McEvilly suggested that perhaps NEPEC should remain strictly responsive to prediction data brought to the council, rather than risk a conflict of interest either by reviewing predictions that the Council will have guided by its review process or by soliciting or sponsoring probability studies of certain sites.

Filson pointed out that the USGS already has "in house" prediction activities: unusual data should be brought to the Director's attention with NEPEC's evaluation and advice.

Aki suggested a prosecuting/defending mode for NEPEC, with the Council acting as a jury, determining the proofs and validity of earthquake predictions. Copies of a new California law (Chapter 1284, Laws of 1984) concerning public immunity from liability for issuing earthquake warnings were distributed.

Zoback countered with the observation that cranks are easy to deal with: data are hard to evaluate, endorse, criticize, and/or recommend.

Wallace made the following recommendation regarding earthquake predictions:

1. Identify regions of long-term earthquake potential.

2. Limit the areas and/or sites that will be evaluated and reviewed.

3. Get background and information data for high-priorty areas.

4. Be prepared to add new data for a site or area and make a statement.

5. Have pre-prepared statement (similar to SCEPP) regarding earthquake areas, sites, and recommendations.

Davies pointed out that by taking an activist role in certain earthquake areas/sites, the NEPEC could compromise its ability to make an impartial judgement.

McEvilly agreed and thought that NEPEC should identify itself as either an "impartial jury" or a "activist participant" in the selection of sites and the gathering of data.

Sykes pointed out that NEPEC would increase the risk of making poor recommendations if it were not fully informed of all or most of the data.

Dieterich wondered what does NEPEC need to do its job? NEPEC needs data to do its job; without it the Council cannot make an intelligent evaluation and decision regarding earthquake prediction statements.

Filson: NEPEC should get more actively involved in critical areas, for the purpose of becoming more knowledgeable about high-priority areas and thereby facilitating its role of advising the Director of the USGS about "issuing predictions". There should also be a familiarization of the data in areas of long-term concern by the NEPEC members; then if there are new data, the NEPEC could meet to evaluate the new or changed data and then make a recommendation to the Director.

The Chairman called for a **CONSENSUS** of the discussion regarding **Long-term Prediction:**

- The NEPEC will take a more activist role within the confines of the Charter.

- The Charter does not need revision at this time.

- NEPEC will look at long-range forecasting on a regular basis and will review updated earthquake probability maps.

- NEPEC will limit areas/sites that it will examine.

- NEPEC will consider predictions brought to it for other areas.

- Speakers will be invited to present prepared data on specific areas to the NEPEC for informational purposes; they are asked to leave a 2-page summary and copies of their figures. They are asked, as far as possible, to include estimates of magnitude and probability of any events predicted.

- Regarding the press/media, NEPEC meetings can't be kept secret; information regarding the meetings must be given to the press. However, sensitive data can be discussed in closed executive session. If there are implications regarding public safety, the press should be included. **Dieterich** supported this proposal with the observation that SCEPP (Southern California Earthquake Preparedness Project) meetings are routinely closed, as the press can be intrusive and demanding and can "interfere with the process of reaching a rational decision in a real crisis." Executive sessions could be called. Edna **King**, (USGS Public Affairs Officer) was consulted, and she observed that cameras can always be excluded, and that there is no need to hold meetings on a "press welcome" basis. It was also noted that at the June 1982 NEPEC meeting, the Council voted to keep its meetings open to the press, with the option to go into executive session if the need arose. **Sykes** recommended that the "press question" be tabled until the next NEPEC meeting, and that at that meeting, legal representation be invited to address both the "open to the press" question and legal liability of NEPEC members.

Agenda Item: DESIGNATION OF TERMS AND SITES FOR EARTHQUAKE PREDICTION

Wallace was asked to present briefly the findings of a paper (co-authored with J. Davis and K. McNally; copies distributed) on earthquake prediction terminology designed to set standards on terms so planning agencies could respond to predictions issued by USGS. The terms below were accepted by the California State Seismic Safety Commission in October of 1983.

SUGGESTED TERMS	DEFINITIONS
Long-term Earthquake Potential	No specific time window; earthquake could occur in a framework of decades, centuries, or millenia.
Earthquake Prediction	A specific time window shorter than a few decades.
Long-term Prediction	Time window of a few years to a few decades.
Intermediate-term Prediction	Time window of a few weeks to a few years.
Short-term Prediction	Time window up to a few weeks.

"Watch" and "forecast" are terms that would be used in conjunction with a prediction regarding a specific event, at a specific magnitude, at a specific location and within a specific time frame (i.e. Parkfield, CA).

Wallace made a motion that these prediction terms be adoped by the NEPEC. The following discussion ensued:

Filson noted that the USGS terms of "notice", "watch", and "warning" have been revised (distributed Federal Register, January 31, 1984) to a one-tier system that encompasses a HAZARD WARNING, defined as a "greater risk than normal and a threat that warrants near-term public response." The USGS makes a probabilistic statement regarding the likelihood of an event, and state and local governments are given notice of hazardous conditions.

Wallace noted that various planning communities have done a good job of making specific contingency plans (preparedness plans) for short-term predictions, and that the proposed prediction terms are targeted for positive psychological impact and public response.

Filson suggested that extant warning statements (distributed for southern California and Yakataga region in Alaska) issued by the USGS be reviewed and recommendations regarding their present status be made to the Director.

Ellsworth raised the question about criteria, or the matrix of probabilities and time windows: high probability/short-term correlation? short-term, low probability of great risk, correlation?

Wallace cited NEPEC agreement of warnings being issued on a high probability/short-term/great risk basis.

Filson added the suggestion that these terms be recommended to the Director, USGS for use as official USGS terminology. **Accepted by consensus.**

Agenda Item: POTENTIAL SITES FOR NEPEC REVIEW

The following sites/locations were cited by **Sykes** for NEPEC consideration:

1. Parkfield, CA, and areas located near northern end of 1857 rupture zone
2. Southern California: San Andreas fault from Tejon Pass to Salton Sea, Anza gap, northern end of San Jacinto fault
3. Alaska: Shumagin and Yakataga Gaps
4. San Francisco Bay Area, CA: San Andreas fault from near San Jose to SE end 1906 rupture zone, Calaveras and Hayward faults, East Bay area
5. Eastern Sierras: area to the north of 1872 rupture zone; but not including volcanic hazards
6. Wasatch Front, Utah: Salt Lake City
7. Puget Sound, Washington: Pacific NW subduction zone
8. Puerto Rico Trench/Virgin Islands
9. Kern County/Coalinga, CA

The following persons addressed the NEPEC on the following sites:

Robert Page of USGS discussed the Yakataga Gap in Alaska.

John Davies discussed the Shumagin Gap, and made the observation that this site is likely to have a major earthquake in the next two decades, and that it is of concern due to increasing population, economic impact, and off-shore drilling.

Ellsworth discussed California, with the observation that the San Andreas fault in the Salton trough is creeping, and that a large earthquake would not be unexpected in Southern California at any time. High probability areas are Anza, Riverside, and Parkfield. In the San Francisco Bay Area, he mentioned the following as potential sites for study and evaluation: San Andreas (especially San Juan Bautista area), Calaveras, Rogers Creek, San Gregorio, and Hayward faults.

Sykes suggested the following two-tiered priority schedule for NEPEC's review over the next one to two years:

I	II
Parkfield, CA	Eastern Sierras
Southern California	Wasatch Front, Utah
S.F. Bay Area	Washington State
Alaska	Puerto Rico - Virgin Islands
	Southern San Joaquin Valley, CA

After discussion, the following priorities were agreed upon. The next meeting will be devoted to the southern San Andreas fault and to the San Jacinto fault.

I	II
Parkfield, Ca	Washington State
Southern California	Wasatch Front, Utah
S.F. Bay Area	Eastern Sierras
Alaska	Puerto Rico - Virgin Islands

Agenda Item: Parkfield Evaluation

Lindh distributed the paper **The Parkfield, California, Prediction Experiment,** by W.H. Bakun and A.G. Lindh, and presented slides indicating that Parkfield earthquakes have a mean recurrence time of 21.7 years; probability estimates are very high for an event to occur within the next 10 to 20 years; and an event can be expected to occur approx. 1988 $\pm$ 4 years (2 standard deviations).

Thatcher mentioned the unique opportunity to anticipate and monitor a "predicted" earthquake.

Paul Siegel and **Kerry Sieh** presented information regarding their work and data evaluations regarding the Parkfield site. (A portion of Sieh's paper was distributed to those present). Sieh argued that the northern end of the 1857 rupture zone to the south of Parkfield could break in conjunction with the next Parkfield shock, producing an earthquake of magnitude 7 to 7½.

Discussion regarding the Parkfield approach:

Aki: good approach, an earthquake will occur there; short-time precursors are being observed and confirmed in the laboratories. Helps fill the gap between long-term and short-term prediction. Present lack of intermediate-term precursors.

Wallace: Suggested that the Council set up scenarios to determine how the Council might respond.

Ellsworth: Suggested development of a series of discussion points as an opportunity to "capture the earthquake;" e.g., what probability does NEPEC desire for a prediciton? 10%, 30%, 50% ? This now becomes a question of nerve and will, and commitments to certain thresholds and instrument maintenance to capture and record every possible bit of data.

Sykes: Research needed on intermediate-term precursors; establish an observation program for high-risk sites. There is a lack of baseline instruments that are field deployable and limitations on access to private lands for conducting experiments and deploying monitoring instruments and equipment.

Dieterich: Noted considerable public education benefits; if USGS/NEPEC are willing to take the risk of making a qualified prediction at Parkfield, which is an optimal location for making an earthquake prediction.

Wallace: Recommends that NEPEC make a decision today as a dry-run of a formal warning that Parkfield will have an earthquake. Go public and deal directly with Parkfield's local government. Accompany the warning with probability maps, calculated intensity maps, public education and information, and details on what will happen to structures, and how to prepare for and mitigate risks. He also noted an operational aspect of sustaining the prediction effort and keeping everyone involved on his or her scientific toes. Also, any statement must be accompanied by telling people what to do to mitigate risks, therefore the State Office of Emergency Services must be included in the warning process. Wallace suggested that a press release be issued as soon as possible about a high probability of long-term potential for a Parkfield earthquake. Follow up with ground motion maps, etc.

Sieh: suggested that USGS/NEPEC put the public welfare into the picture, and endorsed Wallace's comments.

CONSENSUS was reached on the following:

1. The Parkfield Earthquake Prediction Experiment is one of the highest priorities for the U.S. Earthquake Hazards Program and has the highest probability for a successful prediction.

2. Endorsed the general aspects of the prediction made by Bakun and Lindh that a M 6 earthquake will happen in the Parkfield area by 1988 ± 4 years.

3. Advise USGS Director to make an information statement regarding the Parkfield earthquake as a long-term prediction. Include the Bakun and Lindh paper in the recommendation.

4. Add to the Parkfield prediction that there is a significant potential of a larger earthquake (M 7.0 to 7.5) growing out of (in conjuntion with) a seismic event in Parkfield, and which may break to the southeast for as much as 25 miles.

5. Work should be undertaken (especially geologic trenching) to explore the prehistoric record at Parkfield.

6. The Open-file report of this meeting should include the Parkfield paper by Bakun and Lindh.

7. Have a short follow-up on Parkfield, including documentation and maps at next meeting.

8. There is a clear need for more attention to intermediate-term precursors.

9. The experiment needs more real-time digital analysis of the seismic data. Water-level data need to be transmitted and analyzed quickly.

10. USGS must overcome internal turf problems in an effort to be more cooperative in sharing and analyzing data (i.e., wells and water levels,

putting more earthquake monitoring instruments into existing wells).

Agenda Item: OPTION PAPER FOR EARTHQUAKE PREDICITON STRATEGY by USGS

Filson provided background on a draft paper, (copies distributed) explaining that it developed from a request of the Secretary of the Interior for a USGS proposal (including implementation plan and budget for FY 86) before June 1985. The earthquake hazard in Southern Califronia has been a high priority in Washington DC for several years, and Congress has been pushing USGS to become more operational in its approach to earthquake prediction. Proposed options:

1. Continue current research activity.

2. Deployment of strain and seismic equipment in clusters at specific sites of high earthquake potential along the San Andreas Fault.

3. Development of a prototypical earthquake prediction system along the San Andreas Fault in Southern California from Santa Barbara to San Diego: every 20 km along the locked section of the southern San Andreas Fault.

4. Comprehensive employment of 50-60 clusters in Southern California and L.A. basin along the San Andreas Fault and ancilliary faults.

Each cluster would cost approximately $2 million to install and approximately $300,000 annually to maintain and operate. This option paper has been submitted to the National Academy of Science, the California Seismic Safety Commission, and NEPEC for comment. Earthquake prediction is not a mature science and some concern has been expressed that Southern California is not getting the USGS's best effort. The Department of the Interior feels that public safety is important enough to invest in the work to develop a prediction system for earthquakes.

Comments

Aki: emphasis appears to be on short-term prediction; an excellent approach. Caveat that some site proposals don't appear to be at nucleation points of likely earthquakes. **Wallace:** Coherence of instrumentation is a factor for locations: need to find places where there is enough seismic activity to get data. Picking good nucleation points for clustering is a good way to get comprehensive data.

Ellsworth: Automated early-warning systems that react to strong ground motion and shut down critical facilities (nuclear power plants, banking computers, etc.) should be allowed for in an overall strategy. Early-warning systems probably belong in the technical strategy.

McEvilly: There is an assumption that the USGS knows how to do the job; he is not convinced that the USGS is ready or prepared to undertake this sort of program.

Dieterich: Social responsibility indicates that we (USGS & NEPEC) must do the best we can with what's available.

Thatcher: Option 4 is a "star wars" approach unless there is a continuous development in logical sequence from Option 1 to Option 4.

Davies: Option 4 puts too many resources into one program with analysis of cost/benefit.

Dieterich: Pointed out that it will be a political decision among the present options and that the USGS is not in a position to make the final decision among the options.

Davies: Most efficient method may be long-range predictions for hazardous areas and to do pre-event mitigation to lessen earthquake risks rather than put money into "science" that may or may not work.

Sykes: Present U.S. program for prediction and hazards reduction is seriously underfunded. Public interest is mainly in prediction, not mitigation. Substantial increase in funding is needed; it is crucial that the research program be expanded. Better data on depth of earthquakes are needed; better M 3-4 data are needed.

Wallace: Noted the competition with disaster-relief and disaster-planning agencies for funds; he feels the USGS is underfunded in its earthquake prediction program.

Lindh: There is a pragmatic problem with the proposed research in that elaborate instrumentation is a direct result of and dependent upon "brilliant" geophysicists to develop and maintain it. Without trained geophysicists to design, maintain, and interpret data from instrumentation, nothing will happen.

Shearer: Suggested that in cooperation with the National Science Foundation, NEPEC could encourage grants and training programs to develop support personnel and instrumentation.

Wallace: Need for compatible disciplines, i.e. trenching isn't worth much without dating techniques. Also, research and experimentation needs to be done in the sociology and psychology of automated early-warning systems.

NEXT MEETING: MARCH 1985

Agenda: Review of Legal Liability of NEPEC
NEPEC relationship with the media/press
Southern California

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Fall 1984 Meeting
National Earthquake Prediction Evaluation Council

Friday and Saturday, November 16-17, 1984
Menlo Park, California

Friday

Opening remarks, Lynn Sykes, Chairman

General discussion on scope of Council and strategy for future, review of terms and types of statements and reports that should be issued by the Council, press relationships. (See Wallace, Davis, and McNally paper.)

Designation of areas that should be systematically considered. Review of current efforts and earthquake potential in San Francisco Bay area, southern Alaska, and southern California. (Discussion leaders with knowledge of each of these areas will be present.)

Discussion of "Option Paper for Earthquake Prediction Strategy." (Filson can provide background and elaborate on options.)

Review of Parkfield prediction experiment (Kerry Sieh and USGS staff). Should Council endorse current Parkfield prediction?

Saturday

Field trip to Parkfield. We shall leave early and return late to Menlo Park. Details at meeting. About a 4-hour drive from Menlo Park, 4-5 hours in the field, 4 hours back.

NATIONAL EARTHQUAKE PREDICTION EVALUATION COUNCIL

November 1984

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APPENDIX A

The Parkfield, California, Prediction Experiment

W. H. Bakun and A. G. Lindh

in press, Earthquake Prediction Research, Terra Sci. Pub. Co., Tokyo

THE PARKFIELD, CALIFORNIA, PREDICTION EXPERIMENT

W. H. Bakun and A. G. Lindh

ABSTRACT

Moderate-size earthquakes occurred on the Parkfield section of the San Andreas fault in central California in 1881, 1901, 1922, 1934, and in 1966. The earlier Parkfield earthquakes were similar to the 1966 event, leading to the hypothesis of a characteristic Parkfield earthquake with recurring, recognizable source features. A simple recurrence model that explains most of the historic seismicity near Parkfield implies that the next characteristic Parkfield earthquake will occur within a four year time window centered on 1987-1988. A Parkfield Prediction Experiment, designed to monitor the details of the final stages of the earthquake preparation process is underway. Observations and reports of anomalous seismicity and aseismic slip preceding the last characteristic earthquake in 1966 constitute much of the basis for the design of the Parkfield Prediction Experiment; other design considerations involve testing models of the deformation process leading to failure.

INTRODUCTION

Analysis of the probability of damaging earthquakes in California suggest that the Parkfield-to-Cholame section of the San Andreas fault in central California is the most likely site of a damaging earthquake in the next several years (see figure 1). Lindh (1983) found a 67% probability of a magnitude 6 earthquake at Parkfield in the next 10 years. Available data suggest that a much narrower time window, 1986-1989, for the occurrence of the next Parkfield earthquake can be established. Since this time window is near, and because historic Parkfield earthquakes have been so similar, Parkfield provides a unique opportunity to prepare in detail an experiment to observe the final stages of the earthquake preparation process. The results of this experiment should provide the understanding of that process so critical to the design of earthquake prediction efforts in other areas.

The last damaging Parkfield earthquake, on June 28, 1966, had a Richter local magnitude M_L of 5.6 (Bakun and McEvilly, 1979, 1984) and a seismic moment M_o of 1.4×10^{25} dyne- cm (Tsai and Aki, 1969). Although large enough to cause significant damage if located in a metropolitan area, the shock caused only minor damage to the large cattle ranches and sturdy wood frame homes in the sparsely-populated Parkfield region. Maximum modified Mercalli intensities of VIII were observed over an area of a few hundred square kilometers centered on Parkfield and the Cholame Valley.

The source of the 1966 earthquake is adequately described for our purposes here by a simple model: unilateral rupture propagation to the southeast over a 20 to 25-km-long section of the San Andreas fault, herein called the <u>rupture</u>

locus, between two geometric discontinuities in the fault trace (Lindh and Boore, 1981). The northwest discontinuity, adjacent to the epicenter of the 1966 shock, is a 5° change in the strike of the fault trace. The term preparation locus will be used to describe the 1 to 2-km-long section of fault that includes both the fault bend and the main shock epicenter. Available data support the view that earlier damaging Parkfield earthquakes were similar to the 1966 event, leading to the hypothesis that Parkfield main shocks have recurring, recognizable source features (Bakun and McEvilly, 1984). Parkfield shocks with these attributes are called characteristic Parkfield earthquakes. Our working hypothesis is that the next damaging Parkfield earthquake will be characteristic, i.e., resembling in detail earlier shocks, in particular the 1966 event for which much detailed information is available (e.g., McEvilly et al., 1967; Brown et al., 1967).

HISTORIC SEISMICITY

Parkfield earthquake sequences with moderate-size main shocks occurred on February 2 in 1881, March 21 in 1901, March 10 in 1922, June 7 in 1934, and June 28 in 1966. Although the Parkfield-to-Cholame section of the San Andreas fault has been tentatively identified as the locus of the probable epicenter of the 1857 Fort Tejon great earthquake and its two moderate-size foreshocks (Sieh, 1978a), data are not sufficient to constrain slip on the San Andreas fault near Parkfield in 1857 (Sieh, 1978b). Epicenters of one, or both, of the 1857 foreshocks as well as the epicenter of the main shock in 1857 might lie on the San Andreas fault southeast of the Parkfield-to-Cholame section.

The times of Parkfield earthquake sequences, including 1857, are plotted in figure 2 against the earthquake sequence counter; i.e., 1857 is number 1, 1881 is number 2, etc. The time between sequences is remarkably similar, with the mean intersequence time = 21.9±3.1 years. Although the time of the 1934 sequence is not consistent with the regular intersequence interval, the time of the 1966 sequence reestablishes the intersequence spacing in that (1966-1922)/2 = 22 years. The two straight lines represent linear regressions of the dates on the counter I. Using all six dates, origin time = 20.8*I+1837.6 (solid line in figure 2) suggesting that the next Parkfield sequence, i.e. number seven in the series, was due in the spring of 1983. Ignoring the apparently anomolous 1934 date, origin time = 21.7*I+1836.2 (dashed line in figure 2), suggesting that the next sequence will occur at the beginning of 1988. Clearly, occurrence of another Parkfield sequence in the next several years would not be unexpected.

THE CHARACTERISTIC PARKFIELD EARTHQUAKE

The 1934 and 1966 Parkfield sequences were remarkably similar. In addition to the common epicenter, magnitude, fault-plane solution and unilateral southeast rupture of the main shocks, identical M_L = 5.1 foreshocks preceded each main shock by 17 minutes (Bakun and McEvilly, 1979, 1984). The lateral extent of aftershock epicenters over the rupture locus in 1966 (McEvilly et al., 1967) repeated that in 1934 (Wilson, 1936).

Much less data are available for Parkfield sequences prior to 1934. Nevertheless, most of the data are consistent with the hypothesis that the earlier main shocks in 1881, 1901, and 1922 were similar to those in 1934 and 1966. The epicentral location of the main shock in 1922 is constrained by the Love-P_n arrival times at Berkeley, CA (Δ = 240km) to the 18-km-long section of the fault northwest of the preparation locus (Bakun and McEvilly, 1984). The data permit a common epicenter for the 1922, 1934 and 1966 main shocks near the southeast end of the preparation locus. A comparison of seismograms for the 1922, 1934 and 1966 main shocks recorded at the same sites (e.g., see figure 3) suggests that within experimental errors (~ 10-20%), the seismic moment M_0 in 1922 and in 1934 were each equal to the M_0 for 1966 (Bakun and McEvilly, 1984).

Although the features of the main shocks are similar, there are notable differences in the foreshock activity (see figure 4). The 1934 main shock was preceded by a nearly 3-day-long foreshock sequence. The 1934 foreshocks included an M_L 5.0 foreshock 55 hours before the main shock. Whereas the immediate (17 minutes) M_L 5.1 foreshocks in 1934 and 1966 were identical, there was no early foreshock activity in 1966 comparable to that in 1934 (see figure 4). There are no reports of felt foreshocks preceding the main shocks in 1881, 1901, or 1922, so that M_L 5 foreshocks probably did not preceed these early events. Furthermore, there are no foreshocks in 1922 evident on the Berkeley Bosch-Omori seismograms; M_L 4 1/2 Parkfield shocks probably would be noticeable on these records.

The similarities in the main shocks suggest that the Parkfield-to-Cholame section of the San Andreas fault is characterized by recurring earthquakes with predictable features. The notion of a characteristic earthquake with predictable features means that the design of a prediction experiment can be tailored to the specific features of the recurring characteristic earthquake. Also, as shown in the next section, the hypothesis permits the construction of a recurrence model that can explain most of the historic seismicity at Parkfield.

A Recurrence Model for Parkfield Earthquakes

The limited data available on the recurrence of large and great earthquakes along plate boundaries around the world apparently is consistent with a time-predictable model, for which the time interval between successive shocks is proportional to the coseismic displacement of the preceding earthquake (Shimazaki and Nakata, 1980; Sykes and Quittmeyer, 1981). The fundamental principles of the time-predictable model are contained in Reid's (1910) analysis of the mechanics of the 1906 California earthquake. That is, an earthquake occurs when the strain accumulated since the preceding earthquake results in sufficient stress to rupture the fault surface. Adding the concepts of a constant failure stress threshold, a constant rate of strain accumulation, and variable stress drop results in the time-predictable model. Unfortunately this simple model is not supported by the data available for the last three Parkfield earthquakes: although comparable coseismic displacements in 1922, 1934, and 1966 are inferred from the observations, the time intervals differ by more than a factor of 2 (12 yrs versus 32 yrs).

However, simple adjustments to the assumptions that drew the time-predictable model from Reid's analysis result in another model that we call the Parkfield Recurrence Model, which accounts for the historic seismic activity at Parkfield. Like the time-predictable model, the Parkfield recurrence model assumes a constant loading rate and an upper bound stress threshold σ_l, corresponding to the failure or yield stress of the fault. Whereas the time-predictable model permits variable stress drop, the Parkfield recurrence model assumes a characteristic earthquake (constant stress drop) and permits failure before σ_l is reached. Of course such a model is useful in a predictive sense only if these early failures occur infrequently. The Parkfield recurrence model is illustrated in figure 5. The constant stress threshold at which most characteristic earthquakes occur is represented by σ_l. A constant loading rate of 2.8 cm/yr was used to approximate the 3 cm/yr rate of relative plate motion across the creeping section of the San Andreas fault to the northwest of the Parkfield section (Burford and Harsh, 1980). We assume that the Parkfield earthquakes in 1881, 1901, 1922, and 1934 and 1966 were identical, with 60 cm of coseismic slip representing a constant average static stress drop of a few tens of bars.

A simple physical model can qualitatively account for the features of the Parkfield recurrence model. Let σ= the upper stress threshold σ_l correspond to times when the failure stress is approached generally over the entire fault, at which times failure must occur. That is, there are no late characteristic Parkfield earthquakes. Following Brune (1979), we can devise a triggering scenario that permits the occasional early characteristic earthquake. Consider an asperity, i.e., the preparation locus, adjacent to a weak, creeping fault section, i.e., the rupture locus. If a local stress concentration at the asperity exceeds the failure stress there, then the rupture in a resulting relatively high-stress drop small shock might easily extend into the weak rupture locus and continue until resistance to rupture is sufficient to stop the earthquake (e.g., Husseini et al., 1975; Das, 1976). (At Parkfield, the geometrical barrier at the southeast end of the rupture locus provides sufficient resistance to rupture to stop the characteristic Parkfield earthquakes.) Thus a smaller Parkfield shock might grow into a characteristic earthquake when the failure stress is approached only locally in the preparation locus. Local, rather than general approach of the failure stress, would correspond to $\sigma < \sigma_1$.

A triggering mechanism for the occasional early characteristic Parkfield is easily seen in its only example, the 1934 event. The sequence of foreshocks located near the preparation locus (Wilson, 1936) in the 3 days just before the 1934 main shock is a clear expression of localized failure. Apparently these foreshocks in 1934 were sufficient to alter the stress field at the main shock focus so that the trigger mechanism for an early characteristic earthquake outlined above could occur. Clearly the location and source mechanisms of the nearby foreshocks control their effect on the stress field within the preparation locus. Note that the early (55 hours) M_L 5.0 foreshock in 1934 was characterized by unilateral southeast rupture expansion toward the preparation locus (Bakun and McEvilly, 1981), a particularly efficient mechanism for increasing dynamic right-lateral shear stress in the preparation locus. The epicenter of the immediate (17 minutes) M_L 5.1 foreshock in 1934 was 1-2 km northwest of the main shock epicenter so that it too was favorably situated to increase right-lateral shear stress in the preparation locus. While the foreshock swarm is the immediate triggering mechanism, we do not understand the conditions that led to the earthquake sequence. Accelerated loading rate associated with nonuniform regional strain accumulation (Thatcher, 1982) and/or accelerated fault creep near the preparation locus as well as temporal changes in the failure stress associated with fluctuations in pore pressure, etc. must be considered.

The recurrence of $M_L \gtrsim 4$ earthquakes since 1930 is shown by the stick-plot diagram at the bottom of figure 5. The 10-12 years following the 1934 and 1966 Parkfield earthquakes are relatively quiet. Earthquakes with $M_L > 4.0$ tend to occur at a higher rate after σ exceeds a second stress threshold σ_2. Apparently $\sigma = \sigma_2$ corresponds to local stress concentrations approaching the failure stress. The sequence of M_L 3-5 foreshocks in 1934 at $\sigma \simeq \sigma_2$ (see figure 5) suggest that under at least some conditions a characteristic Parkfield earthquake can occur at $\sigma = \sigma_2$. According to the Parkfield recurrence model shown in figure 5, the lower stress threshold σ_2 was reached in 1975, when $M_L \gtrsim 4$ Parkfield earthquakes again occurred. That is, an early characteristic earthquake this cycle might have occurred as early as 1975.

The stress threshold σ_1, at which the next characteristic Parkfield earthquake must occur, should be reached early in 1988. Since the 1934 shock did not occur at $\sigma = \sigma_1$, it is ignored in estimating the uncertainty in the predicted time of the next characteristic shock. The appropriate relation, origin time = 21.7*I + 1836.2, where I = characteristic earthquake counter (dashed line in figure 2), results in observed-predicted occurrence times of -0.9 yr for 1857, 1.5 yr for 1881, -0.1 yr for 1901, -0.6 yr for 1922, and 0.2 yr for 1966. The rms difference is 0.9 yr. Using 2 std dev. to define the duration of the time window, these calculations imply that the next Parkfield earthquake should occur in 1988.0$\pm$ 1.8, i.e., between 1986 and 1989.

RECENT SEISMICITY

Although earthquakes occur throughout central California, most of the shocks in recent years lie along the San Andreas fault (see figure 6). Not shown here are the sequences of earthquakes east of the San Andreas near New Idria in October 1982 (M_L5.4) and near Coalinga in May 1983 (M_L6.5). Earthquakes on the San Andreas are shown as a lineation of epicenters 3-5 km southwest of the San Andreas fault trace. This apparent mislocation is presumably the result of lateral variations in crustal velocity not adequately modeled in the location algorithm. Most of the shocks on the San Andreas occur on the creeping section to the northwest of the preparation locus. The section southeast of Cholame that broke during the great Fort Tejon earthquake of 1857 is currently locked, with no measureable fault creep and only infrequent small shocks. A cross section of the seismicity along the fault (figure 7) illustrates the predominance of the activity to the northwest of the preparation locus, defined by the locations of the main shock and the immediate M_L5.1 foreshock in 1966. This activity northwest of the preparation locus is concentrated at focal depths less than about 5 km. Focal depths of the main shock and the immediate foreshock in 1966 are about 8 km (Lindh et al., 1983), deeper than most of the events to the northwest of the preparation locus and deeper than the majority of aftershocks in the rupture locus (see figure 7)). The recent clusters of seismicity within the 1966 aftershock zone (shaded area in figure 7) occur at the concentrations of aftershocks identified by Eaton et al. (1970).

Prominent features of the seismicity near the 1966 hypocenter are illustrated in the schematic cross-section shown in figure 8. Since 1975 a number of magnitude 4 to 5 earthquakes have occurred near the preparation locus. This is the seismicity that, according to the Parkfield recurrence model shown in figure 5, occurred at σ greater than the second stress threshhold σ_2. The 1934 and 1966 Parkfield sequences were proceded by M_L5.1 foreshocks located at the northwest edge of the preparation locus. The immediate foreshocks had larger stress drops than had other M_L5 earthquakes that occurred in the area in the past 50 years (Bakun and McEvilly, 1981). These other M_L5 earthquakes all occurred a few kilometers northwest or southeast of the preparation locus (Bakun and McEvilly, 1981). It is not clear whether the larger stress drops of the immediate foreshocks result from their location at the edge of the preparation locus or because they preceded their respective main shocks by only 17 minutes. Note that the early M_L5 foreshock located 2 kilometers northwest of the preparation locus that preceded the 1934 earthquake by 55 hours was a relatively low stress drop source (Bakun and McEvilly, 1981). A magnitude 4 earthquake in June 1982 near the same location and the magnitude 5 shock in September 1975 located 5 km northwest of the preparation locus were lower stress drop sources as well (O'Neill, 1984; Bakun and McEvilly, 1981). Stress drops for a number of smaller earthquakes that have occurred near the preparation locus indicate a similar spatial pattern (see figure 9). Lower stress drop sources tend to occur around the higher stress drop sources. Note that the focal depths of the main shock and immediate foreshock in 1966 are relatively uncertain so that the hypocenters of these events whose epicenters define the extent of the preparation locus might lie within the group of higher stress drop sources shown in figure 9. The implication is that the preparation locus is characterized by relatively high stress drop sources, whether or not the sources are foreshocks. Under this interpretation, the immediate foreshocks in 1934 and in 1966 were relatively high stress drop sources because of their location at the edge of the preparation locus rather than because they immediately preceded the main shocks.

The historic seismicity suggests that the preparation locus is critical in the nucleation of characteristic Parkfield earthquakes. The last two characteristic earthquakes, in 1934 and in 1966, were preceded by foreshocks within the preparation locus. These events, like other shocks within the preparation locus, are relatively high stress drop sources, consistent with the notion that the 5^0 bend in the fault at the preparation locus is the point where stress is concentrated. Clearly any earthquakes located in the preparation locus, or any other anomalous behavior there, might be precursors to the next characteristic Parkfield earthquake.

SEISMIC INSTRUMENTATION

The seismic instrumentation now deployed near Parkfield (see figure 10) is focused to monitor the details of seismic activity in and near the preparation locus. Eleven seismographs of the U.S. Geological Survey's (USGS) central California seismic network (CALNET) are located within a few focal depths of the preparation and rupture loci. In addition, ten Terra-Technology DCS-302 digital event recorders are deployed in a temporary network near the preparation locus; these temporary stations are being replaced by the more-reliable 3-component low-gain CALNET stations. The dense seismograph coverage around the preparation locus should provide documentation of any seismic precursors to the next Parkfield characteristic earthquake.

In addition to the seismograph networks, nearly 50 SMA-1 strong-motion accelerographs are deployed near the rupture locus (see figure 10). The conception and design of this strong-motion network was a cooperative effort of the USGS and the California Division of Mines and Geology (CDMG). The network is operated and maintained by the CDMG. A much sparser strong-motion network was operated near the southeast end of the rupture locus during the 1966 sequence of earthquakes (Murray, 1967) by the U.S. Coast and Geodetic Survey and the California Department of Water Resources. Data recorded by that network was the basis of important research on the focal mechanism of earthquakes and the interpretation of near-field strong motion recordings (eg., Aki, 1968; Haskell, 1969; Boore et al. 1971; Lindh and Boore, 1981). While data from that earlier sparse strong-motion network stimulated much discussion, it left unresolved some important questions. In particular, the location of the southeast end of the rupture locus in 1966 is uncertain; the current strong-motion network shown in figure 10 is designed to provide definitive answers to some of these questions.

STRAIN MEASUREMENTS

Reports consistent with signficant precursory aseismic slip along the rupture locus in 1966 provide a strong incentive to deploy strain-measuring instrumentation near the rupture and preparation loci. An irrigation pipeline that crosses the main trace of the San Andreas in the rupture locus near creepmeter XCR (see figure 11) broke and separated about 9 hours before the occurrence of the main shock in 1966. Brown et al. (1967) attribute the break to 1-2 feet of southeast movement of the northeast end relative to the southwest end. This movement is consistent with the right lateral strike-slip displacement across the fault observed in the 1966 afterslip (Brown et al., 1967) and on creepmeter recordings near Parkfield since the early 1970s (Burford and Harsh, 1980). However, the time history of the movement that resulted in the broken irrigation pipe is unknown; perhaps only a small fraction of the postulated 1-2 feet of displacement occurred in the days and weeks just before the 1966 earthquakes.

Also of interest are the reports of very fresh appearing en echelon cracks observed in the rupture locus near creepmeter XDR (see figure 11) twelve days before the 1966 earthquakes (Brown et. al., 1967). (Note that cracks tend to appear each spring in the Cholame Valley (R. Burford, personal communication, 1982) as the clay soil desiccates following the winter rains.) The discovery of the cracks in June 1966 by delegates to the Second United States-Japan Conference of Research Related to Earthquake Prediction led to the deployment of a microearthquake study in the area on 18-19 June 1966, eight days before the 1966 sequence began; a 24-hour record from that study shows no identifiable magnitude ≥ 0 earthquakes within 24 km (Allen and Smith, 1966). Thus, if of tectonic origin, the en echelon cracks resulted from aseismic slip or fault creep in the rupture locus. The occurrence of 1-2cm of fault creep, inferred from the en echelon cracks, would be 4-8 times the annual creep rate at Parkfield.

An optimistic interpretation of the broken irrigation pipeline and the fresh en echelon cracks described above is that significant anomalous precursory fault creep occurred at least in the rupture locus in the days and weeks just before the 1966 earthquake. If comparable aseismic slip precedes the next Parkfield earthquake, the strain measuring instruments deployed along the rupture locus (see figure 11) will provide clear precursory signals that might be used to issue a short-term prediction. Six creepmeters (see Burford and Harsh, 1980) span the main trace of the San Andreas fault in the rupture locus. Signals from these sensors are recorded on site and also are telemetered to the U.S.G.S. analysis facilities in Menlo Park, California.

Line lengths will be measured each night on a two-color laser distance measuring instrument located at the center of the radial array shown in Figure 10; this instrument provides long term repeatability at the 10^{-7} level on lines of 3-8 km length. The two-color laser project is a cooperative effort of the University of Colorado and the U.S. Geological Survey. Two Sacks-Evertson volumetric borehole strainmeters are now installed near the southeast end of the rupture locus (DGH in figure 10); the borehole strainmeters have a sensitivity better than 10^{-10} and are isolated from first order surface noise sources such as rain and temperature. The borehole dilatometer project is a cooperative effort of the Carnegie Institute, Washington, D.C., and the U.S. Geological Survey. The two-color laser geodimeter and borehole strainmeter observations should provide corroborative evidence of changes in seismicity and/or creep rate. On a more fundamental basis, they provide the means to define any tectonic deformation leading up to the next characteristic Parkfield earthquake.

DISCUSSION

Although our understanding of Parkfield earthquakes is far from complete, the available information summarized in this paper suggest some guidelines for short-term prediction of the next characteristic Parkfield earthquake.

SCENARIO 1: FORESHOCKS IN THE PREPARATION LOCUS, FAULT CREEP IN THE RUPTURE LOCUS. Based on the observations in 1966, we might expect significant foreshock activity in the preparation locus in the hours and minutes before the next characteristic shock and perhaps significant fault creep in the rupture locus in the weeks and days before the event. If such precursors occur, then the current deployment of instrumentation shown in figures 10 and 11 should unambiguously capture the short-term precursory signals and might provide sufficient evidence to support a short-term prediction.

SCENARIO 2: NO FORESHOCKS, NO FAULT CREEP IN THE RUPTURE LOCUS. According to the Parkfield recurrence model shown in figure 5, the occurrence times of the Parkfield sequences in 1881, 1901, 1922, and 1966 were not anomalous. While the 1966 event was preceded by significant foreshock activity, the absence of reports of felt foreshocks in 1881, 1901, and 1922 suggests that these events were not preceded by M_L 5 foreshocks. Whereas the evidence for significant precursory fault creep in the rupture locus before the 1966 event is ambiguous, there is no information at all concerning analogous changes before the 1881, 1901, or 1922 earthquakes. Clearly the worst short-term prediction scenario - no foreshocks and no fault creep - would probably lead to the occurrence of the next characteristic shock without a short-term prediction.

Note however that the epicenter of the main shock in 1922 occurred near the preparation locus. It seems reasonable to assume that some precursory changes, albeit without $M_L \geq 4$ 1/2 foreshocks, occurred near the preparation locus in 1922. Under the characteristic earthquake hypothesis, the epicenter of the next characteristic Parkfield earthquake will be located near the preparation locus. Hence precursory changes, with or without foreshocks, in the preparation locus are likely. Whereas the two-color laser and dilatometers are favorably sited to detect deformation along the rupture locus, they are relatively insensitive to strain or creep in the preparation locus. Thus, if the only precursors are less-than-gross deformations in the preparation locus (scenario 2), the current instrumentation would likely fail to provide evidence of that deformation sufficient to permit a short-term prediction. Additional strain-measuring instrumentation near the preparation locus would significantly increase our ability to detect precursors in the worst-case short-term prediction scenario of no foreshocks and no significant fault creep along the rupture locus.

SCENARIO 3: EARLY (1934-LIKE) OCCURRENCE. Scenarios 1 and 2 dealt with circumstances likely to precede a characteristic Parkfield earthquake in 1986-1989, i.e., when $\sigma \simeq \sigma_1$. The next characteristic Parkfield earthquake might occur early, i.e. at $\sigma < \sigma_1$, as in 1934. Could such an earthquake be predicted? Unfortunately, data from only one such occurrence, in 1934, is available to address that question. Fortunately, the foreshock swarm in 1934 was so pronounced and prolonged (see figure 4) that it would be easy to recognize a repeat of the sequence of events in 1934, even if no precursory fault creep occurred in the rupture locus. Note the failure of isolated M_L 5 Parkfield shocks in 1939, 1956, and 1975 (see figure 4) to be followed by early characteristic Parkfield earthquakes. This admittedly limited data set suggests that not only are early characteristic Parkfield earthquakes preceded by significant prolonged foreshock activity, but that M_L 5 Parkfield earthquakes either isolated in time, e.g., 1939 and 1956 in figure 4, or only followed within a few hours by small aftershocks, e.g., 1975 in figure 4, are not sufficient in themselves to warrant the short-term prediction of a characteristic Parkfield earthquake. Of course the next characteristic Parkfield earthquake can only be early by at most 3 or 4 years in contrast to the 10-year-advance of the 1934 sequence; perhaps the sequence of events in 1934 cannot be used to anticipate the circumstances preceding a characteristic earthquake early by only a few years.

SCENARIO 4: A CHARACTERISTIC PARKFIELD EARTHQUAKE TRIGGERS A LARGER SHOCK. Scenarios 1, 2, and 3 describe circumstances that might precede the next characteristic earthquake, i.e., an M_L 5.6 shock bound by the geometrical barriers at the ends of the rupture locus. In this final scenario, we consider the situation where the characteristic earthquake breaks through the right-step en echelon offset at the southeast end of the rupture locus and continues southeast along the San Andreas fault, growing into a major earthquake. Mechanisms for rupture continuing through an unbroken, or broken, asperity have been developed by Das and Aki (1977). Alternatively, the characteristic earthquake might stop at the echelon offset, and, in analogy to the triggering mechanism of the early M_L 5.0 foreshock in 1934, increase the right-lateral shear stress on the fault southeast of the rupture locus so that another shock eventually starting there would rupture to the southeast. The latter case has been suggested (Sieh, 1978a; Lindh and Boore,

1981) as the triggering mechanism for the great Fort Tejon earthquake of 1857.

How might scenario 4 be discriminated in advance? Clearly this scenario presents technical, social, and political problems of the most serious nature. Slip in 1857 along the 50-km-long section of the San Andreas southeast of Cholame was about 3 1/2 m, significantly less than the 9 m offset further to the southeast (Sieh, 1978b). Continuation of a Parkfield earthquake to the southeast might result in a rupture length of about 90 km and offsets of about 3 1/2 m to the southeast of Cholame (Sieh and Jahns, 1984). Such an event would perhaps be as large as surface-wave magnitude M_s 7 1/2 (Sieh and Jahns, 1984). Social and economic consequences of such an earthquake would certainly be more severe than for the characteristic Parkfield earthquake considered in the first three scenarios. Since the average Holocene offset rate across the San Andreas fault at Wallace Creek is 3.5 cm/yr (Sieh and Jahns, 1984), it seems likely that the 3 1/2 m of slip in 1857 largely has been recovered so that the possibility of an earthquake breaking this segment must be taken seriously. Unfortunately, there is little data available to suggest what precursors might discriminate scenario 4 from scenarios 1, 2, or 3. Models of rupture through asperities (e.g., Das and Aki, 1977) suggest that minor differences in the stress field near the asperity, the strength of the asperity, and the dynamic stress ahead of the rupture could all be important. Although foreshocks and/or deformation at the southeast end of the Parkfield rupture zone might portend a shock significantly larger than a characteristic Parkfield earthquake, there is certainly no evidence that such need be the case.

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Figure Captions

Figure 1. Annual earthquake probabilities for selected segments of the San Andreas fault system in California (Taken from Lindh, 1983). These estimates are preliminary and should only be used to obtain an overview of the relative earthquake likelihood for different individual fault segments.

Figure 2. Series of earthquake sequence at Parkfield since 1850 (taken from Bakun and McEvilly, 1984). Solid line is the linear regression of the time of the sequence using the last six sequences. Dashed line is the linear regression obtained without the 1934 sequence. The anticipated time of the seventh, i.e., the next, Parkfield sequence for the two regressions is 1983.2 and 1988.0.

Figure 3. Surface waves recorded on the De Bilt, the Netherlands, east-west (DBN-EW) and north-south (DBN-NS) component Galitzin seismographs for the 1922, 1934, and 1966 Parkfield events (taken from Bakun and McEvilly, 1984). Amplitude and time scales are constant. Brackets indicate the Love- and Rayleigh-wave phases.

Figure 4. Parkfield seismicity relative to the origin times of M_L 5 shocks in 1934, 1939, 1956, 1966, and 1975. The times in 1934 are relative to the origin time of the early M_L 5.0 foreshock; felt foreshocks in 1934 for which Buhr and Lindh (1982) assign no magnitude are shown as M_L 3 events. Except for the aftershock sequences in 1934 and 1966, no known $M_L \geq 3$ Parkfield earthquakes occurred within several days of the 75-hour-long time intervals shown.

Figure 5. The Parkfield recurrence model. σ_1 represents the failure stress of the fault. Constant 2.8cm/yr loading rate and 60cm coseismic slip for the Parkfield earthquake sequences in 1881, 1901, 1922 and 1934 and 1966 are assumed. According to the model, the next Parkfield sequence is expected in 1988 $\pm$ 2 yr. $M_L > 4.0$ shocks since 1930 are shown at bottom. $M_L > 4$ shocks tend to occur when the stress exceeds σ_2.

Figure 6. Earthquake epicenters for 1969-1981 and the location of permanent seismographs in central California relative to geologic features. Most of the area shown is blanketed by Cretaceous and Tertiary marine sediments. Large outcrops of Franciscan melange (Fr) of Mesozoic age are shown, as is the western edge of the San Joaquin Valley, marking the boundary between Tertiary sediments and Quaternary alluvium. Symbols refer to the earthquake focal depths (..., 9, A, B, ...for...,

9-10 km, 10-11 km, 11-12 km,...). Symbol size is proportional to magnitude (see key). Epicenters were obtained using a one-dimensional crustal velocity model; the band of epicenters located on the San Andreas fault are displaced 3-5 km to the southwest because the higher crustal velocity southwest of the fault are not properly accounted for in the location procedure. Priest Valley (PRI) operated by the Univerity of California Berkeley Seismographic Station and the CALNET station at Gold Hill (GDH) were seismograph stations installed before the 1966 Parkfield sequence.

Figure 7. Cross section of the seismicity along the San Andreas fault near Parkfield for the years 1975-1980. The hypocenter of the main shock and the M_L 5.1 immediate foreshock in 1966 are shown as stars. Symbol size is proportional to magnitude. No vertical exaggeration.

Figure 8. Schematic cross section of seismicity ($M_L > 3$) along the San Andreas fault near Parkfield for 1969-1983. No vertical exaggeration. The shaded vertical band corresponds approximately to the location of a 5° bend in the surface trace of the fault. The preparation locus is inferred to lie within the shaded region between the hypocenters of the main shock and the M_L 5.1 immediate foreshock in 1966 (the two stars). The aftershocks in 1966, i.e., the rupture locus, lie southeast of

the preparation locus at depths shallower than 8-10 km. Since 1975, M_L 3-5 earthquakes have occurred near the preparation locus; these sequences are shown together with estimates of their source dimensions based on aftershock locations.

Figure 9. Cross section along the San Andreas fault zone near Parkfield showing the distribution of static stress drops for a number of earthquakes in 1977-1982 (taken from O'Neill, 1984). The numbers next to the symbols are stress drops in bars. The hypocenter of the main shock and the M_L 5.1 immediate foreshock in 1966 are shown as filled circles. Focal depths of the 1966 shocks are uncertain to within 1-2 km so that their hypocenters might easily coincide with the locus of greater stress drop sources shown as filled triangles.

Figure 10. Seismograph and accelerograph deployment along the Parkfield-to-Cholame section of the San Andreas fault relative to the preparation locus and rupture locus of the characteristic Parkfield earthquake. The epicenter of the 1966 main shock is shown as a star. The location of the southeast end of the rupture locus is problematic; in 1966, numerous aftershocks and surface cracks were observed over the 20-km-long section (cross hatching) immediately southeast of the preparation locus. Surface cracks and some small aftershocks were observed over a 15-km-long section further to the southeast.

Figure 11. Strain-measuring instrument deployment along the Parkfield-to-Cholame section of the San Andreas fault relative to the preparation locus and rupture locus of the characteristic Parkfield earthquake (see caption for figure 10). Names of sites of invar-wire strainmeters, bubble-level tiltmeters, Sacks-Evertsen dilatometers and creepmeters begin with S, T, D, and X respectively. Creepmeter XMM is located at the epicenter of the 1966 main shock.

TABLE 1. $M_L \geq$ 4 Earthquakes Near Parkfield (1930-1983)*

#	YEAR	MO-DAY	ORIGIN TIME HR-MIN(OCT)	LATITUDE (°N)	LONGITUDE (°W)	M_L
1	1934	06-05	21-48	35°48.0'	120°20.0'	5.0
2	1934	06-05	22-52	35°48.0'	120°20.0'	4.0
3	1934	06-08	04-30	35°48.0'	120°20.0'	5.1**
4	1934	06-08	04-47	35°48.0'	120°20.0'	5.6***
5	1934	06-08	05-42	35°48.0'	120°20.0'	4.5
6	1934	06-08	09-30	35°48.0'	120°20.0'	4.0
7	1934	06-08	23-23	35°48.0'	120°20.0'	4.0
8	1934	06-10	08-03	35°48.0'	120°20.0'	4.5
9	1934	06-14	14-55	35°48.0'	120°20.0'	4.0
10	1934	06-14	15-54	35°48.0'	120°20.0'	4.0
11	1934	06-14	19-26	35°48.0'	120°20.0'	4.5
12	1934	12-02	16-07	35°58.0'	120°35.0'	4.0
13	1934	12-24	16-26	35°56.0'	120°29.0'	4.7**
14	1935	01-06	04-04	35°56.0'	120°29.0'	4.0
15	1935	10-22	18-37	35°55.0'	120°29.0'	4.0
16	1937	02-20	09-58	35°56.0'	120°29.0'	4.0
17	1938	11-22	15-30	35°52.7'	120°28.13'	4.2
18	1939	05-02	18-49	35°59.2'	120°21.28'	4.0
19	1939	12-28	12-15	35°58.17'	120°24.62'	5.2
20	1941	12-22	00-54	35°56.0'	120°29.0'	4.0
21	1942	10-31	10-51	36°01.86'	120°25.71'	4.0
22	1953	05-28	03-51	35°57.0'	120°28.98'	4.3
23	1953	06-22	15-22	35°55.9'	120°25.8'	4.4
24	1954	03-09	19-55	36°00.0'	120°20.0'	4.0
25	1956	11-16	03-23	35°57.9'	120°25.7'	5.0
26	1956	12-11	10-56	35°56.6'	120°28.0'	4.0
27	1958	09-01	11-31	36°06.0'	120°29.91'	4.6
28	1961	07-31	00-07	35°49.4'	120°15.8'	4.7
29	1961	12-14	11-51	36°00.0'	120°30.0'	4.0
30	1966	06-28	04-08	35°56.6'	120°30.5'	5.1
31	1966	06-28	04-26	35°56.0'	120°29.6'	5.6
32	1966	06-28	04-28	35°55.9'	120°29.6'	4.5
33	1966	06-28	04-32	35°48.9'	120°16.8'	4.0
34	1966	06-28	04-34	35°48.9'	120°16.8'	4.0
35	1966	06-29	02-19	35°55.8'	120°27.5'	4.0
36	1966	06-29	19-53	35°56.8'	120°28.6'	4.9**
37	1966	06-30	01-17	35°52.0'	120°21.5'	4.2
38	1966	10-27	12-06	35°56.9'	120°41.4'	4.2
39	1967	07-24	07-08	35°55.7'	120°26.25'	4.1
40	1967	08-12	18-57	35°51.2'	120°23.09'	4.2
41	1967	12-21	23-58	35°45.3'	120°26.8'	4.3
42	1967	12-31	23-48	35°55.31'	120°27.15'	4.5
43	1975	01-06	11-17	35°56.78'	120°30.90	4.4
44	1975	09-13	21-20	35°59.54'	120°33.22'	4.9**
45	1977	01-24	18-05	35°47.23'	120°20.96'	4.0
46	1977	11-29	16-42	35°56.51'	120°29.59'	4.1
47	1977	12-28	02-59	35°48.49'	120°21.89'	4.0
48	1982	06-25	03-58	35°58.32'	120°31.38'	4.0

* Events for 1930-1979 taken from Buhr and Lindh (1982). Locations for early events are approximate. Data for 1980-1983 taken from preliminary USGS earthquake catalogs.

** M_L taken from Bakun and McEvilly (1981).

*** M_L taken from Bakun and McEvilly (1984).

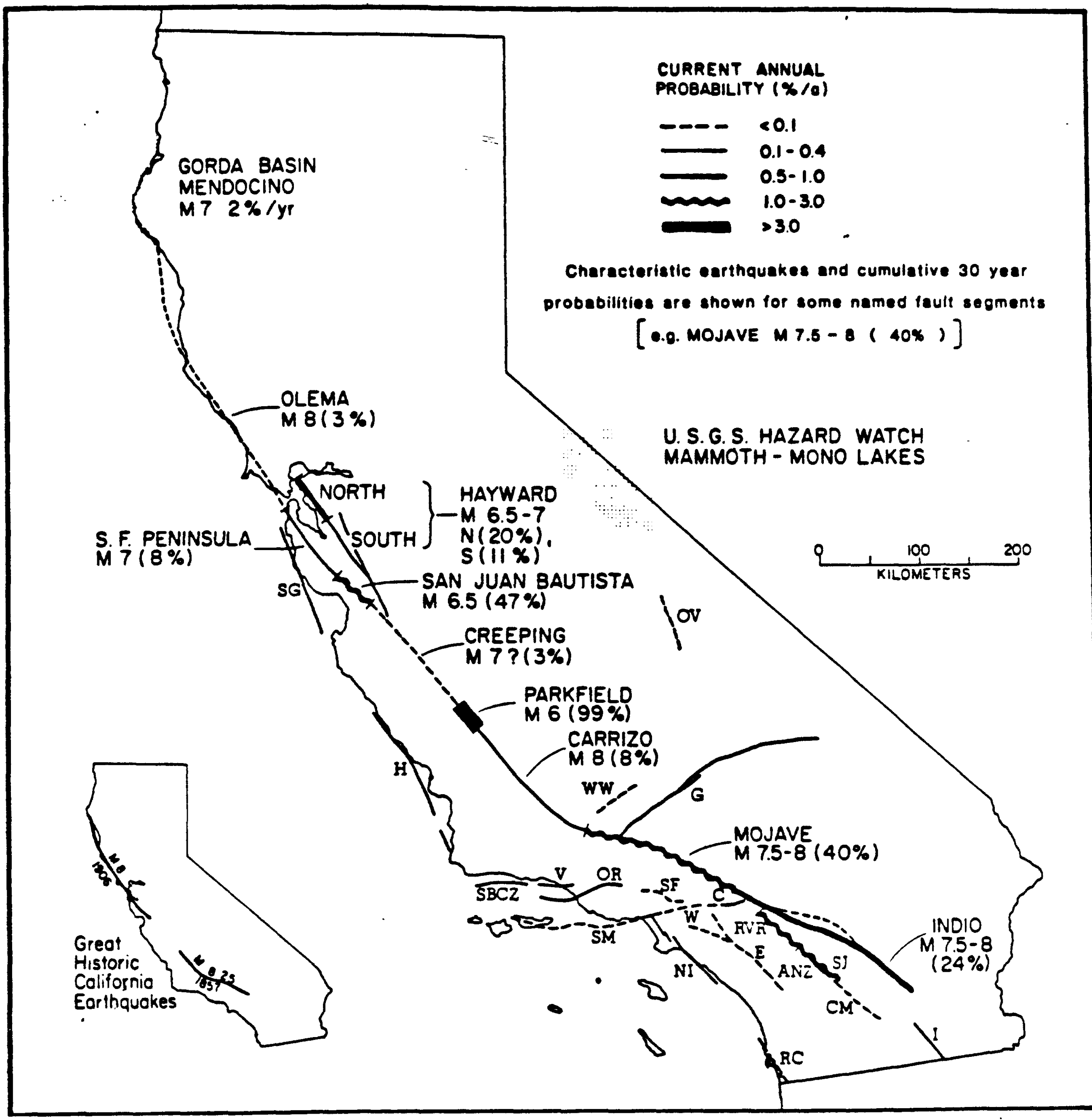

CURRENT ANNUAL PROBABILITY (%/a)
<0.1
0.1-0.4
0.5-1.0
1.0-3.0
>3.0
Characteristic earthquakes and cumulative 30 year probabilities are shown for some named fault segments
[e.g. MOJAVE M 7.5 - 8 (40%)]
GORDA BASIN
MENDOCINO
M 7 2%/yr
OLEMA
M 8 (3%)
U. S. G. S. HAZARD WATCH
MAMMOTH - MONO LAKES
NORTH
SOUTH
HAYWARD
M 6.5-7
N(20%),
S(11%)
S. F. PENINSULA
M 7 (8%)
SAN JUAN BAUTISTA
M 6.5 (47%)
SG
OV
CREEPING
M 7?(3%)
PARKFIELD
M 6 (99%)
CARRIZO
M 8 (8%)
0 100 200
KILOMETERS
H
WW
G
MOJAVE
M 7.5-8 (40%)
V
OR
SF
SBCZ
C
W
RVR
SM
E
NI
ANZ
SJ
INDIO
M 7.5-8
(24%)
CM
I
RC
M 8
1906
M 8.25
1857
Great
Historic
California
Earthquakes

Figure 1

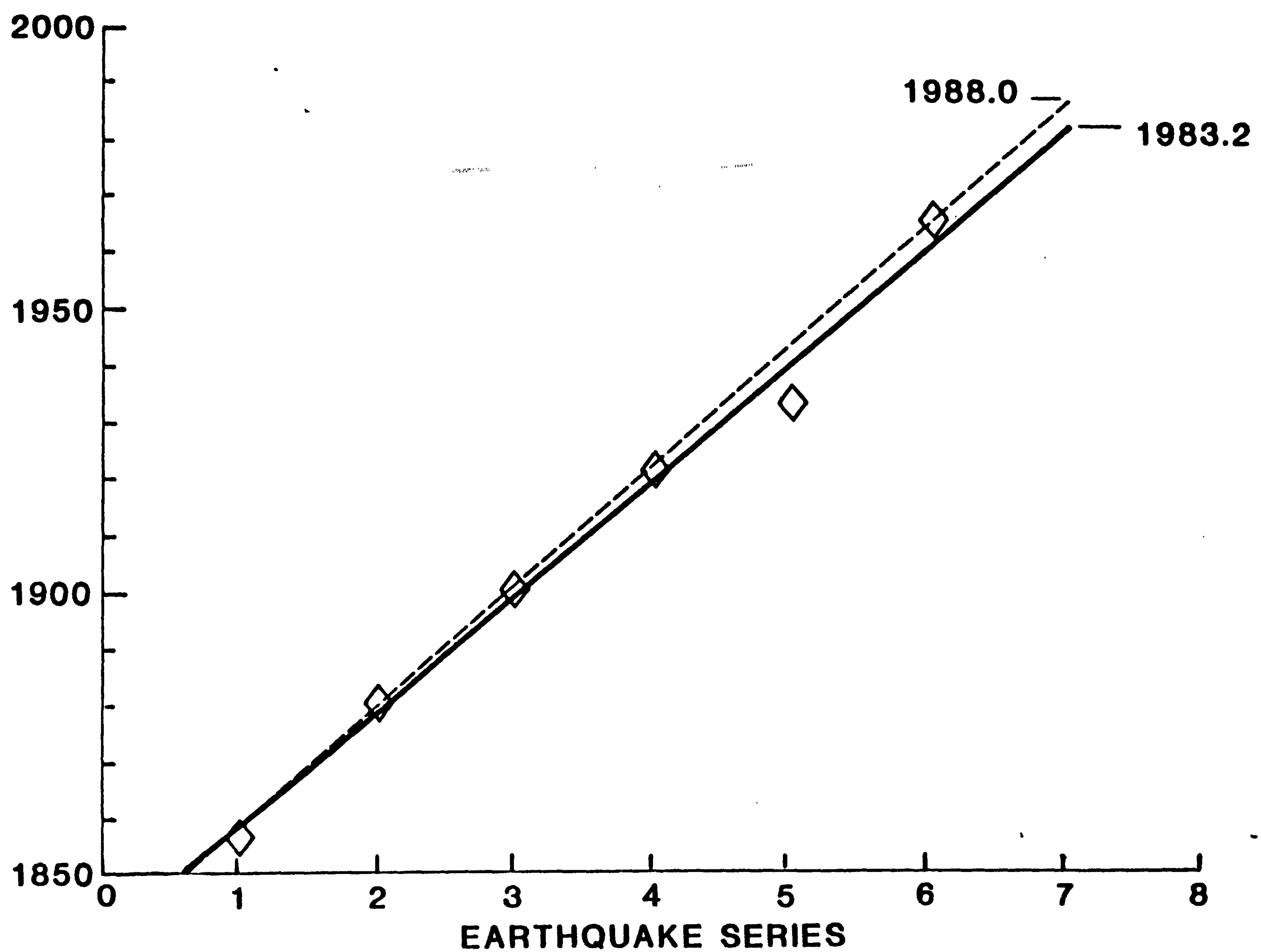

2000
1950
1900
1850
1988.0
1983.2
0
1
2
3
4
5
6
7
8
EARTHQUAKE SERIES

Figure 2

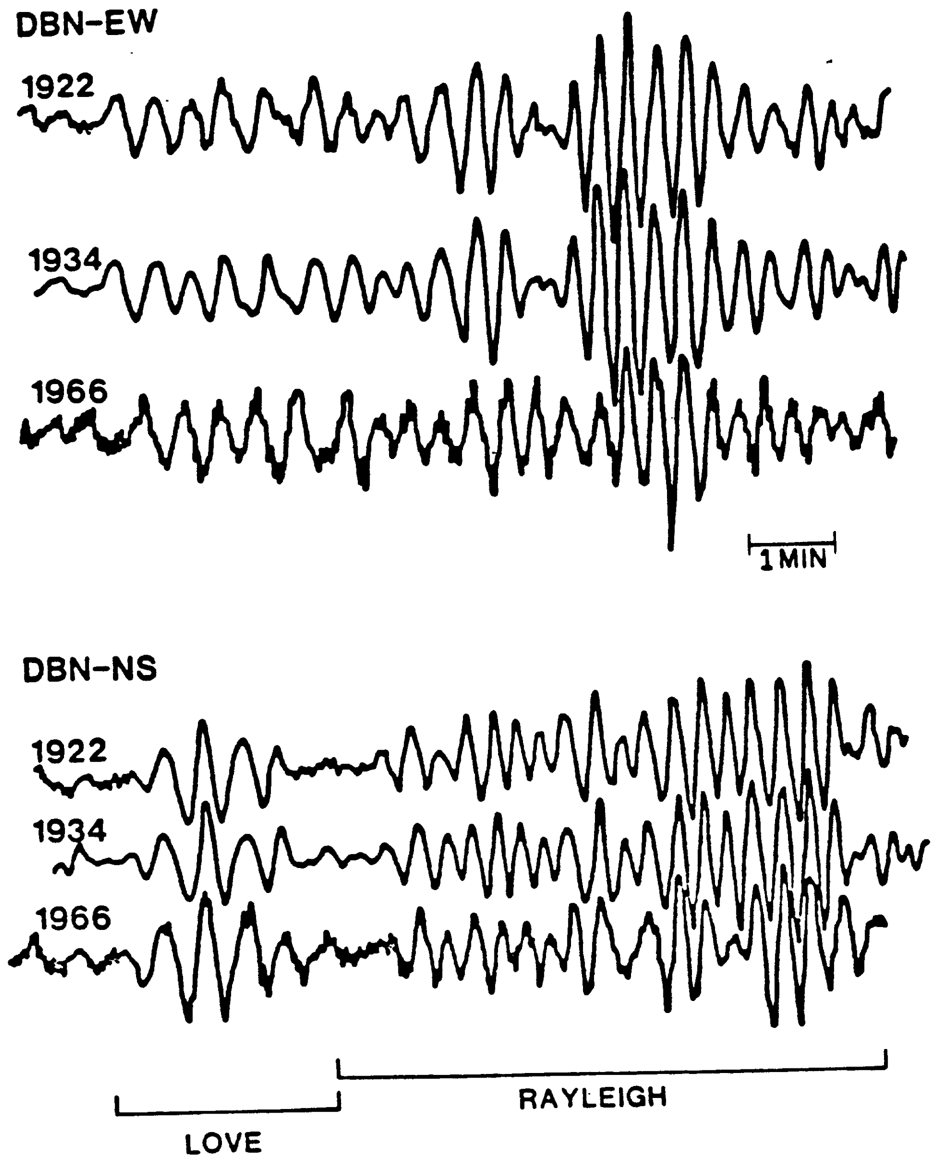

DBN-EW
1922
1934
1966
1 MIN
DBN-NS
1922
1934
1966
RAYLEIGH
LOVE

Figure 3

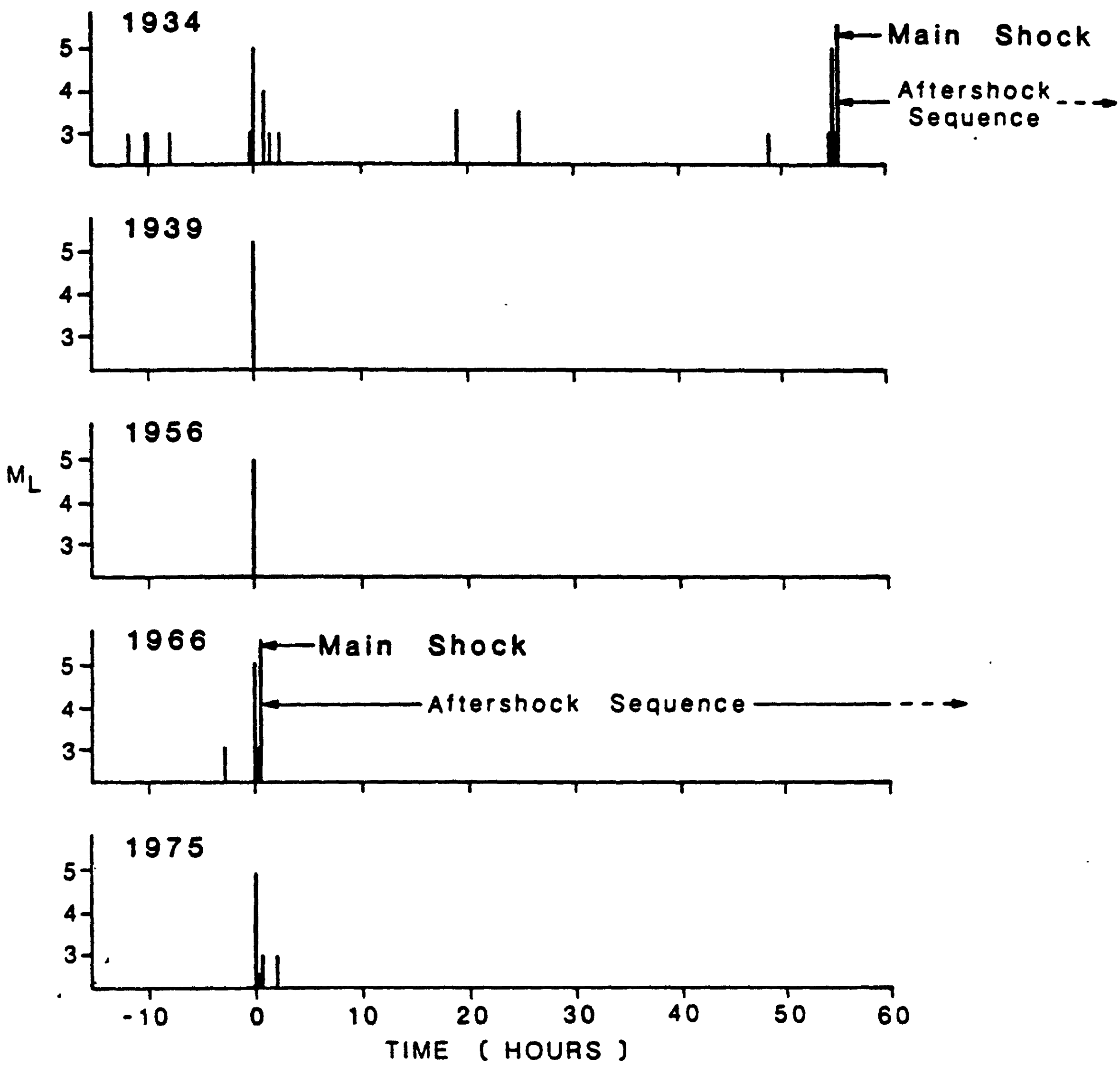
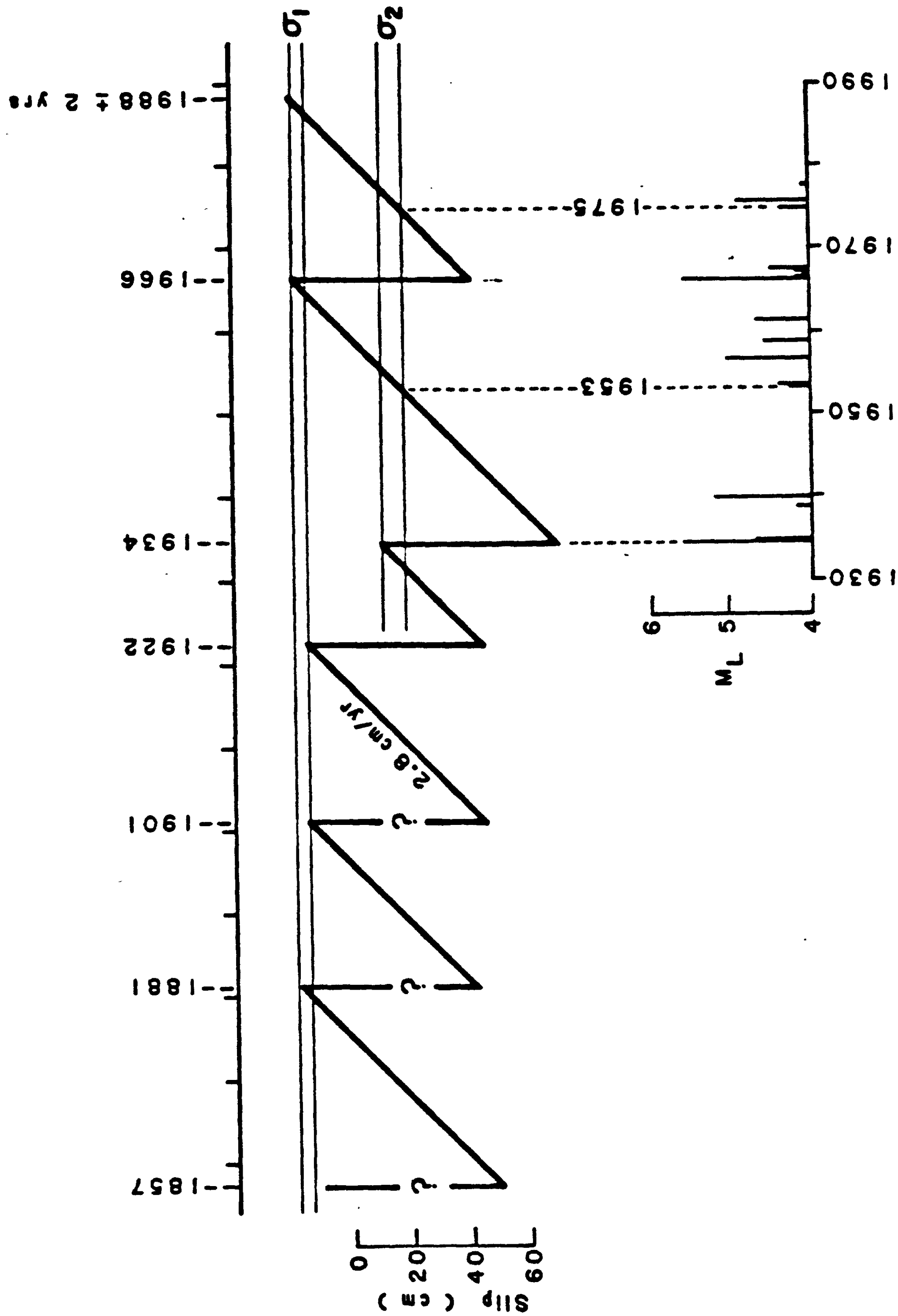

1934
Main Shock
Aftershock Sequence
1939
1956
1966
Main Shock
Aftershock Sequence
1975
M_L
5
4
3
-10
0
10
20
30
40
50
60
TIME (HOURS)

Figure 4



σ1
σ2
1857
1881
1901
1922
1934
1966
1988 ± 2 yrs
2.8 cm/yr
?
1953
1975
1930
1950
1970
1990
M_L
4
5
6
Slip (cm)
0
20
40
60

Figure 5

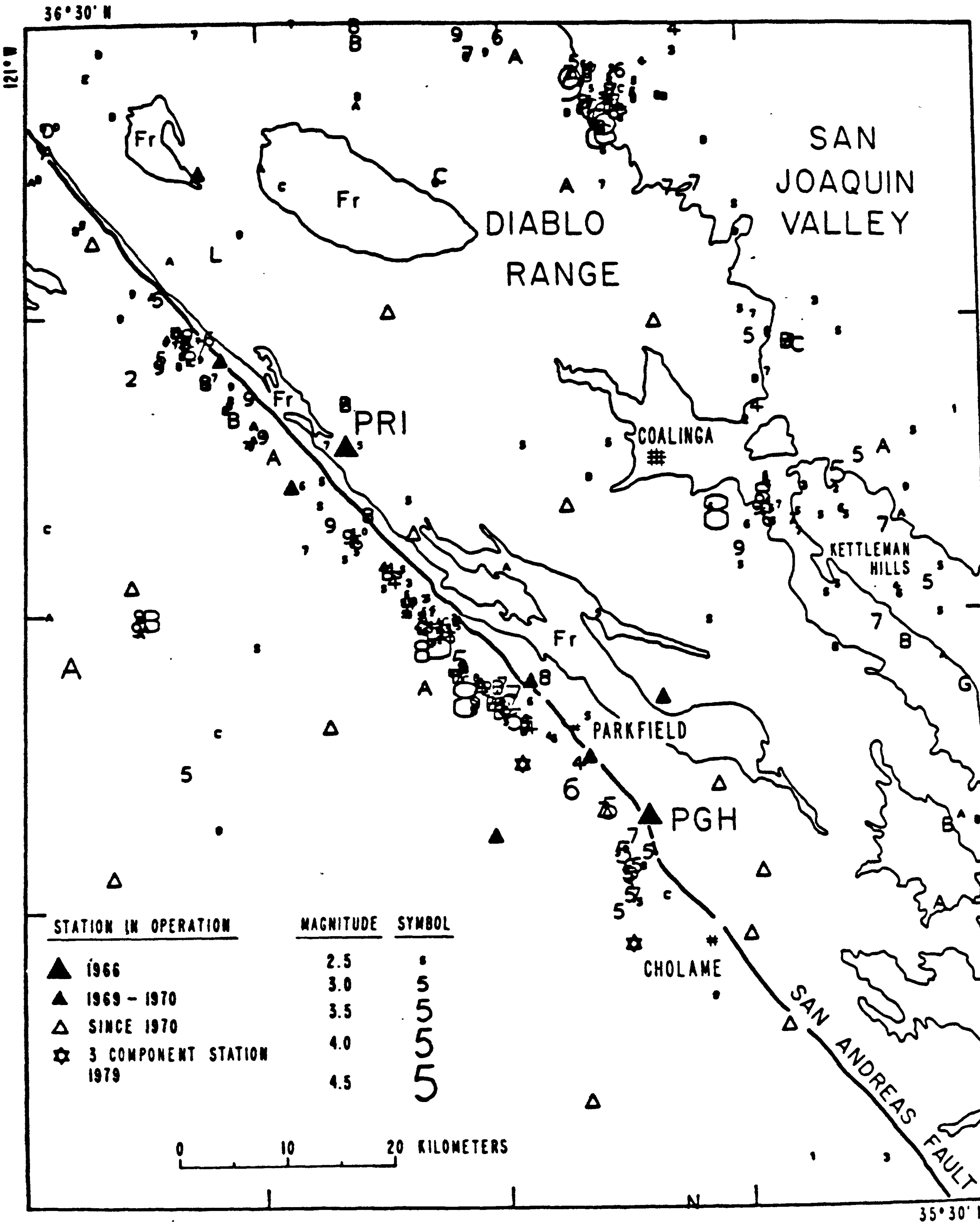
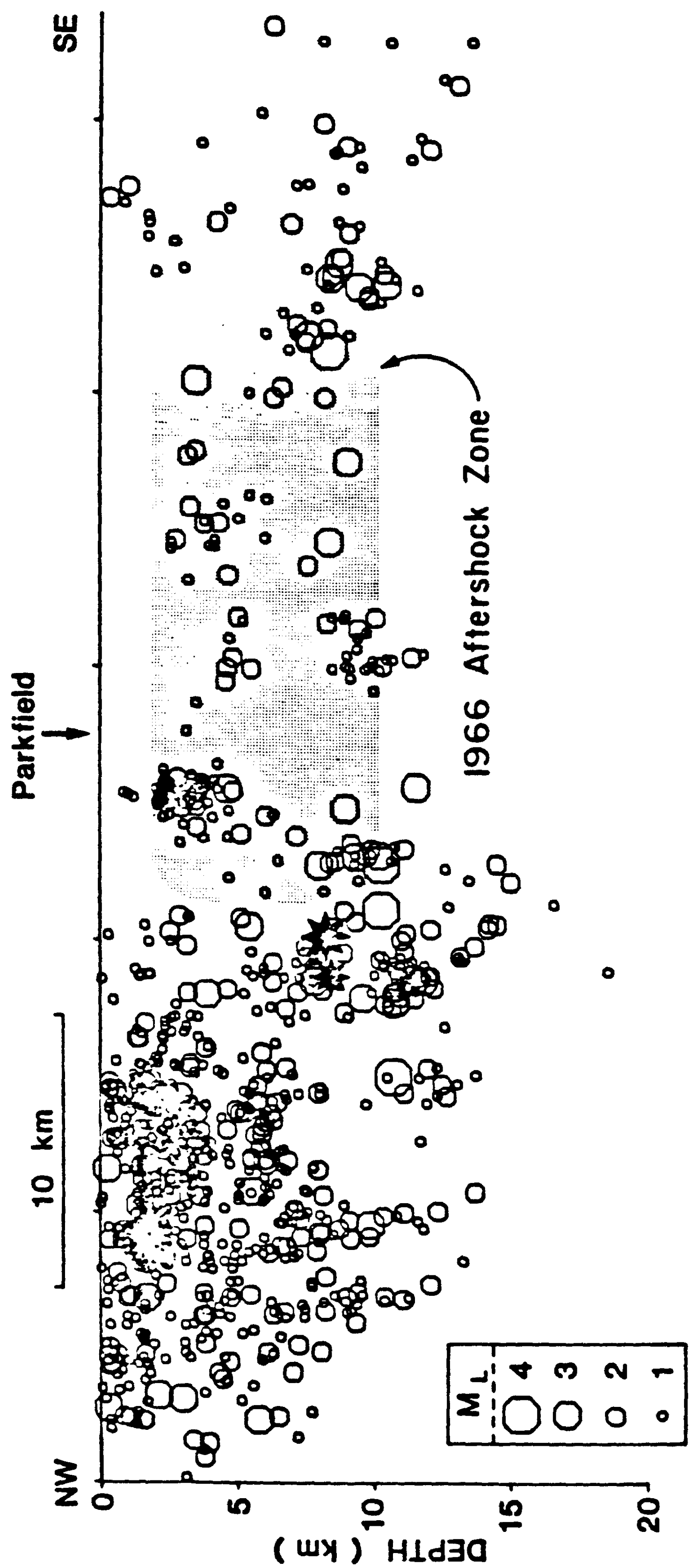

36°30' N
121° W
SAN
JOAQUIN
VALLEY
DIABLO
RANGE
Fr
PRI
COALINGA
KETTLEMAN
HILLS
PARKFIELD
PGH
CHOLAME
SAN ANDREAS FAULT
STATION IN OPERATION
1966
1969 - 1970
SINCE 1970
3 COMPONENT STATION
1979
MAGNITUDE
SYMBOL
2.5
3.0
3.5
4.0
4.5
0
10
20 KILOMETERS
35°30' N

Figure 6



NW
SE
Parkfield
10 km
1966 Aftershock Zone
DEPTH (km)
0
5
10
15
20
M_L
4
3
2
1

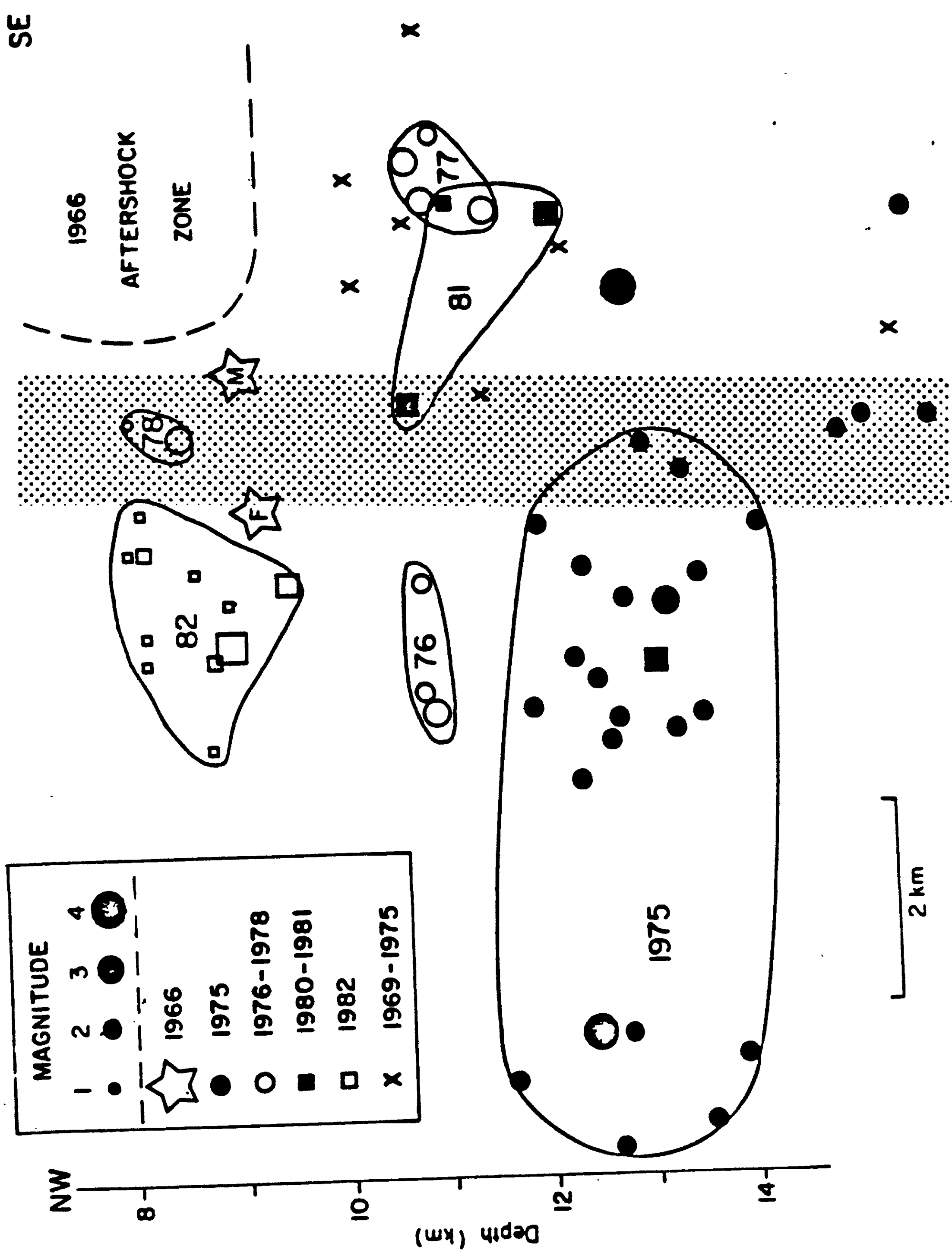

NW
SE
1966
AFTERSHOCK
ZONE
MAGNITUDE
1 2 3 4
1966
1975
1976-1978
1980-1981
1982
1969-1975
Depth (km)
8
10
12
14
2 km
82
76
78
77
81
1975
M
F

Figure 8

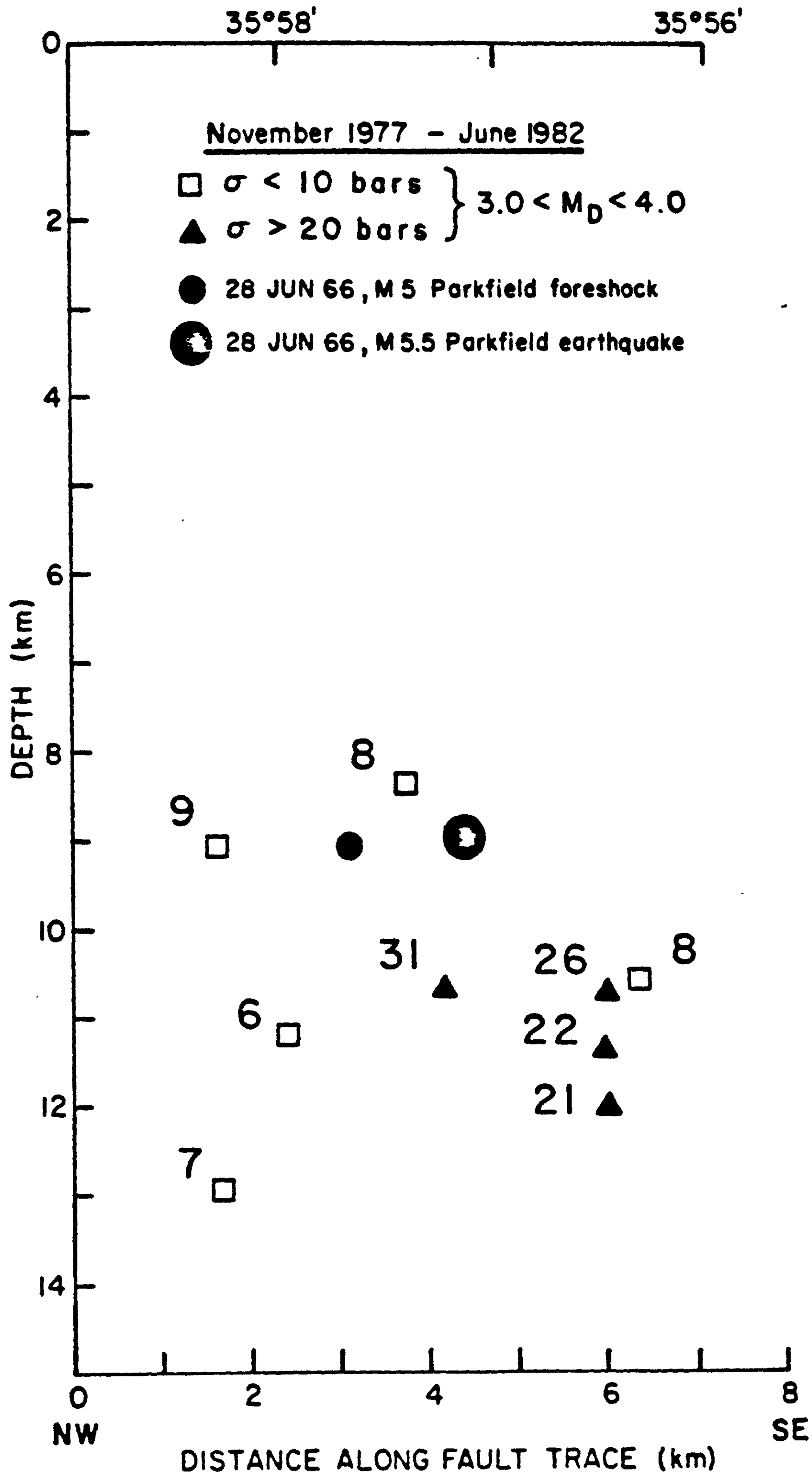

35°58'
35°56'
November 1977 - June 1982
σ < 10 bars
σ > 20 bars
3.0 < M_D < 4.0
28 JUN 66, M 5 Parkfield foreshock
28 JUN 66, M 5.5 Parkfield earthquake
DEPTH (km)
0
2
4
6
8
10
12
14
9
8
6
7
31
26
8
22
21
0
NW
2
4
6
8
SE
DISTANCE ALONG FAULT TRACE (km)

Figure 9

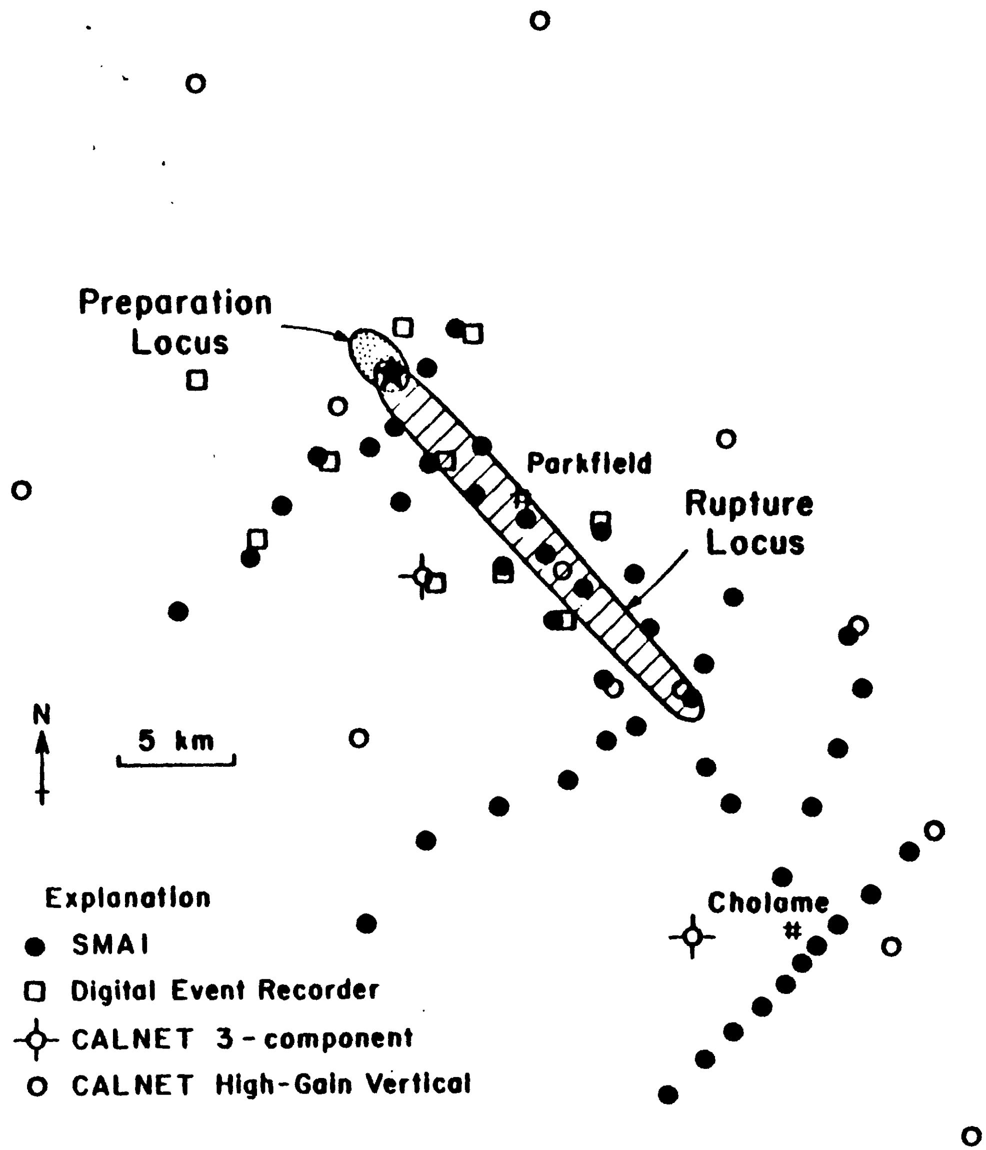

Preparation Locus
Parkfield
Rupture Locus
Cholame
N
5 km
Explanation
SMAI
Digital Event Recorder
CALNET 3-component
CALNET High-Gain Vertical

Figure 10

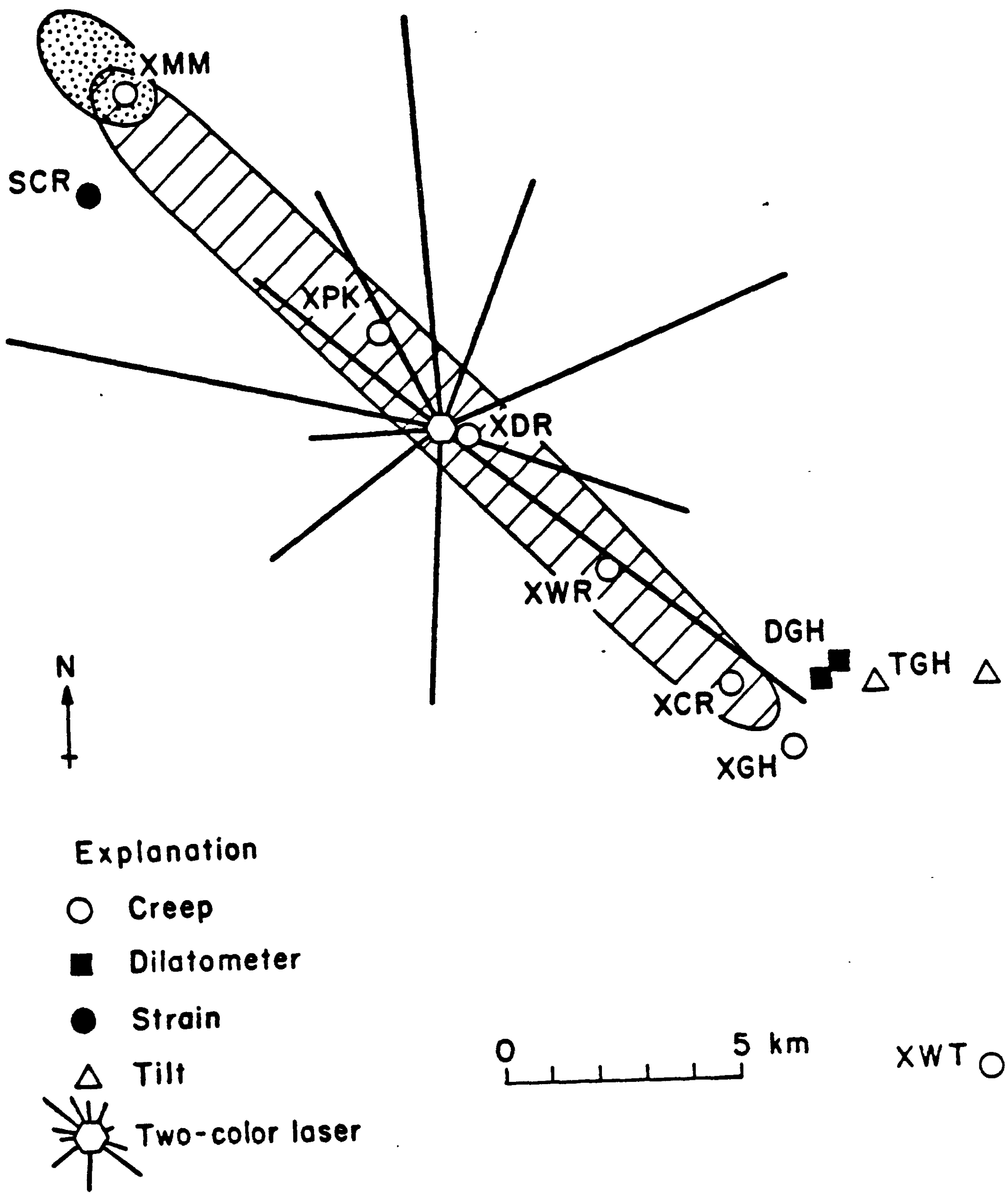

XMM
SCR
XPK
XDR
XWR
DGH
TGH
XCR
XGH
N
Explanation
Creep
Dilatometer
Strain
Tilt
Two-color laser
0
5 km
XWT

Figure 11

APPENDIX B

Holocene Activity of the San Andreas Fault at Wallace Creek, California

Kerry E. Sieh and Richard H. Jahns

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Holocene activity of the San Andreas fault at Wallace Creek, California

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ABSTRACT

Wallace Creek is an ephemeral stream in central California, the present channel of which displays an offset of 128 m along the San Andreas fault. Geological investigations have elucidated the relatively simple evolution of this channel and related landforms and deposits. This history requires that the average rate of slip along the San Andreas fault has been 33.9 ± 2.9 mm/yr for the past 3,700 yr and 35.8 + 5.4/-4.1 mm/yr for the past 13,250 yr. Small gullies near Wallace Creek record evidence for the amount of dextral slip during the past three great earthquakes. Slip during these great earthquakes ranged from ~9.5 to 12.3 m. Using these values and the average rate of slip during the late Holocene, we estimate that the period of dormancy preceding each of the past 3 great earthquakes was between 240 and 450 yr. This is in marked contrast to the shorter intervals (~150 yr) documented at sites 100 to 300 km to the southeast. These lengthy intervals suggest that a major portion of the San Andreas fault represented by the Wallace Creek site will not generate a great earthquake for at least another 100 yr. The slip rate determined at Wallace Creek enables us to argue, however, that rupture of a 90-km-long segment northwest of Wallace Creek, which sustained as much as 3.5 m of slip in 1857, is likely to generate a major earthquake by the turn of the century.

In addition, we note that the long-term rates of slip at Wallace Creek are indistinguishable from maximum fault-slip rates estimated from geodetic data along the creeping segment of the fault farther north. These historical rates of slip along the creeping reach thus do represent the long-term—that is, millennial—average, and no appreciable elastic strain is accumulating there.

Finally, we note that the Wallace Creek slip rate is appreciably lower than the average rate of slip (56 mm/yr) between the Pacific and North American plates determined for the interval of the past 3 m.y. The discrepancy is due principally to slippage along faults other than the San Andreas, but a slightly lower rate of plate motion during the Holocene epoch cannot be ruled out.

*Deceased.

INTRODUCTION

California has experienced many episodes of tectonic activity during the past 200 m.y. During the past 15 m.y. horizontal deformations due to the relative motion of the Pacific and North American plates have been dominant. On land, the major actor in this most recent plate-tectonic drama has been the San Andreas fault, across which ~300 km of right-lateral dislocation has accumulated since the middle Miocene (Hill and Dibblee, 1953; Crowell, 1962, 1981; Nilsen and Link, 1975).

The San Andreas fault traverses most of coastal California, running close to the populous Los Angeles and San Francisco Bay regions (Fig. 1a). Its historical record of occasional great earthquakes (Lawson and others, 1908; Agnew and Sieh, 1978) amply demonstrates that it poses a major natural hazard to inhabitants of these regions. The future behavior of the San Andreas fault thus has long been a topic of great interest to Californians. Interpretations of historical, geodetic, and geologic data have yielded estimates of one century to several centuries for the time between great earthquakes along the fault in the San Francisco Bay region (Reid, 1910; Thatcher, 1975). Geologic data indicate that similar recurrence intervals apply in southern California (Sieh, 1978b, and in press).

The behavior of the San Andreas fault during the past few thousands of years is one of the best clues to its future behavior. Useful forecasts concerning the likelihood or imminence of a great earthquake along the fault will be much more difficult without greater understanding of its behavior during the past several millennia.

In this paper, we present and discuss the geologic history of Wallace Creek, a locality about halfway between San Francisco and Los Angeles that contains much information about the Holocene behavior of the San Andreas fault (Fig. 1a). For the purpose of determining rates of slip in Holocene time, the channel of Wallace Creek offers excellent possibilities. The channel crosses and is offset along a well-defined, linear trace of the San Andreas fault in the Carrizo Plain of central California (Fig. 1b). It is relatively isolated from other large drainages, and, therefore, its history is not complicated by involvement with remnants of other drainages that have been brought into juxtaposition.

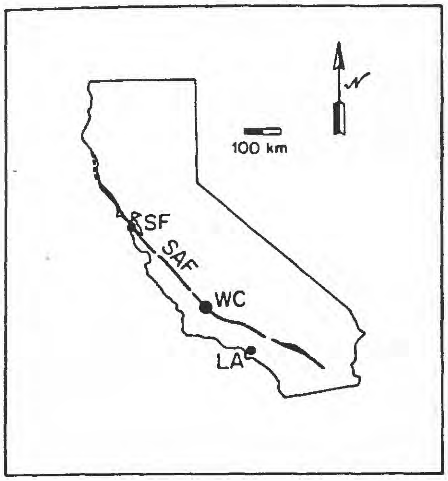
The simple geometry of Wallace Creek suggests a simple history of development. Arnold and Johnson (1909) inferred 120 m of offset on the San Andreas fault, because the modern channel of the creek runs along the fault for about that distance. Wallace (1968) also inferred a simple history of offset involving incision of a channel into an alluvial plain, offset of ~250 m, then channel filling and new incision across the fault. The latest dextral offset of 128 m then accumulated. These interpretations are verified and quantified by us in this paper.

STRATIGRAPHY AND GEOMORPHOLOGY

Figure 2 is a geologic map of the Wallace Creek area that is based upon surficial mapping and study of sediments encountered in numerous excavations. The map shows four main geologic units: older fan alluvium (uncolored), younger fan alluvium (green), high-channel alluvium (dark orange), and low-channel alluvium (light orange). A mantle of slope wash and local alluvium, which is extensively burrowed by rodents, overlies most of the deposits. This unit has been mapped (brown) only where it is thicker than ~1 m and does not cover units and relationships that need to be shown on the map.

Geological Society of America Bulletin, v. 95, p. 883–896, 11 figs., 3 tables, August 1984.

Figure 1. a. Wallace Creek (WC) is along the San Andreas fault (SAF) between Los Angeles (LA) and San Francisco (SF), in the Carrizo Plain of central California. b. This oblique aerial photograph shows the modern channel, which has been offset ~130 m, and an abandoned channel that has been offset ~380 m. An older abandoned channel, indicated by white arrow at left, has been offset ~475 m. Photograph by R. E. Wallace, 17 September 1974. View is northeastward.



a

b

Older Fan Alluvium

Underlying all other units exposed at the site, there is a late Pleistocene alluvial fan deposit derived from the Temblor Range to the northeast. This deposit, here termed the "older fan alluvium," consists of thin sheets, lenses, and stringers of indurate silty clay, pebbly sandy clay, and sandy gravel. Most of the trenches (Figs. 2 and 3) exposed this unit. Southwest of the fault, the older fan alluvium is covered by various deposits, but northeast of the fault, the deformed fan surface is incised.

Charcoal disseminated within the older fan alluvium 4 m below the surface of the fan in trench 5 (Fig. 3), yielded an age of 19,340 ± 1,000 yr B.P. (Table 1). The lack of major unconformities and paleosols in the older fan alluvium below or above this dated horizon implies that all of the exposed 13 m of the unit formed during the late Pleistocene epoch. Evidence discussed below supports a conclusion that the fan surface on the northeast side of the fault had become inactive by about 13,000 yr B.P.

FIGURE 2 EXPLANATION

UNITS

- Hl — Low-channel alluvium
- Hh — High-channel alluvium
- Hs — Slope wash (mantles most of area, but mapped only where boundaries are distinct)
- Py — Younger-fan alluvium (dots indicate edges of individual lobes)
- Po — Older-fan alluvium

SYMBOLS

- Contacts (solid where geomorphically apparent or exposed in trench, dotted where buried, dashed where inferred
- 0.3' — Faults (as above; hachures on downthrown side; numbers indicate height of scarp)
- Selected small gullies offset ~9m in 1857
- 5, 10 — Trenches {backhoe, bulldozer}
- Crests of small fans and source gullies offset ~9m in 1857
- 0.3' — Landslide, showing headscarp, scarp height, and direction of movement

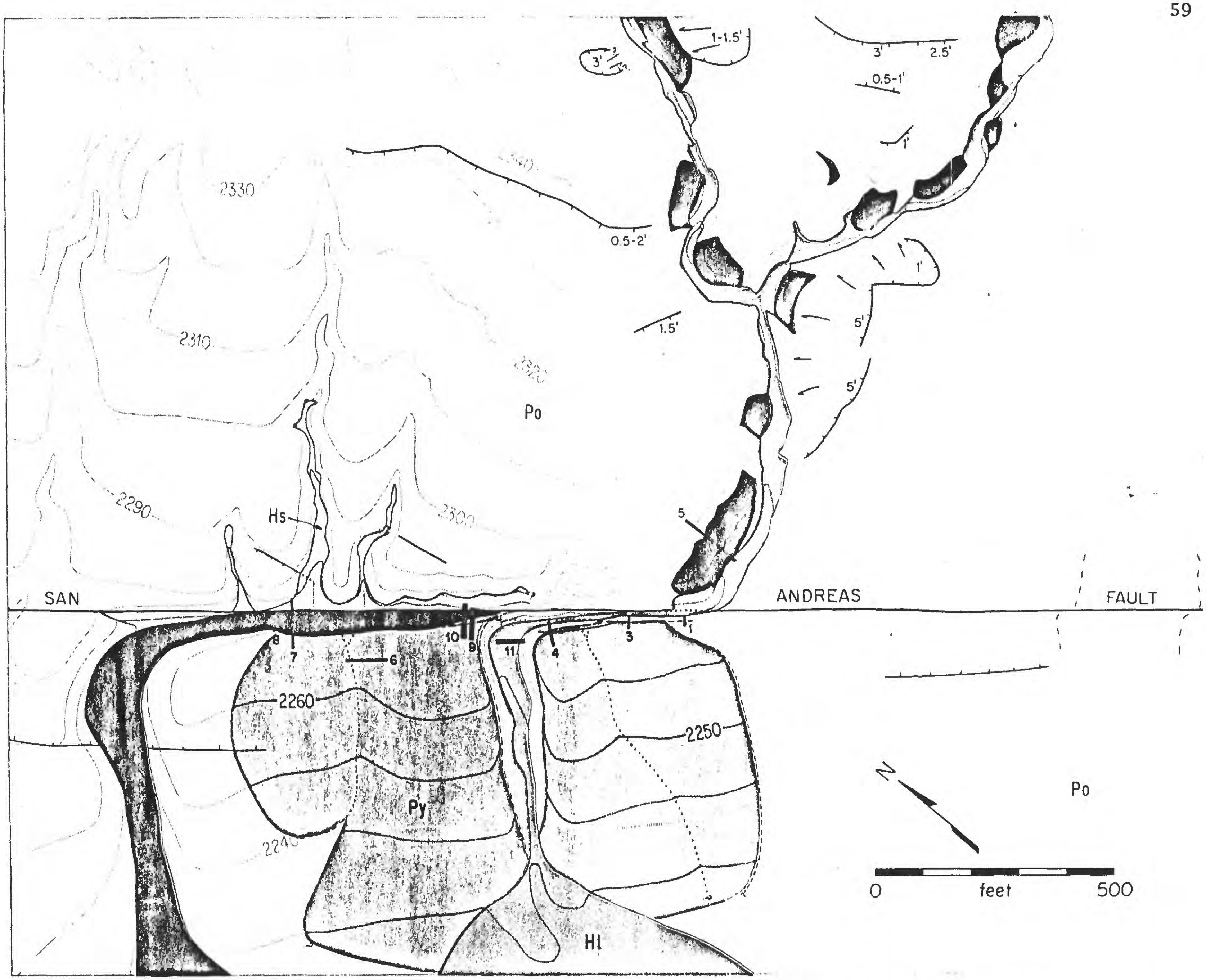
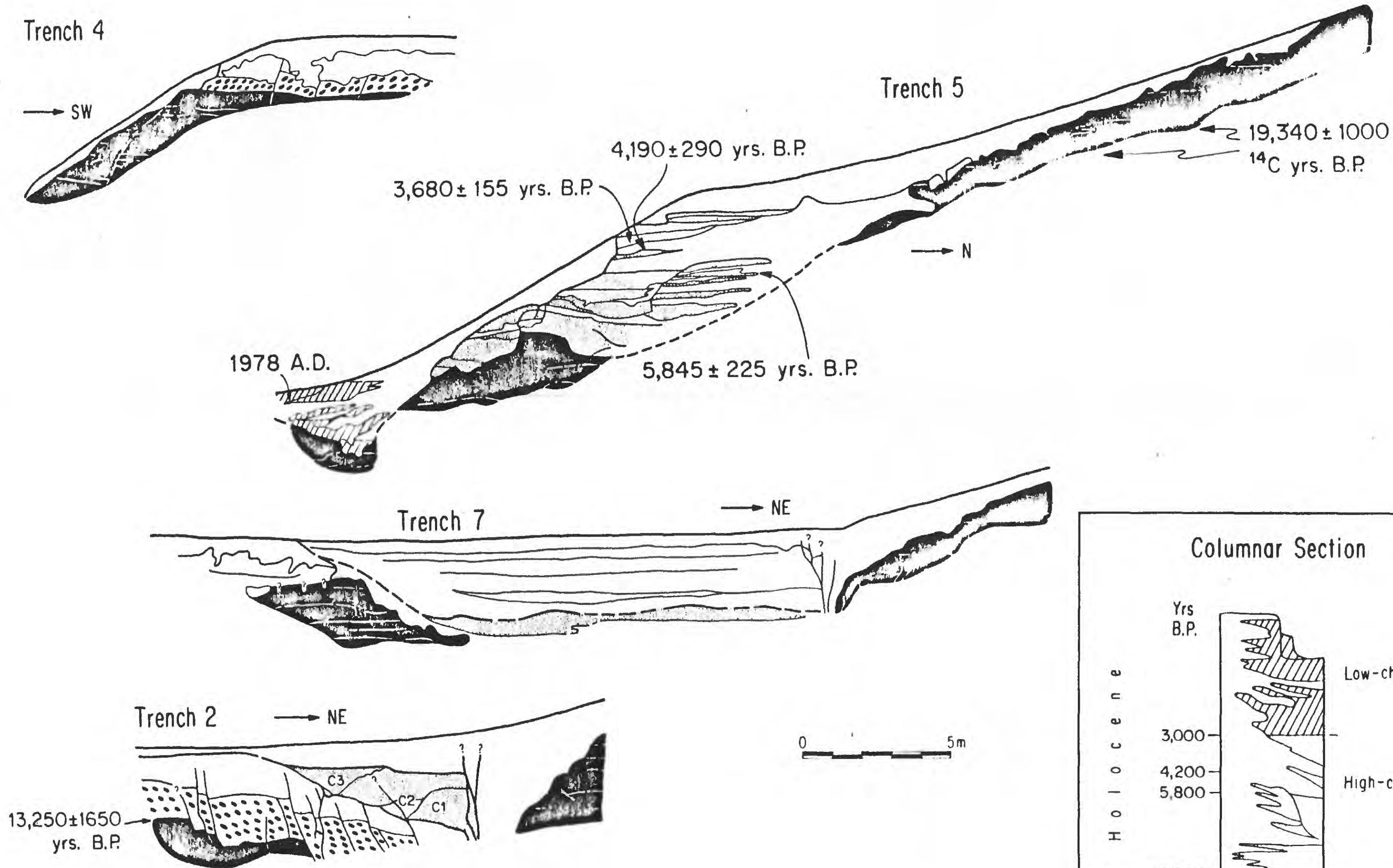


Figure 2. Geologic map of Wallace Creek. Contours of topographic base map show elevation (in feet) above sea level.



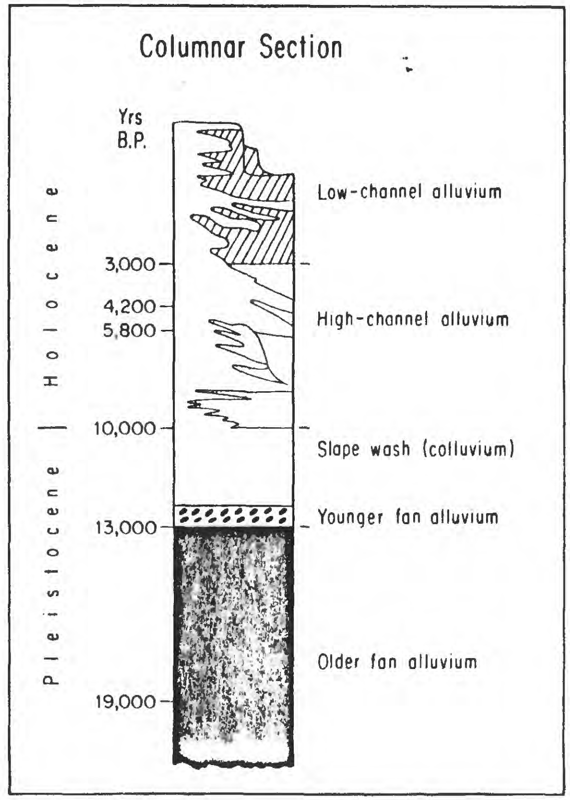


Figure 3. Records of selected excavations at Wallace Creek, California. See Figure 2 for locations. Detailed logs of these and other excavations are available upon request from the author.

TABLE 1. RADIOCARBON ANALYSES

Sample no.		Conventional ^{14}C age (yr B.P.)	$\delta^{13}C$	Reservoir corrected age[§]	Calendric age (yr B.P.)
Caltech	Univ. Wash.				
WC-5	UW-567	18,750 ± 450	22.37	18,782 ± 450	19,340 ± 1000**
WC-2	UW-572	12,865 ± 1650			13,250 ± 1650**
WC-6	UW-564	5,040 ± 180	21.51	5,096	5,845 ± 225††
WC-7	UW-565	3,730 ± 170	22.40	3,772	4,190 ± 290††
WC-9-2	UW-744	3,720 ± 140	10.5	3,956	4,480 ± 270††
WC-3	UW-563	3,495 ± 110	-19.71	3,580	3,680 ± 155††
WC-3	UW-563b	3,285 ± 100	-19.71	3,370	
McKS-1	UW-355	3,340 ± 120	·	·	
WC-10-1	UW-742	3,320 ± 100	-15.4	3,476	3,780 ± 155††
WC-11-1	UW-745	1,110 ± 180	-10.8	1,341	1,035 ± 235§§

Note: all date uncertainties in the table are at 95% confidence level.
[†]As defined by Stuiver and Polach (1977, p. 356).
[§]As explained in Stuiver and Polach (1977), conventional ages must be corrected for isotopic fractionation.
**Corrected using half-life of 5,730 yr; uncertainty estimated following suggestion of Klein and others (1982, p. 117).
[††]From Klein and others (1982, Table 2).
[§§]From Stuiver, 1982.

Younger Fan Alluvium

Southwest of the fault (Fig. 2), there is a lobate deposit that we have termed the "younger fan alluvium." This deposit overlies and is less indurated than the older fan alluvium. It is a well-sorted gravelly sand with a distinctive imbrication of pebbles that indicates southwestward current flow. The unit is thickest near trenches 2, 9, and 10 and thins to the northwest, southeast, and southwest. The boundary of this composite alluvial fan is inferred from the topography and the trench exposures. A radiocarbon date from charcoal in the upper centimetre of the older fan alluvium (trench 2) indicates that the younger fan alluvium began to accumulate 13,250 ± 1,650 yr B.P. (Table 1).

High-Channel Alluvium

Nestled within the channel of Wallace Creek above the modern stream bed, there are numerous remnants of an ancient terrace (Fig. 2). This surface is referred to as the "high terrace," and it is underlain by sand and gravel beds characterized by scour-and-fill structures, which we refer to as the "high-channel alluvium" (trench 5 in Fig. 3). The massive and poorly sorted nature of some of these "high-channel" beds indicates that they are debris-flow deposits. Other beds that are well sorted and laminated must have been transported as bedload in the waters of Wallace Creek.

Radiocarbon analyses (3) of charcoal from within the high-channel deposits in trench 5 demonstrate that these beds were accumulating through a period from 5845 ± 225 yr B.P. to 3680 ± 155 yr B.P. (samples WC-3, WC-6, and WC-7 in Table 1).

Southwest of the San Andreas fault, the high-channel deposits occur in the abandoned channel of Wallace Creek (Figs. 1 and 2). Trenches 2, 7, and 8 (Fig. 3) and 9 and 10 (Fig. 4) show these sands and gravels residing in a 3- to 4-m-deep channel cut into colluvium. Like their correlatives northeast of the fault, these beds exhibit major episodes of scour and fill. A radiocarbon analysis of organic matter from trench 10 yielded an age of 3,780 ± 155 yr B.P. This sample was collected from a colluvial wedge in the middle of the deposits in the abandoned channel, and its age indicates that the abandoned-channel deposits are contemporaneous with the high-channel deposits across the fault and upstream.

Figure 5 includes a profile of the high terrace. The height of the high terrace above the modern channel is greatest at the fault; the terrace merges with a low terrace ~1 km upstream from the fault. Judging from the elevation difference of the high terrace across the fault, vertical slip during the past 3,800 yr is 3 m, which is a mere 2.3% of the horizontal slip during that time period. It is worth noting that within 1 km to the northwest and to the southeast, this vertical slip diminishes to zero and reverses sense.

Modern-Channel Alluvium

Younger sand and gravel beds very similar to the high-channel alluvium have been deposited in the modern channel of Wallace Creek (Fig. 2, and trench 5 in Fig. 3). Like the high-channel alluvium, this "modern-channel alluvium" also exhibits scour-and-fill structures and interfingers with debris derived from the channel walls.

In trench 5, the base of the modern-channel alluvium is ~2.5 m beneath the creek bed, and along the entire channel, there is a low terrace that occurs 1.5 m above the modern creek bed (Fig. 5). This terrace represents the highest level reached by the modern-channel deposits; it formed and was incised within the past 1,000 yr, as indicated by the radiocarbon date of 1035 ± 235 yr B.P. on charcoal 2.5 m below the terrace surface in trench 11 (Fig. 6). An early photograph of the channel shows that the low terrace was incised by the creek prior to A.D. 1908 (Sieh, 1977, p. 61).

GEOLOGIC HISTORY

The evolution of Wallace Creek has been rather simple. It is divisible into four periods, each of which ends in a sudden change of channel configuration.

Accumulation of Older Fan Alluvium and Initial Entrenchment of a Channel

Prior to initial incision of Wallace Creek, during the late Pleistocene epoch, the older fan alluvium gradually accumulated as broad, thin beds on an alluvial fan or apron that extended southwestward from the Temblor Range across the San Andreas fault (Fig. 7a). The lack of small channels within the older fan alluvium indicates either that any scarps that formed along the fault during this interval were buried before they accumulated even 1 m of height, or that they faced mountainward and served to pond the older fan alluvium on the upstream side of the fault. About 13,000 yr B.P., the first major entrenchment of the older fan alluvium occurred (Fig. 7b). Several small gullies were eroded into the fault scarp, and their debris, the younger fan alluvium shown in Figure 2, was deposited at the foot of the scarp. At about the same time, the initial entrenchment of Wallace Creek occurred. The downstream segment of this initial channel now lies outside the mapped area, ~475 m northwest of Wallace Creek (beneath the white arrow at left margin of Fig. 1b).

Initial Offset of Wallace Creek and Re-entrenchment

After ~100 m of right-lateral slip had been registered by the features formed ~13,000 yr B.P., the initial downstream segment of Wallace Creek was abandoned, and a new segment was cut, so that a straight-channel configuration was restored across the fault (Fig. 7c). This new segment is the one labeled "abandoned channel" in Figure 1.

More Offset and Re-entrenchment of the Channel

For several millennia the newly re-entrenched Wallace Creek served as a narrow conduit for materials being transported fluvially out of the nearby Temblor Range. The depth of initial incision of this channel is poorly constrained, but it cannot have been more than 12 m, which is the depth of the base of the high-channel deposits below the surface of the old alluvium in trench 5. As slip accumulated along the San

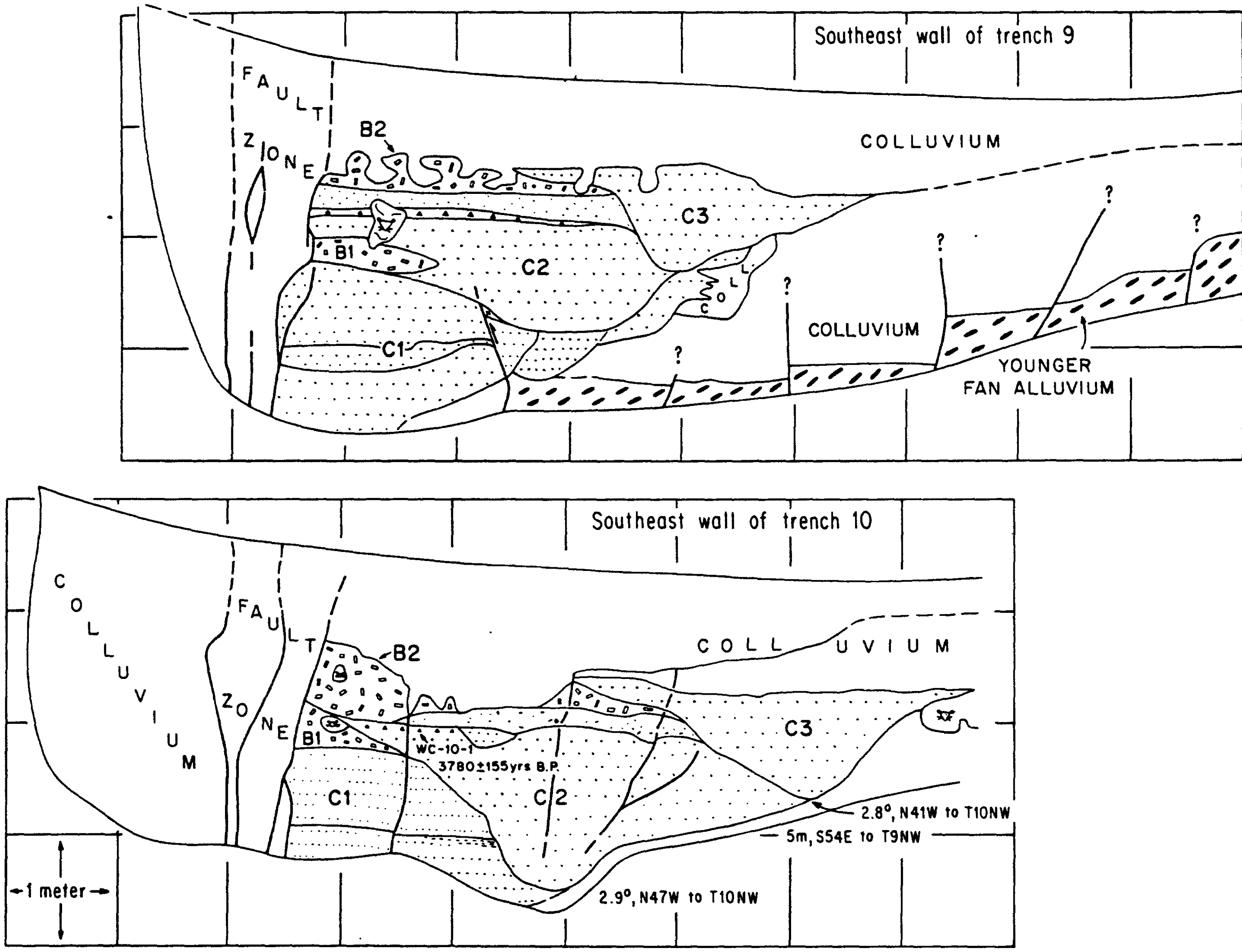


Figure 4. Trenches 9 and 10 reveal the various deposits of the abandoned channel. B_1 and B_2 are scarp-derived breccias. C_1, C_2, and C_3 are fluvial sands and gravels. Solid triangles indicate location of charcoal that yielded date for channel deposits.

Andreas fault early during the Holocene epoch, Wallace Creek developed a bend along the fault that reflected the offset accumulated since entrenchment (Fig. 7d). Water and debris flowing within the channel were diverted to the right at the fault, flowed along the fault for a distance equal to the accumulated offset, and then were diverted left and away from the fault. These two bends in the channel will be referred to hereinafter as the right bend and the left bend.

Trench 5 indicates that by ~6000 yr B.P., 3.0 to 3.3 m of sediment had been deposited within the channel at the right bend. Trench 5 also shows that, locally, at least 1.5 and perhaps 3.3 m of these high-channel deposits subsequently was eroded away. About 3800 yr B.P., after the channel had been offset ~240 m, critical changes began to occur within the channel. For reasons that we do not understand, debris began to accumulate in the channel to greater thicknesses than ever before (Fig. 7e). Trench 5 reveals that at the right bend, the accumulation was at least 5.5 m deep. Trenches 2, 9, and 10 show that this accumulation all but filled the channel at the right bend. This filling set the stage for abandonment of the channel downstream from the right bend and re-entrenchment of Wallace Creek straight across the fault (Fig. 7e). The new channel was cut no more than 8.5 m below the level of the old channel, as the maximum depth of the new channel is only 8.5 m below the top of the high terrace in trench 5.

Offset and Future Re-entrenchment of the New Channel

The new channel has been offset ~130 m subsequent to its creation about 3800 yr B.P. (Fig. 7f). The modern-channel deposits have accumulated in the new channel during this period of time. They are now ~2.5 m thick at the right bend and more than 2.5 m thick at the left bend.

Although the active channel floor is now ~3 m below the crest of the channel bank at the

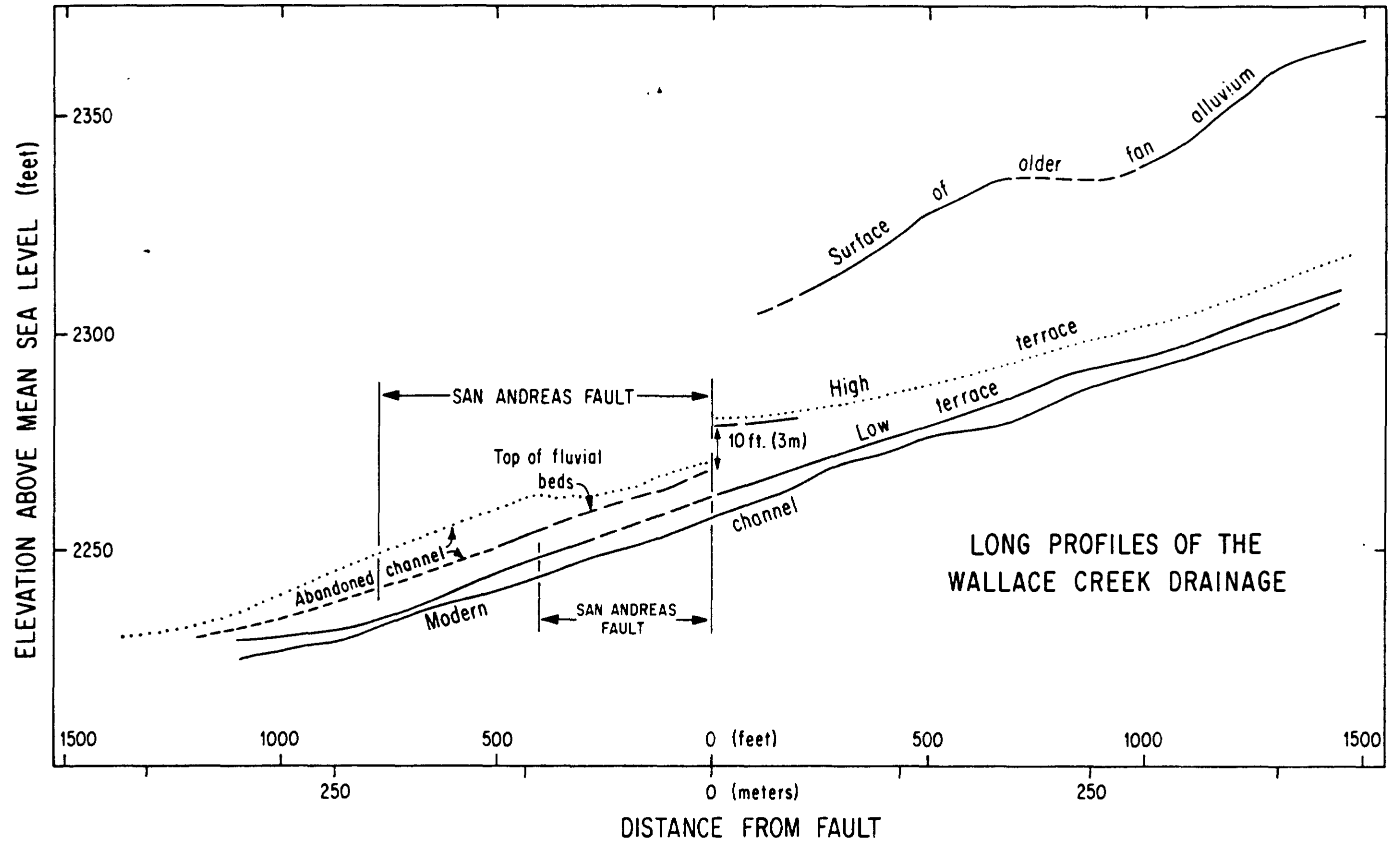


Figure 5. Stream profiles of the modern and the abandoned channels of Wallace Creek. High terrace, indicated by dotted lines, and top of high-channel alluvium, indicated by solid and dashed lines, are offset ~3 m vertically.

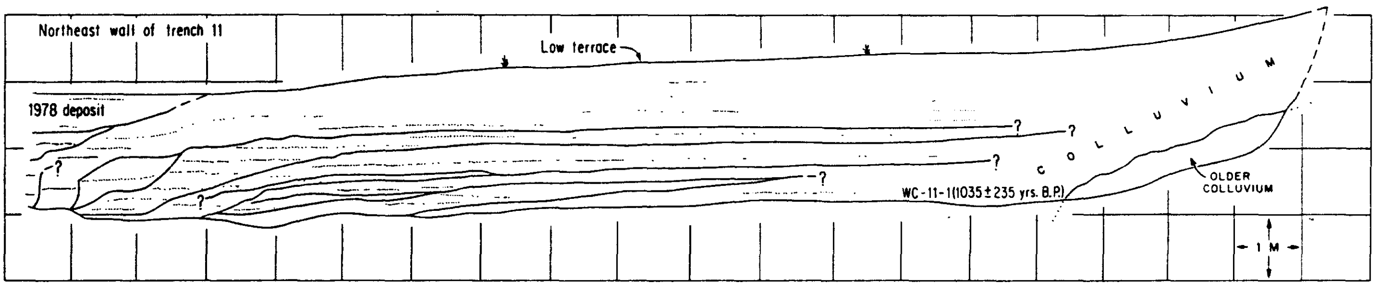


Figure 6. Trench 11 exposes the upper 2.5 m of low-channel deposits in the modern channel. Solid lines are contacts of individual fluvial beds. Dotted lines represent locally visible layering within these beds.

right bend, older modern-channel deposits form a low terrace surface that is only 1 m below the crest of the bank there. Mr. Ray Cavanaugh, who farms at Wallace Creek, reported to us that water actually spilled over the edge at the right bend in the winter of 1971–1972 or 1972–1973. It is not hard to envision a third entrenchment of Wallace Creek (Fig. 7g), given another metre or two of channel filling and a moderately high discharge. Such a re-entrenchment would establish the creek once again straight across the fault.

SLIP RATE OF THE SAN ANDREAS FAULT

Slip Rate during the Late Holocene

Knowing the date of the most recent entrenchment of Wallace Creek and the offset that has accumulated since that entrenchment, one can calculate rather precisely the rate of slip for the San Andreas fault. That rate is 33.9 ± 2.9 mm/yr, and its derivation is explained in detail below.

The offset of the modern channel of Wallace Creek is 128 ± 1 m. This figure is obtained by extrapolating the southwestern edge of the abandoned channel (labeled 1 in Fig. 8) to its

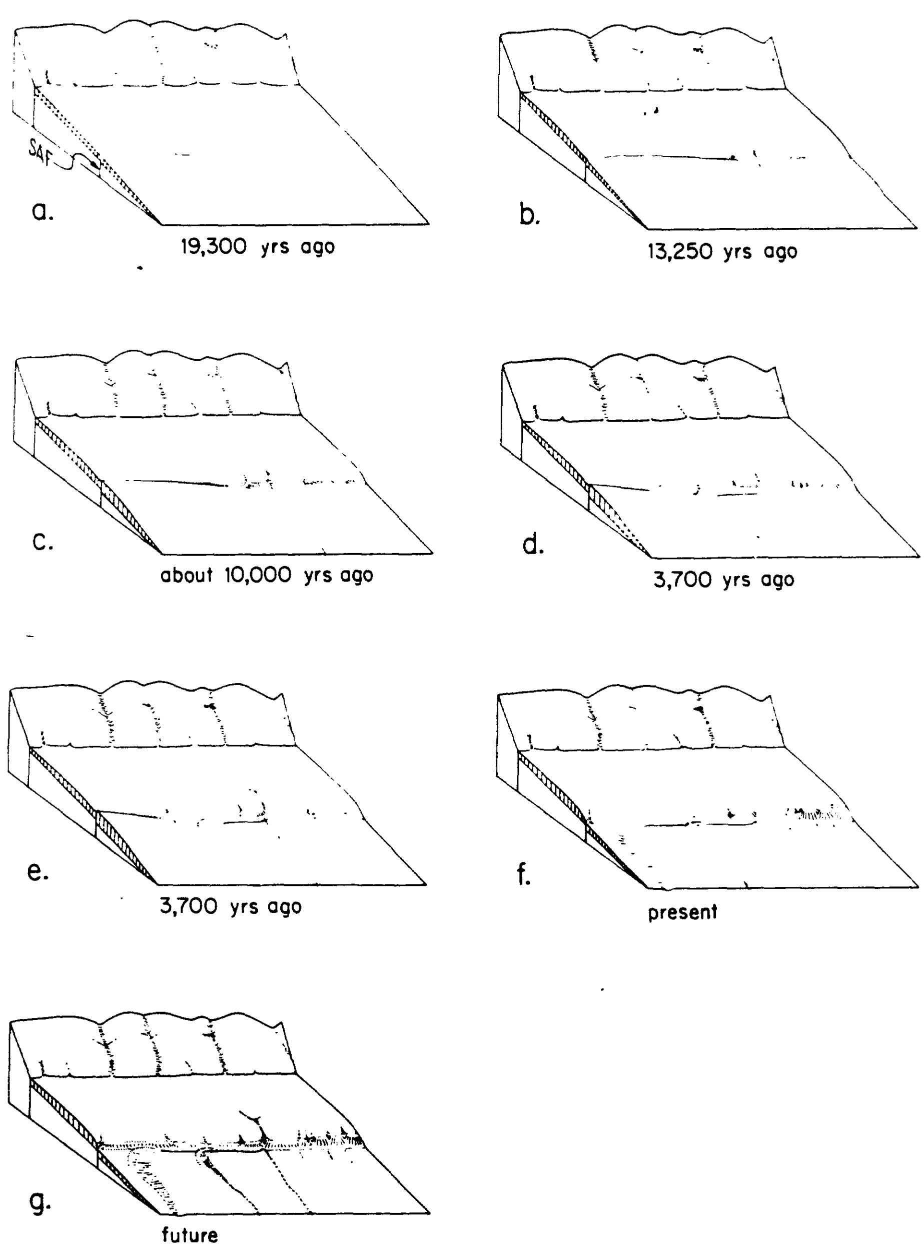


Figure 7. The Holocene–late Pleistocene evolution of Wallace Creek. An aggrading "older alluvial fan" during the period including 19,300 yr ago progressively buried small scarps formed along the San Andreas fault (SAF) during major strike-slip events (a). Right-lateral offsets accumulated during this period, but no geomorphologically recognizable offsets began to form until 13,250 yr ago, when the "older alluvial fan" became inactivated by initial entrenchment of Wallace Creek (b). At this time, erosion of small gullies to the right (southeast) of Wallace Creek also resulted in deposition of the "younger fan alluvium" downstream from the fault. These features then began to record right-lateral offset, and scarps began to grow along the fault. About 10,000 yr ago, a new channel was cut across the fault at Wallace Creek, and the initial channel, downstream from the fault, was abandoned (c). The new channel remained the active channel of Wallace Creek during the early and middle Holocene, during which ~250 m of slip accumulated (d). This channel filled with "high-channel alluvium" 3,700 yr ago, and Wallace Creek cut a new channel straight across the fault (e). Between 3,700 yr ago and the present, this youngest channel has registered 128 m of right-lateral offset (f). Aggradation of this channel, accompanied by continued offset, will probably lead to its abandonment and the creation of a new channel, cut straight across the fault (g).

intersection with the fault and then measuring the distance from that intersection to the intersection of the modern channel edge (labeled 2 in Fig. 8) with the fault. The same value is obtained if one measures the distance between the offset segments of the modern channel (labeled 3 and 4 in Fig. 8). In making the latter measurement of offset, it is important to realize that the outside edge of the left bend has been eroded by flood waters that have swept against it as they have passed around the left bend. The right bend has not been eroded in this manner, because it is refreshened each time the fault slips.

The fact that feature 1 and feature 3 (Fig. 8) intersect the fault at almost the same point strongly suggests that the abandonment of the high channel and entrenchment of the modern channel were contemporaneous. This coincidence also indicates that the new channel was cut straight across the fault without any initial nontectonic deflection of the stream along a fault scarp. The absence of any initial, nontectonic deflection is also confirmed by the fact that the modern channel is entrenched through a broad topographic high immediately downstream from the fault (consider contours in Fig. 2). If the channel had been deflected along a fault scarp, one would expect it to have cut through a low point on the downstream side of the fault rather than a high point. The measured separation of 128 m thus is ascribable entirely to tectonic offset.

The youngest date from the deposits of the abandoned high channel (3680 ± 155 yr B.P.) provides a maximum age for the modern channel, because all of the high-channel sediments were deposited before the modern channel was cut. All offset of the modern channel thus occurred between this date and A.D. 1857. The average slip rate, therefore, can be no slower than 35.7 ± 1.9 mm/yr [128 ± 1 m/3,680 ± 155 – 93 yr]. (93 yr is the time between A.D. 1950, which has been designated zero B.P., and A.D. 1857.)

Additional considerations are necessary to provide an upper limit to the slip rate. For this constraint, trenches 9 and 10 (Fig. 4) are useful. The high-channel deposits here consist of three distinct units, labeled C1, C2, and C3, that represent three distinct scourings and fillings. The uppermost sediment of channel C2 in trench 10 contained the radiocarbon sample the age of which is 3780 ± 155 yr B.P. At the time of deposition, C1, C2, and C3 in trenches 9 and 10 must have been at or northwest of the right bend of Wallace Creek. Trench 9 is now 145 m northwest of the right bend, and so no more than 145 m of dextral slip has accumulated since channel C2 was filled 3780 ± 155 yr B.P.

The trend of C2 between trenches 10 and 9 suggests that the edge of C2 actually intersects

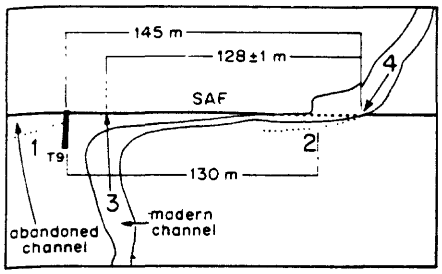


Figure 8. The edge of the abandoned channel (1) intersects the fault 128 ± 1 m northwest of the intersection of the modern channel edge (2) and the fault. The offset of the modern channel (from point 3 to point 4) is also 128 m. These provide the best measure of offset during the past 3,700 yr.

the fault at least 10 m closer to the modern right bend. In support of this, we note that the channel is ~5 m wide and rests entirely southwest of the fault in both trench 9 and trench 10. Sufficient channel width to accommodate a similar deposit southwest of the fault in the modern channel does not exist until at least 15 m downstream from the modern right bend. There, the crest of the channel bank is ~5 m southwest of the fault trace, and, were the channel to fill this year, a 5-m wide deposit analagous to the channel fill in trenches 9 and 10 would be deposited. From trench 9 to this geometrically analagous point in the modern channel (labeled 2 in Fig. 8) is ~130 m. It seems, therefore, that no more than 130 m of dextral slip accumulated between 3780 ± 155 yr B.P. and A.D. 1857. This yields an *upper* limit of 35.3 ± 1.5 mm/yr [130 m/(3,780 ± 155 − 93 yr)] for the slip rate. This maximum limiting rate is indistinguishable from the minimum limiting rate of 35.7 ± 1.9 mm/yr determined previously and independently. The rate must therefore be 35.3 ± 1.5 mm/yr, which includes the highest maximum value (35.3 + 1.5 mm/yr) and the lowest minimum value (35.7 − 1.9 mm/yr).

The calculations thus far have assumed continuous fault displacement between 3680 yr B.P. and A.D. 1857. It is very likely, however, that much, and possibly all, of the slip accumulates sporadically, during large earthquakes, such as that which occurred in 1857. If, as we argue below, this segment of the fault is characterized by coseismic displacements of ~10 m, followed by several centuries of quiet repose, the fault could have been at any point in its earthquake cycle 3680 yr B.P. If, in that year, the region bisected by the fault was in the middle or toward the end of a period of elastic strain accumulation, the rate calculated using this data will be slightly too high, because the 128-m offset accumulated between then and 1857 is in small part due to loading that occurred slightly earlier. Put in a different way, the 3,680-yr date may be any fraction of a recurrence interval younger than the beginning of a strain accumulation cycle. The beginning of the loading cycle corresponding to the earliest increment of the 128-m offset thus may be any time between 3680 yr B.P. and 3680 plus one recurrence interval. As is seen below, the average recurrence interval here is ~310 yr, or 8% of the time between A.D. 1857 and 3680 yr B.P. The actual slip rate thus could be as much as 8% lower than that just calculated, or 32.5 ± 1.5 mm/yr. The late Holocene slip rate thus could be any value between 32.5 ± 1.5 and 35.3 ± 1.5 mm/yr. This range is conveniently expressed as 33.9 ± 2.9 mm/yr.

Slip Rate since 13,250 yr B.P.

An additional determination of slip rate along the San Andreas fault at Wallace Creek comes from the 475-m offset of a 13,250-yr-old alluvial fan from its source gullies. This provides an average slip rate of 35.8 + 5.4/−4.1 mm/yr, which is not appreciably different from the late Holocene rate of 33.9 ± 2.9 mm/yr.

The 13,250-yr-old alluvial fan constitutes the "younger fan alluvium" mapped in Figure 2. The fan radiated from a point that is now located very near the modern left bend of Wallace Creek. Its existence is reflected in the bulging of the 2,240-, 2,250-, and 2,260-ft contours toward the southwest (Fig. 2). Even though it is now buried by 1.5 to 2 m of unmapped slope wash and bioturbated materials, the bulging of the contours and measurements of thickness in trenches 2, 3, 4, and 6 enable construction of the isopach map of the younger fan alluvium shown in Figure 9.

Trench 2 (Fig. 3) exposes the sediments of the fan near its apex. There, the sediments constitute a 1.3-m-thick bed of well-sorted, imbricated sandy gravel. The gravel is composed of tabular pebbles of diatomaceous Tertiary marine mudstone. Imbrication of these tabular pebbles clearly indicates a flow direction toward the southwest. The source of the alluvial fan thus must be on the opposite side of the San Andreas fault. Although the fan is composed of three discrete beds in trench 2 (see detailed log of trenches, available from author), the lack of bioturbation or weathering of the two horizons between these beds suggests that the fan was deposited very rapidly, perhaps in a matter of a few decades or less.

The deposit overlies a massive, poorly sorted sandy loam that represents either a colluvial unit or an alluvial deposit that was extensively bioturbated prior to burial. The unit probably lay at the ground surface for a long time prior to burial by the alluvial fan. The presence of charcoal pebbles and granules in this unit, no more than a centimetre or two beneath the base of the fan, suggests that a range fire occurred just prior to deposition of the fan. The charcoal certainly would have been oxidized if it had not been buried deeply very soon after its formation. Erosion of the fan materials from their source within the burned area may have been a direct result of the fire, which removed protective vegetative cover from the ground surface. The charcoal age of 13,250 ± 1,650 yr B.P. thus represents the age of the basal unit of the overlying alluvial fan.

If the source of the younger fan sediments were Wallace Creek, the fan would be offset a mere 128 m. This would imply that the fault was inactive between about 13,000 yr and about 3700 yr B.P., because we have just shown that 128 m of slip has occurred since about 3700 yr B.P. Such a long period of dormancy along the San Andreas fault seems very unlikely to us, and so we seek a source for the younger fan that is farther to the southeast.

The volume of the fan is ~25,000 m^3. Candidates for the source gully (or gullies) must have total eroded volumes at least as great as this and preferably somewhat larger, because some of the material transported out of the source region must have been carried beyond the alluvial fan as suspended load and bedload.

Given this constraint, only two plausible sources for the fan exist within 1 km of Wallace Creek. The first is a solitary channel ~730 m southeast of the fan apex (E in Fig. 1). This channel originates in the Temblor Range but drains a much smaller area than Wallace Creek. If this is the source, an average slip rate of ~63 mm/yr for the period 13,250 to 3700 yr B.P. is calculated:

$$\frac{(730 - 128)\text{ m}}{(13{,}250 - 3{,}680)\text{ yr}} = 63\text{ mm/yr}.$$

This would indicate fluctuations in slip rate of at least several centimetres per year during the past 13,000 yr, because the average rate for the past 3,800 yr has been ~34 mm/yr.

More likely sources for the alluvial fan are four closely spaced gullies several hundred metres southeast of the fan apex (A, B, C, and D in Fig. 1). In Figure 9, these have been restored to their probable location at the time of formation of the fan. None of these four small gullies, which extend only a few hundred metres back from the fault scarp, could have been the sole provider of enough material to construct the entire fan. The volumes of A, B, and C are only ~13,000 m^3 each, and D is much smaller. In any combination, however, they could have delivered enough material.

The proper matching of this multiple source with the younger fan deposit can be determined rather precisely. If the general reconstruction shown in Figure 9 is correct, the southeastern

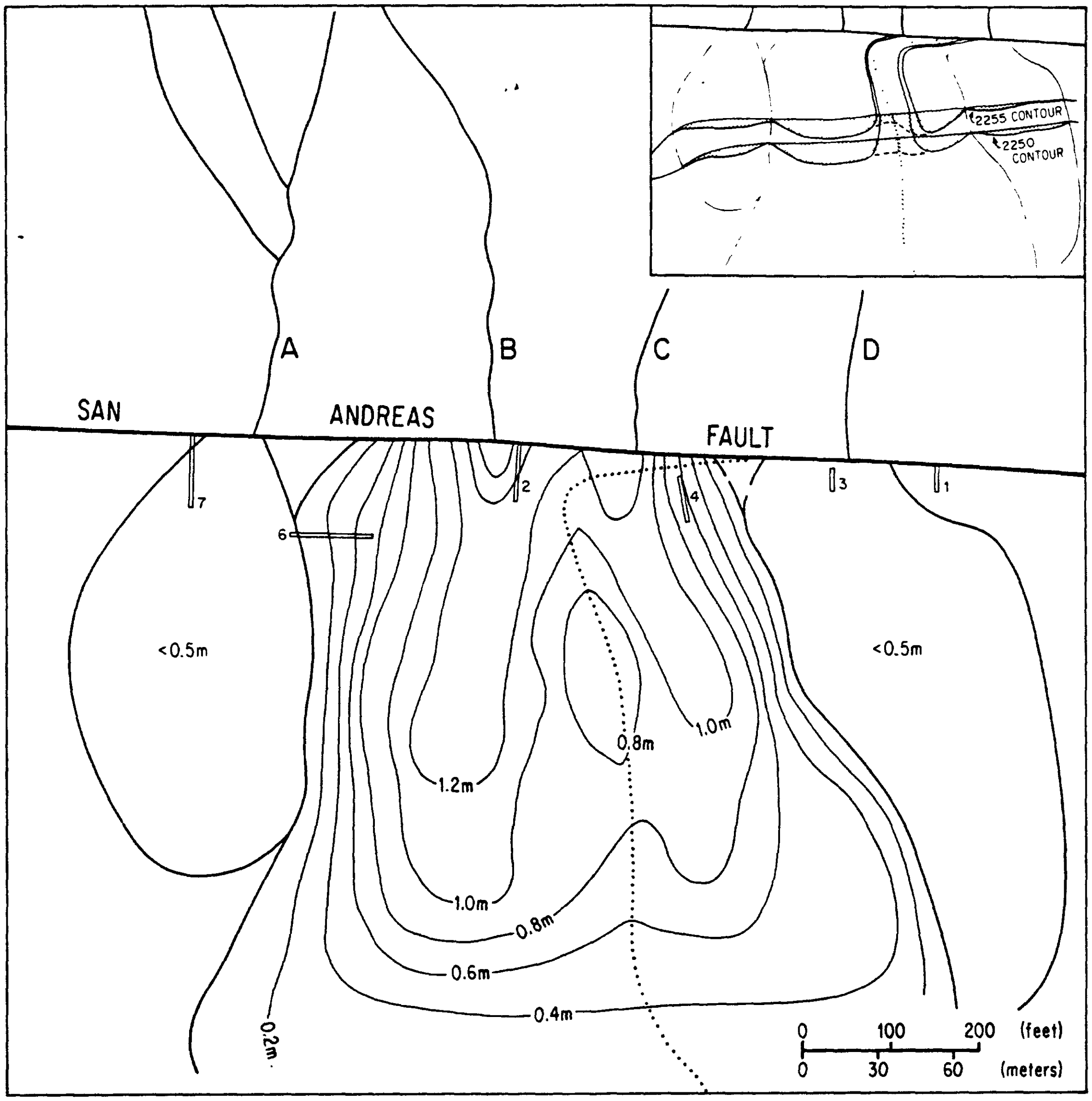


Figure 9. Isopach map of 13,250-yr-old alluvial fan and source gullies B and C. In this figure, the gullies have been restored 475 m to their late Pleistocene position upstream from the fan. The same gullies are indicated by letters B and C in Figure 1b. For reference, dotted line represents location of modern channel of Wallace Creek. Isopach map is based on trench exposures (thick, open bars) and geometry of contours. Insert in upper right illustrates use of topographic contours in constructing isopach map. Lower edge of stippled region is topographic contour. Upper edge is contour prior to deposition of fan. Southwestward bulging of contours indicates presence and thickness of alluvial fan.

flank of the main fan complex had to be southeast of channel C. The offset thus is no less than 472 m. At the same time, the crests of the two distinct lobes of the fan shown in Figure 9 should have had their apexes at the mouths of two of the middle gullies. Only gullies B and C are spaced appropriately to meet this constraint. The mouth of gully B cannot be offset more than 478 m, if B is the source of the northwestern lobe of the fan. It is of interest that the younger fan deposits are offset from gullies A, B, C, and D, only slightly less so than the oldest, beheaded channel of Wallace Creek itself (marked with a white arrow at the left margin of Fig. 1). The creation of gullies A, B, C, and D must, therefore, be nearly contemporaneous with the first entrenchment of Wallace Creek.

These considerations constrain the offset of the younger fan deposits to 475 ± 3 m. In that the younger fan formed 13,250 ± 1650 yr B.P., the average slip rate must be 35.8 + 5.4/−4.1 mm/yr. Within the level of resolution, this cannot be distinguished from the average late Holocene rate of 33.9 ± 2.9 mm/yr.

RECURRENCE INTERVALS BETWEEN PAST LARGE EARTHQUAKES AT WALLACE CREEK

The average Holocene and late Holocene rates of slip at Wallace Creek are important new measurements of strain across the San Andreas

TABLE 2 SMALLEST STREAM OFFSETS NEAR WALLACE CREEK AND PROPOSED INTERVALS BETWEEN GREAT EARTHQUAKES

(1) Stream offsets (m)	(2) Remarks	(3) Produced by	(4) Slip associated with earthquake (m)	(5) Proposed interval between events (yr)
9.5 ± 0.5(± 1σ)	Average of 5 measurements	1857 event	9.5 ± 0.5(± 1σ)	
				240 to 320§
21.8 ± 1.1	Average of 4 measurements**	1857 plus last prehistoric event	12.3 ± 1.2*	
				300 to 440§
32.8 or 33.5 ± 1.9	Average of 3 measurements**	1857 plus latest 2 prehistoric events	11.0 or 11.7 ± 2.2†	240 to 450§

*21.8 − 9.5 ± $(0.5^2 + 1.1^2)^{1/2}$
†32.8 − 21.8 ± $(1.1^2 + 1.9^2)^{1/2}$ or 33.5 − 21.8 ± $(1.1^2 + 1.9^2)^{1/2}$
§Slip during following earthquake in column 4 divided by average late Holocene slip rate (33.9 ± 2.9 mm/yr)
**Offset gullies are all between Wallace Creek and Gully D in Figure 1

TABLE 3 SMALLEST STREAM OFFSETS NEAR WALLACE CREEK AND PROPOSED DATES AND CORRELATION OF LATEST FOUR GREAT EARTHQUAKES

(1) Stream offsets (m)	(2) Time required to accumulate offset as elastic strain using average late Holocene slip rate (years)	(3) Proposed dates for latest earthquakes (A.D.)	(4) Possible correlations with events recognized at Pallett Creek	(5) Possible correlations with events recognized at Mill Potrero by Davis (1983)
		1857	Z(1857)	Z(1857)
9.5 ± 0.5 (± 1σ)	240 to 320			
		1540 to 1630*	V(1550 ± 70)	V(1584 ± 70)
21.8 ± 1.1	560 to 740			
		1120 to 1300†	R(1080 ± 65)	
32.8 or 33.5 ± 1.9	840 to 1140			
		720 to 1020§	F(845 ± 75)	

*1857 − (240 to 320 yr)
†1857 − (560 to 740 yr)
§1857 − (840 to 1140 yr)

fault in central California, because they are the first to span more than a fraction of a great earthquake cycle of strain accumulation and relief. These millennial averages can be used in conjunction with other data to infer earthquake recurrence intervals.

For example, the length of the cycle of strain accumulation that preceded and led to the great 1857 earthquake can be calculated. In 1857, the San Andreas fault sustained 9.5 m of right-lateral slip at Wallace Creek. This is indicated by five small offset gullies nearby (A, B, C, D, and E in Fig. 1; Table 2), as well as by small offset gullies at distances of as much as several kilometres to the northwest and southeast. These gullies were incised across the fault prior to the 1857 event, but after the previous large event (see Sieh, 1978c, for a more detailed discussion). If one assumes that the 9.5 m of fault slip associated with the 1857 earthquake relieved elastic strains that had accumulated in the adjacent crustal blocks at an average rate of 34 mm/yr, one calculates that the 1857 earthquake was preceded by a 280-yr period of strain accumulation. This calculation does not assume that annual strain accumulation was uniform during the 280-yr period, but only that the *average* annual rate was equal to the millennial average of 34 mm/yr. Periods of faster or slower accumulation thus could be accommodated within the over-all loading cycle. Table 2 (top of col. 5) displays the actual range of values for the period of strain accumulation if the uncertainties in the 1857 offset value and average slip rate are taken into account. In lieu of a direct dating of the large event that preceded the 1857 event at Wallace Creek, this range (240–320 yr) is probably the best estimate that can be made for the recurrence interval between the 1857 earthquake and its predecessor.

Estimates of the duration of two earlier periods of strain accumulation can also be made, using the average late Holocene slip rate and the amount of fault slip associated with each of the last two prehistoric earthquakes. Table 2 lists the data that suggest these 2 events were associated with ~12.3 and 11.5 m of fault slip at Wallace Creek. At 34 mm/yr, these values would have accumulated in 360 and 340 yr, respectively. The actual range in value for both of these recurrence intervals, calculated using the ranges in value for the slip rate and the offsets, is displayed in column 5 of Table 2. From the table, one can see that the latest 3 recurrence intervals are estimated to be within the range of 240 to 450 yr.

Of course, it is possible that the 4,000-yr and 13,000-yr average slip rates do not represent the average rate of strain accumulation during the periods of fault dormancy prior to 1857 and the 2 previous great earthquakes. For example, the rate of accumulation actually could have been much higher during the past millennium and much slower during the previous 4,000-yr interval. If so, the recurrence intervals between the latest few earthquakes would be much shorter than those calculated above. Perhaps a future study of a currently undiscovered 1,000-yr-old feature near Wallace Creek will resolve this issue by providing a 1,000-yr average rate. Alternatively, the past several earthquakes may be dated directly, as has been done at Pallett Creek (Sieh, 1978b, in press). In the meantime, the validity of using the 3,700-yr average slip rate in calculating recurrence intervals of recent and future great earthquakes must be assessed in other ways.

First, the slip rate averaged over the past 3,700 yr (33.9 ± 2.9 mm/yr) does not differ appreciably from the 13,000-yr average (35.8 + 5.4/−4.1 mm/yr), although the 13,000-yr average conceivably could be as much as 10 mm/yr (~30%) faster than the late Holocene average, given the imprecision of the 2 determinations.

Second, geodetic data on modern rates of strain accumulation across the fault are available from the "Carrizo" net, which spans the fault and 80 km of adjacent territory at the latitude of Wallace Creek (Savage, 1983, and 1982, written commun.). These data are available, however, only for the period 1977.6 to 1981.5. The deformation observed during this period averages 0.29 ± 0.06 μstrain/yr (extension) N89° ± 4°W and −0.09 ± 0.06 μstrain/yr (contraction) north-south. Numerous models of lithospheric deformation can produce this observed surficial deformation. One class of model involves the assumption that the observed deformations are the result of aseismic right-lateral slip on the San Andreas fault beneath its locked, brittle upper 10 or 20 km. In this case, the observed deformations of the Carrizo net are resolved as right-lateral shear strains parallel to the San Andreas fault. The average shear strain over the entire 80-km-wide network is 0.38 ± 0.04 μrad/yr. This translates into a deep slip rate on the fault of 30.4 ± 3.2 mm/yr, if one assumes that the network spans the entire zone of deformation due to slip on the fault. If it does not span the entire zone, the rate of deep slip on the fault must be higher. Like the 13,000-yr average rate, the geodetically determined modern rate does not differ significantly from the 3,700-yr average.

The similarity of the 13,000-yr, 3,700-yr, and 4-yr averages suggests that strain accumulation across the fault may be fairly uniform. Of course, numerous histories could be invented that include these three data points and yet involve large fluctuations in the strain accumulation rate between earthquake cycles or recurrence intervals. To date, however, no known data support large fluctuations. A reasonable assumption, thus, is that the late Holocene average slip rate represents the average rate of strain accumulation between large earthquakes. The recurrence intervals displayed in Table 2 may, therefore, be realistic estimates of the dormant intervals that preceded the past three great earthquakes.

In the next section, we attempt to assess when the current earthquake cycle will end at Wallace Creek; that is, when the next great earthquake, accompanied by rupture at Wallace Creek, will occur. We also attempt to use the 3,700-yr average slip rate to assess the likelihood of large earthquakes elsewhere along the San Andreas fault.

FORECASTS OF THE BEHAVIOR OF THE SAN ANDREAS FAULT

Along the South-Central (1857) Segment

If the crust adjacent to the San Andreas fault has been accumulating strain at 34 mm/yr since 1857, as much as 4.3 m of potential slip has now been stored and conceivably could be released along all or part of the 1857 rupture. Geomorphologic data, however, suggest that this is likely only along two portions of the 1857 rupture. Wallace Creek is not within either of these portions.

Figure 10 displays offsets measured along the south-central segment of the San Andreas fault. The 1857 segment is divisible into at least three parts, based on slippage during the 1857 earthquake and one to four previous large earthquakes. The southeastern part is ~90 km long and seems to have been characterized by 3- to 4.5-m slip events. The central 160 km, including Wallace Creek, has experienced 7 to 12.3 m of slip during the most recent 3 great earthquakes. The lower values along this central portion occur along the reach between km 90 and km 200, where several other active faults to the north and northeast exist, and so the lower values may reflect distributed deformation, away from the San Andreas fault. A 30-km segment northwest of Wallace Creek experienced 3 to 4 m of slip in 1857 and probably 1 or 2 during previous large earthquakes, as well.

These data suggest that each part of the fault has experienced a characteristic amount of slippage during the past three to four large earthquakes. Although, of course, so few data do not provide a statistically sound basis for predicting all previous and future events, we are confident that this pattern offers some insight into the long-term behavior of the fault.

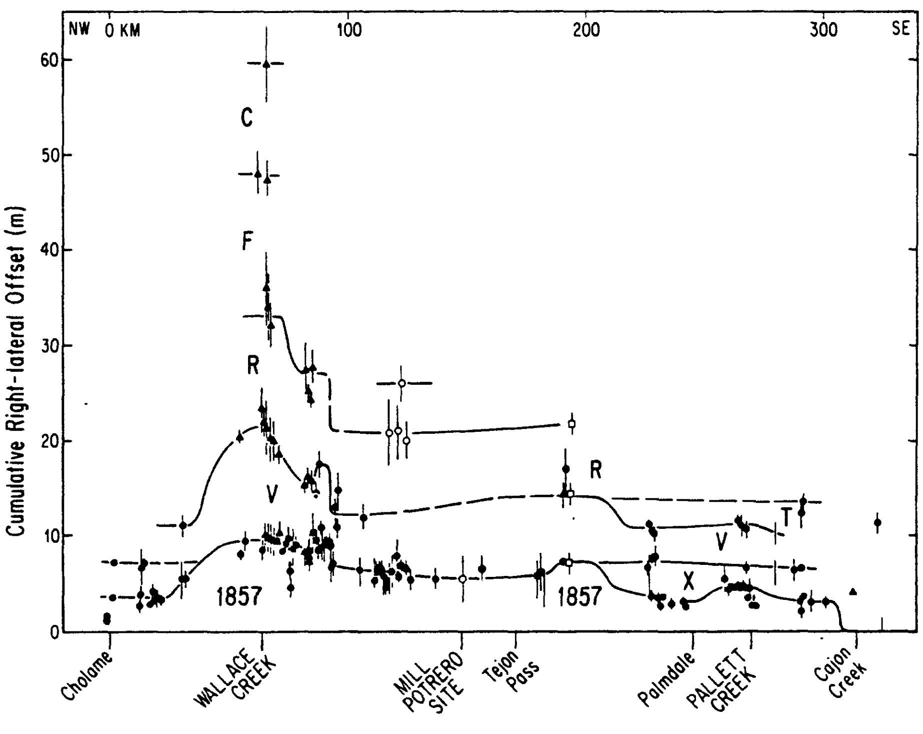


Figure 10. Right-lateral offsets measured along the south-central (1857) segment of the San Andreas fault suggest that slip at each locality is characterized by a particular value. Solid circles are data from Sieh (1978c), with poor-quality data deleted. Open circles are data from Davis (1983). Triangles are new data and remeasurements at sites reported by Sieh (1978c). Open squares are new data. Vertical bars indicate magnitude of imprecision in measurement.

At least two explanations are worth considering. First, we consider the possibility that the northwestern 40 km and southeastern 90 km are loaded more slowly, and, therefore, when the earthquake occurs, they experience lesser amounts of slip than does the central 160-km-long part. This is unlikely, because the average Holocene slip rate along these two parts must be nearly equal to the rate determined at Wallace Creek. Just beyond the south-central segment, at Cajon Creek (Fig. 10), the San Andreas has average Holocene and late Holocene slip rates of 25 ± 3 mm/yr (Weldon and Sieh, 1981). The nearby San Jacinto and related subparallel faults probably carry ~10 mm/yr at this latitude (based on data of Sharp, 1981, and Metzger, 1982). These fault systems end and nearly merge with the San Andreas fault just northwest of Cajon Creek. Farther northwest, the San Andreas fault is the only major active structure, and so northwest of Cajon Creek, it must have a slip rate of ~35 mm/yr. In addition, the average recurrence interval for large earthquakes at Pallett Creek (location in Fig. 10) is in the range of 145 to 200 yr, which is appreciably shorter than the 240- to 450-yr range at Wallace Creek. For this reason, some of the slip events shown in Figure 10 in the Palmdale–Pallett Creek region must have their northwestern rupture tip southeast of Wallace Creek, and 1857-like events cannot be the only type of slip event along this part of the south-central segment.

The northwestern 30 km of the south-central segment (Fig. 10) must also share the long-term average slip rate of Wallace Creek. No diversion of a large fraction of the Wallace Creek rate along other structures is plausible. The only known major active(?) fault nearby is the San Juan Hill fault, which runs 3 to 14 km west of and subparallel to the San Andreas from about Cholame to Wallace Creek (Jennings and others, 1975). Its rate of slip is probably no more than a few millimetres per year.

A second explanation for the different behavior of the three parts of the south-central segment is based on the hypothesis that each part is imbued with a different strength. If, for reasons of geometry or rock properties, the central 160 km of the segment were 2 or 3 times stronger than the 2 other parts, 2 or 3 times as much elastic loading of the adjacent crustal blocks would be necessary before failure occurred.

Each failure thus would result in two to three times as much slippage as on the two adjacent parts. Such an explanation is compatible with our judgments that (1) slip rate does not vary greatly along the south-central segment, and (2) large earthquakes are more frequent at Pallett Creek than at Wallace Creek.

Table 3 lists our best estimates of the dates of large earthquakes at Wallace Creek and proposed correlations with large earthquakes that have been directly dated at Pallett Creek (Sieh, in press) and at Mill Potrero (Davis, 1983). The capital letters in Figure 10 reflect our best judgment regarding correlation of the latest events at Wallace Creek, Pallett Creek, and Mill Potrero. Event X at Pallett Creek (A.D. 1720 ± 50) has no correlative at Wallace Creek, although Davis (1983) discovered evidence for and dated a relatively small slip event at Mill Potrero that may well be event X. Event V at Pallett Creek occurred about A.D. 1550, which is about the time we estimate that the last prehistoric event at Wallace Creek occurred, and also about the time of a large slip event that Davis (1983) discovered at Mill Potrero. Similarly, events R and F at Pallett Creek occurred at about the time we estimate that the third and fourth events occurred at Wallace Creek.

On the basis of the foregoing discussion, we judge that the central 160 km of the south-central segment of the San Andreas fault is unlikely to generate a great earthquake for at least another 100 yr. Recurrence intervals appear to be in the range of 250 to 450 yr, and yet the time elapsed since the great earthquake of 1857 is only 127 yr. Slip during the latest 3 great earthquakes has been 7 to 12.3 m, and yet we suspect that only a little more than 4 m of potential slip has been stored in the past 127 yr.

The southeastern 90 km and the northwestern 30 km of the south-central segment are good candidates for producing a large earthquake within the next several decades. Geomorphologic measurements seem to indicate that 3 to 4.5 m of slip is characteristic during large events, and >4 m of potential slip may well have been stored in the adjacent crustal blocks since 1857. Based on studies at Pallett Creek, the probability of a great event along the southeastern 90 km of the south-central segment within the next 50 yr is between 26% and 98% (Sieh, in press).

Along the Creeping Segment

The long-term average slip rates determined at Wallace Creek are indistinguishable from the geodetically determined rates of slip at deep levels along the fault from Wallace Creek to Monterey Bay (Savage, 1983; Lisowski and Prescott, 1981). The long-term rates at Wallace Creek are also identical to the historical rate of slip at shallow levels along the central 50 km of the creeping segment (see data compiled by Lisowski and Prescott, 1981, Fig. 6). These similarities could be coincidental, but they suggest that the central 50 km of the creeping segment is creeping annually at its millennial-average rate of slip. If this were true, it would mean that large elastic strains are not accumulating across the central 50 km of the creeping segment, and that this segment will not participate in the generation of the next large earthquakes along the San Andreas fault.

From a geological point of view, it is reasonable to suspect that the long-term slip rate along the San Andreas fault at Wallace Creek should not be different from its long-term rate along the creeping segment, except along its northernmost 50 km, adjacent to which runs the actively creeping Paicines fault (Harsh and Pavoni, 1978). No other large, active structures in the latitudes of the creeping segment can be called upon to absorb a large portion of the slip rate observed farther south at Wallace Creek. Likewise, there are no obvious geological structures near the San Andreas that would lead one to suspect that the long-term slip rate along the creeping segment is appreciably higher than the long-term rate farther south.

Along the 90-km Segment Centered on Cholame

Between the central 50 km of the creeping zone and Wallace Creek, there is a stretch of the San Andreas fault that historically has been a zone of transition between the fully creeping and fully locked portions of the fault. On the basis of available data, this segment is a prime candidate for generating a large earthquake in the near future. In the period of historical record, it has not experienced as much slip as have segments to the northwest or southeast, and it is therefore a "slip gap."

One interpretation of the historical data is illustrated in Figure 11, in which cumulative right-lateral slip for the past two centuries is

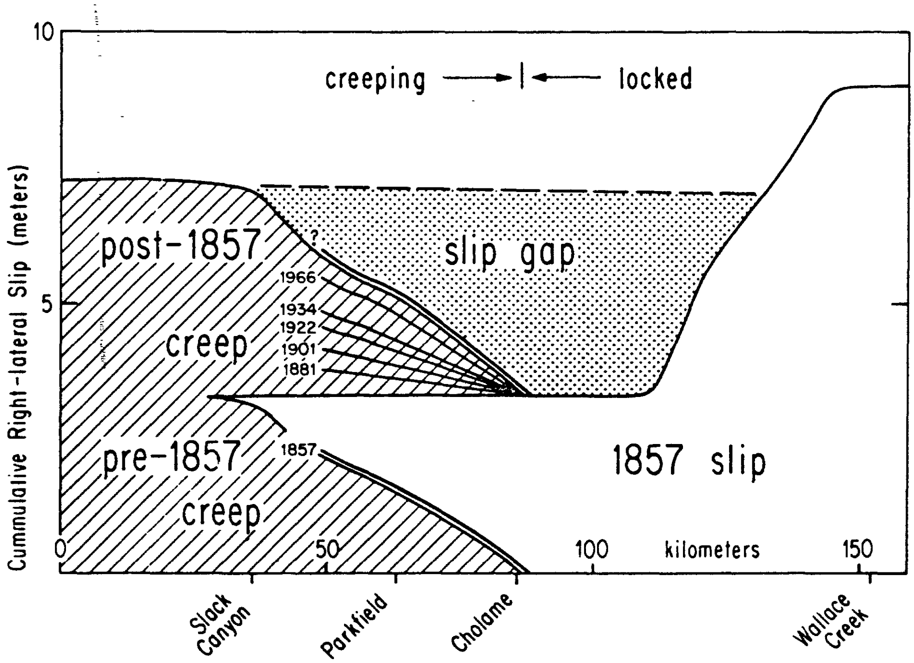


Figure 11. Hypothetical source of future major earthquake along the San Andreas fault includes ~60 km of the currently creeping segment and 30 km of the locked segment. Cumulative right-lateral slip plotted against distance along the fault indicates that this 90-km segment is slip-deficient relative to adjacent stretches of the fault. Slip in 1857 is from Sieh (1978c). Cumulative slip along the creeping segment is extrapolated from alignment array slip rates for period 1968–1979 (Lisowski and Prescott, 1981, Fig. 6). Dates of moderate earthquakes generated by slip along the fault in the Parkfield-Cholame region are shown, because such an event probably triggered the great 1857 rupture and conceivably could trigger the rupture of the slip gap.

plotted as a function of location along the fault. We assume that creep rates northwest of Cholame have been constant for the past few hundred years, so that the alignment array data for the period 1968–1979 are representative of the pre- and post-1857 creep rates. We also assume that Cholame has been the edge of the creep zone throughout this period. In the century preceding 1857, 3 to 3.5 m of slip would have accumulated by creep northwest of Slack Canyon. Less slip would have accumulated by creep, and perhaps during occasional moderate earthquakes, between Slack Canyon and Cholame.

In 1857, ~3.5 m of slip occurred along the 30-km stretch of the fault southeast of Cholame, and 9.5 m of slip occurred in the vicinity of Wallace Creek. The sparse historical accounts are compatible with our inference in Figure 11 that slippage during the earthquake decreased northwestward from Cholame and died out near Slack Canyon (Sieh, 1978c, p. 1423–1424).

Following 1857, creep resumed northwest of Cholame. Northwest of Slack Canyon, ~4.5 m of slip now has accumulated at the full, long-term rate of loading of the fault (that is, 34 mm/yr). The 60-km-long section between Slack Canyon and Cholame, however, has crept at rates that are significantly lower than the loading rate, and strain is being stored in the rocks adjacent to the fault there. Similarly, elastic strains are accumulating in the rocks adjacent to the locked portion of the fault, and the northernmost 30 km of this portion, which seems to fail in 3- to 4-m slip events, may well be loaded nearly to the point of failure.

We suggest that this northernmost part of the locked segment and the southernmost part of the creeping segment might fail in unison and produce a major earthquake. This hypothetical event would be associated with ~90 km of surface rupture and a maximum of ~4.3 m of right-lateral slip.

In discussing this hypothetical event, it is important to note that the great 1857 earthquake seems to have originated in this region. Sieh (1978a) documented that at least 2 moderate foreshocks occurred in this vicinity about 1.5 and 2.5 hr prior to the main shock. Within the past century, 5 moderate (M5.5 to 6) earthquakes have been produced by slippage along the San Andreas fault northwest of Cholame. Sieh (1978a) inferred that the 1857 foreshocks emanated from a source similar to that which produced these historical shocks. If this is true, then the next moderate "Parkfield-Cholame" earthquake might well be a foreshock of the hypothetical major event described above.

ROLE OF THE SAN ANDREAS FAULT IN THE RELATIVE MOTION OF THE NORTH AMERICAN AND PACIFIC PLATES

Minster and Jordan (1978) determined from a circumglobal data set that the relative motion of the Pacific and North American plates has averaged ~56 mm/yr during the past 3 m.y. The geological record at Wallace Creek shows that, at least during the past 13,000 yr, only ~34 mm/yr of this has been accommodated by slip along the San Andreas fault. If one assumes that the 3-m.y. average represents the Holocene average rate across the plate boundary as well, then clearly the San Andreas fault is accommodating only ~60% of the relative plate motion. The remainder of the deformation must be accomplished elsewhere within a broader plate boundary. The San Gregorio–Hosgri fault system, which traverses the coast of central California, may have a late Pleistocene–Holocene slip rate of 6 to 13 mm/yr (Weber and Lajoie, 1977), and the Basin Ranges, to the east of the San Andreas fault, may be opening N35°W on oblique normal faults at a late Pleistocene–Holocene rate of ~7 mm/yr (Thompson and Burke, 1973). Most of the 56 mm/yr plate rate thus may be attributed to the San Andreas, San Gregorio–Hosgri, and Basin Range faults. Long-term slip rates on these three major fault systems are not known precisely enough to preclude or confirm the possibility that the rate of relative plate motion during the Holocene is equal to the 3-m.y. average. No clear basis exists, however, for suggesting that the Holocene rate is less than or more than the longer-term rate.

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Wallace Creek is named after Robert Wallace, who elucidated the basic history of the channel more than 15 years ago and provided us with a special topographic base map. N. Timothy Hall drew our attention to the study site. He and Laurie Sieh participated in initial studies. Art Fairfall and John Erickson at the University of Washington provided all of the radiocarbon analyses. Robert Wallace, David Schwartz, David Pollard, Christopher Sanders, and Ray Weldon provided helpful criticisms of earlier manuscripts. This work was supported by the National Earthquake Hazards Reduction Program, U.S. Geological Survey Contract nos. 14-08-0001-15225, 16774, 18385, and 19756.

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APPENDIX C

Terms for Expressing Earthquake Potential, Prediction, and Probability

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TERMS FOR EXPRESSING EARTHQUAKE POTENTIAL, PREDICTION, AND PROBABILITY

BY ROBERT E. WALLACE, JAMES F. DAVIS, AND KAREN C. MCNALLY

ABSTRACT

Terms for expressing earthquake potential and prediction include two main categories, "long-term earthquake potential" and "earthquake prediction." Earthquake prediction is subdivided into three categories "long-term prediction," "intermediate-term prediction," and "short-term prediction." Long-term prediction is not subdivided, but two terms, "watch" and "forecast," are recognized as having similar meanings. "Short-term prediction" is subdivided into "alert" and "imminent alert." The subdivisions of earthquake prediction are based on different time frames.

Earthquake potential or probability can be expressed either numerically or verbally according to a variety of schemes.

INTRODUCTION AND HISTORY

In response to the Earthquake Hazards Reduction Act of 1977, a report, published in 1978 under the auspices of the Office of Science and Technology Policy (Working Group on Earthquake Hazard Reduction, 1978), was concerned with "issues for an implementation plan." One of the issues cited was the need for standardization of terms such as "prediction," "alert," and "warning." In 1980 the Southern California Earthquake Preparedness Project (SCEPP) was begun under the auspices of the California Seismic Safety Commission and the Federal Emergency Management Agency, and a similar need for standardized terms for emergency service and public response planning was recognized. The present authors were designated as a committee of the Policy Advisory Board of SCEPP to consider predictive terms and their application.

An early version of the terminology, which included a probability element as part of the definitions, was tentatively adopted by SCEPP in December 1981 and by the California Earthquake Prediction Evaluation Council in April 1982. The version described in this report, which excludes probability from the definitions, has been incorporated into some SCEPP planning documents of 1983 and was formally approved by the Policy Advisory Board of SCEPP on 28 September 1983 and by the California Seismic Safety Commission on 13 October 1983. The earlier version of proposed terminology was reviewed by the National Earthquake Prediction Evaluation Council in June 1982, but action was postponed pending further study and possible revisions. The present version reflects some concerns and suggestions of that panel.

In a report by the National Academy of Science–National Research Council (U.S. National Research Council, Panel on Earthquake Prediction of the Committee on Seismology, 1976), earthquake prediction was defined as follows: "An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Moreover, scientists should also assign a confidence level to each prediction." In other documents, a distinction between "prediction" and "warning" is recommended (Panel on Public Policy Implications of Earthquake Prediction, U.S. National Research Council, 1975; McKelvey, 1975). Both define "prediction" much as does the National Research Council, but, according to McKelvey, "warning is a recommendation or an order to take some defensive action," and, according to The Panel on Public Policy Implications of Earthquake Prediction "warning is a declaration that normal life routines should be revised for a time." Interpretation of the meaning of the term "warning" has not remained constant; e.g., in the following paragraph, the term "warning" has been defined as similar to "prediction" above.

Under the Disaster Relief Act of 1974, the Director, U.S. Geological Survey (USGS) was given, by redelegation, the responsibility for issuing information about geologic hazards. After that time, terms for use in issuing warnings were published in the Federal Register (1977), and the following three terms were used by the USGS until October 1983 for official releases for all geologic hazards including earthquakes, volcanic eruptions, and landslides.

Notice of potential hazard—The transmission to Federal, State, and local officials of information about the location and nature of potentially hazardous geologic conditions. Evidence is insufficient to suggest that a hazardous event is imminent or to determine the time of occurrence.

Hazard watch—The transmission of information that a change is taking place in a geologically hazardous situation that may be interpreted as precursor to a potentially hazardous event within an unspecified period of time.

Hazard warning—The transmission of information about precursory phenomena that appear to signal a potentially hazardous event within a specific period of time (possibly days or hours).

Official "earthquake watches" were issued by the Director, USGS for the southern part of the San Andreas fault in California in 1976 and for the Mammoth Lakes area of eastern California in 1980.

The three-level classification, "notice," "watch," and "warning," although useful, seemed to confuse some public officials as well as the media and general public. A notice published in the Federal Register on 11 October 1983 (Devine, 1983) proposed that the USGS should henceforth use the term "Geologic Hazard Warning." The type of geologic hazard and its characteristics, such as area affected and imminence, are dealt with in a supplementary text.

Terminology needs appear to be somewhat different for different geologic hazards. Long-term predictions of volcanic eruptions, e.g., are viewed in a time frame of weeks (Swanson *et al.*, 1983), whereas long-term predictions of earthquakes are viewed in the time frame of decades.

The National Weather Service (NWS) has developed a comprehensive set of weather-related terms, and although some of the principles used in that terminology can be transferred to earthquakes, specific terms cannot. The use of adjective modifiers as employed by NWS, such as in "traveler's advisory" or "stockman's advisory," is a self-explanatory way of creating terms more specific than implied by the base term and is highly recommended.

Despite formalization of terms to be used for any discipline or problem, the news media seldom abide by the technical definitions of terms. For example, the terms "notice," "watch," and "warning" were reported in newspapers as meaning "alert stage one, two, and three." Air pollution also is reported commonly in southern California as "alert stages one, two, or three" even though the term "air pollution episodes" is used officially (South Coast Air Quality Management District, 1981).
Management District, 1981).

Standardization of terminology is necessary for accurate and simple communication. But three principal audiences for earthquake-prediction terminology have rather diverse needs and different capabilities of understanding terms. The scientist must communicate with other scientists, the scientific community must communicate with the disaster-response administrative community, and these two communities must communicate with the public. The terms suggested in this paper are aimed primarily toward the chain of communication, scientist to administrator to the public, but we have also considered what the scientist-to-scientist link may need (e.g., Aki, 1980).

Usage will ultimately determine the success of any term, and so it will be with the terms suggested here.

Terms Suggested

We adopt and recommend use of the basic definition of earthquake prediction as presented by the U.S. National Research Council, Panel on Earthquake Prediction of the Committee on Seismology (1976), and here focus on the time element of a prediction as a needed refinement of the basic definition. Other elements of a prediction, i.e., place, size of earthquake, and likelihood of an event occurring as predicted are not a part of the defined terms except for the interdependence, to some extent, of statements of time and magnitude, a relation discussed later. The place or area in which an earthquake may occur are handled in a descriptive way and, for one example, are represented by maps of active faults. The size of the predicted earthquake can be expressed as Richter magnitude, seismic moment, or moment magnitude, or other commonly used expressions of earthquake size. The likelihood of an earthquake occurring as predicted can be stated in mathematical probability terms or by percentage chances per unit of time or in verbal form.

The terminology framework suggested includes a ranking system similar to the family-genus-species ranking of biologic taxonomy. Thus, the terms "prediction" and "long-term earrthquake potential" are the highest of three ranks. The terms "short-, intermediate-, and long-term predictions" are second highest rank. Earthquake "alert" is of the lowest rank. As earthquake-prediction science improves, new subdivisions of each may be warranted and can be accommodated, we hope, without restructuring the overall framework.

Use of the term "time window" (see below) may carry two connotations: (1) that the earthquake can occur at any time from the present through the period of the time window, or (2) that the period of the time window will pass before the earthquake is likely to occur. We suggest that for the present state of earthquake-prediction science connotation (1) will be the most useful, and should constitute the meaning unless otherwise indicated, but as the state of prediction science advances, connotation (2) may become needed. At such a time, subdivisions of long-, intermediate-, and short-term prediction can be created and used to distinguish the two meanings, or the specific meaning can be described.

SUGGESTED TERMS

	Time Window
Long-Term Earthquake Potential	No specific time window. Can refer to decades, centuries, or millennia.
Earthquake Prediction	Any specific time window shorter than a few decades.
Long-term prediction	Few years to a few decades.
Intermediate-term prediction	Few weeks to few years.
Short-term prediction	Up to a few weeks.

DEFINITIONS AND DISCUSSION

Long-term earthquake potential. The potential or probability of an earthquake occurring in a given area or region, or on a given fault, can be expressed, e.g., in percentage chance per year or average recurrence interval for earthquakes of designated magnitude levels. No *specific* period of time of occurrence and no *specific* future earthquake is designated. The potential may remain the same for long periods of time, even hundreds of years.

Discussion. Statements of "long-term potential" relate to probability based either on the historical or geologic record, or both. The long-term potential can be stated as average recurrence interval or percentage chance per year at designated magnitude levels. For very active faults, such as major elements of the San Andreas fault system, the values may fall in the range of 0.2 to 2 per cent per year for M 7 or greater earthquakes. For most other faults in the Western United States, the value is less than 0.2 per cent per year for major earthquakes. For example, earthquakes of M 7.5 to 8 on the northern San Andreas and Hayward faults are assigned a probability of 1 per cent chance per year, and an earthquake of M 7.5 on the Newport-Inglewood fault system is assigned a probability of less than 0.1 per cent chance per year (Federal Emergency Management Agency, 1981; Lindh, 1983). Most of the faults in the Basin and Range province are assigned a probability of less than 0.1 per cent chance per year for generating earthquakes greater than M 7 (Wallace, 1981).

Earthquake prediction. An earthquake prediction specifies the expected magnitude range, the geographical area within which a *specific future earthquake* will occur, and the time interval within which it will happen. A confidence level is included in each prediction. Note that this definition is the same as that suggested by the U.S. National Research Council, Panel on Earthquake Prediction of the Committee on Seismology (1976), but emphasizing a "specific future earthquake" helps to distinguish a prediction from a statement of long-term potential.

Discussion. A prediction designates a *specific period of time* for the occurrence of a *specific future earthquake* of a given magnitude range; in contrast, statements of earthquake potentials apply for indefinite periods of time. The distinction between potential and prediction may not always be clear, and to some extent the designation is optional with the predictor. For example, if a statement were made that a 0.1 per cent probability per year exists, few would interpret such a statement to mean that an earthquake is predicted to occur within 1 yr. If, on the other hand, the probability was 50 per cent or greater per year, the statement would be interpreted by most as a "prediction" of an earthquake occurring in 1 yr. In general, we believe that if a probability greater than 50 per cent is expressed for any specific period of time, the public will consider the statement to be a prediction for that period.

Probability values increase as the length of the time window increases, or the stated magnitude decreases, thus large probabilities can be stated if the time window is made long enough or the magnitude of the expected earthquake is made small enough. Conceivably, however, premonitory evidence may suggest a very specific time in the future for an event of a given size. Furthermore, a situation can be imagined in which data would indicate a specific time and magnitude, but the confidence level would be very low. In such cases, an interchange between probability, magnitude, and length of time window would not be possible.

The subcategories of "prediction," i.e., "long-term prediction," "intermediate-term prediction," and "short-term prediction," are based only on length of time windows, even though, as stated above, an interdependence of time frame, magnitude, and probability exists. Two possible meanings of "time window" are discussed above, but we suggest that the science should be permitted to evolve further before specific terms are adopted to include these differences in a formal taxonomy.

Long-term prediction. A prediction of an earthquake that is expected to occur within a few years up to a few decades.

Discussion. The terms "forecast" and "watch" have been used previously and carry connotations similar to long-term prediction. The term "forecast" is a statement of future expectation and, for the present, may be used synonymously with long-term prediction. To some, the term "forecast" connotes less specificity than prediction, but the distinction is moot. The term "watch" carries the connotation of continuous attention to the situation, possibly including increased monitoring of an area.

Intermediate-term prediction. A prediction of an earthquake that is expected to occur within a period of a few weeks to a few years. No subdivisions are suggested now.

Short-term prediction. A prediction of an earthquake that is expected to occur within a few hours to a few weeks.

Discussion. The terms "alert" and "imminent alert" may be used as subdivisions of short-term predictions. The term "alert" carries a sense of urgency, e.g., Webster defines "alert" as "an alarm or other signal to warn of danger." The news media commonly have used the term "alert" regardless of what terms are used by public officials or scientists in formal notices or advisories. The term "alert" is applied to the period of 3 days to a few weeks. The term "imminent alert" is applied to a period up to 3 days. Advice from disaster-response administrators suggests that maintenance of the highest level of readiness beyond 3 days would be difficult. Because the terms "alert" and "imminent alert" convey a sense of urgency, we suggest that these subdivisions or "species" of short-term prediction be used only when the probability level is high. If the probability level is low or moderate, use of only the generic form "short-term prediction" is recommended.

OTHER TERMS

Numerous other terms are useful and, to the extent that they convey general meaning, may be employed. We caution against restricting the definitions of any word or term in such a way that the restricted definition carries the meaning outside the bounds of the generally understood dictionary meaning or excludes elements of the generally understood dictionary meaning. Misinterpretations are too easily drawn.

Advisory—A formal message giving earthquake information or advise to take action.

Area of intensified study—Either a formal or informal recognition of special interest, study, or monitoring in an area, because of an increase in the perceived likelihood of an impending earthquake (see Japanese National Land Policy Series, Law No. 73). Intensified study of an area may be initiated for scientific purposes, such as to conduct a prediction experiment, or because the area is densely populated and the hazard potential is high.

Notice—The formal communication of earthquake information, especially earthquake-potential information.

Tendency—A term implying a dynamic, changing situation as contrasted to the static long-term potential. It relates to prediction and is used by the Chinese, who hold National Earthquake Tendency Conferences. The term indicates that a physical process is under way that may lead toward an eventual earthquake. The "tendency" can be "weak," "moderate," or "strong" and can "increase" or "decrease."

Warning—The generally understood meaning of "warning," as defined by Webster's dictionary, is "the action or fact of putting one on his guard by intimating danger." Various restricted definitions of the term "warning" have been proposed and used in connection with earthquakes as well as other natural hazards such as severe weather. The USGS defines "'geologic hazard warning' as a formal statement by the Director of the U.S. Geological Survey that discusses a specific geologic condition, process or potential event that poses a significant threat to the public, and for which some timely response would be expected" (Devine, 1983).

Potential and Probability

Potential and probability can be expressed in various ways, and the form will depend to a large extent upon the audience. The scientific community may have a different perception of the significance of hazard probability than the public. For example, a probability gain from 0.009 to 0.09 means an order of magnitude increase to the scientist and yet the 0.09 translated into 9 per cent chance could be considered a low probability by the public. Furthermore, the probability of a geological event (hazard) occurring compared to the probability of a risk (lives or dollar value) are different aspects. Further study of these problems is needed.

Long-term potentials have been expressed as percentage chance per year for earthquakes of a given magnitude, as average recurrence intervals on individual faults, as recurrence intervals normalized for areas, in map form showing expected accelerations and velocities of ground motion region by region, as well as other ways.

For long-term predictions, probabilities have been expressed for a specific future event as probability (in a mathematical notation of 1 equal to 100 per cent chance) per day (Aki, 1981), percentage chance per year, and percentage chance per 30 yr (Lindh, 1983). As an example, Lindh estimates that the Parkfield segment of the central San Andreas fault has a 99 per cent chance of generating an M 6 earthquake in the next 30 yr. According to the suggested terminology, such a statement is a "long-term prediction."

We have been convinced by discussion with members of the news media that, in general, expressions of percentage are not well understood by all members of the lay audience. We suggest, therefore, that the following words be used as equivalent to a three-fold division of percentage values regardless of time period

0–10 per cent—Slight, as "slight chance of an earthquake"

11–49 per cent—Moderate

50–100 per cent—High

Some members of the lay public appear to understand percentage better if stated as "one chance in ten" or "seven chances in ten," as chances of rain commonly are stated.

Termination or Reduction of Any Level

Any of the levels of prediction can be terminated, reduced, or modified at any time as the geophysical or other anomalies or interpretation of anomalies change.

RESPONSIBILITY OF PREDICTORS

At the meeting of the Board of Directors of the Seismological Society of America in April 1983, a set of "Guidelines for Earthquake Predictors" was approved by the Board and these guidelines are published in the Bulletin of the Seismological Society of America (1983). We urge all scientists engaged in formulating or issuing earthquake predictions to familiarize themselves with the problems considered in those guidelines.

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APPENDIX D

USGS, Terminology for Geologic Hazards Warnings

Geological Survey

Terminology for Geologic Hazard Warnings

SUMMARY: This notice describes changes in the terms and criteria used by the U.S. Geological Survey for issuing statements concerning geologic-related hazards to public officials and the public.

For the purpose of this statement, a geologic hazard is a geologic condition, process, or potential event, such as an earthquake, volcanic eruption, or landslide, that poses a threat to the health, safety, or welfare of the public or to the functions or economy of a community or larger governmental entity. In this context a Geologic Hazard Warning is a formal statement by the Director of the U.S. Geological Survey that discusses a specific geologic condition, process, or potential event that poses a significant threat to the public, and for which some timely response would be expected. Directives or advisories to the public to take action, based on a Geologic Hazard Warning, may be issued by officials of State and local governments, and other Federal agencies, with authority and responsibility to use such statements.

The term Hazard Warning is reserved for those situations posing a risk greater than normal and warranting considerations of a timely response in order to provide for public safety. Information regarding hazardous conditions that do not meet the criteria for a Hazard Warning may, however, also be sent to public officials as it becomes available. Transmittal of such information would not constitute a Hazard Warning.

1. The criteria for a Geologic Hazard Warning are:

   a. a degree of risk greater than normal for the area; or a hazardous condition that has recently developed or has only been recently recognized; and

   b. a threat that warrants consideration of a near-term public response.

2. A Geologic Hazard Warning consists of:

   a. a description of the geologic or other pertinent conditions that cause the concern;

   b. factors that indicate that such conditions constitute a potential hazard;

   c. location or area that may be affected;

   d. estimated severity and time of occurrence, if such estimates are justified by available information;

e. if possible, a probabilistic statement on the likelihood of a given event or events within a specified time period; and

f. a description of continued Geological Survey involvement and estimate of what and when additional information might be available.

If a life or property-threatening event is thought to be imminent, and immediate response is warranted by the public and public officials, the emergency nature of the Hazard Warning will be stated clearly either in the heading or the first sentence of the text of the warning statement. If the immediate crisis passes, either with or without the anticipated event, a revised statement will be issued to reflect the changed conditions and a re-evaluation of the geologic hazard.

These changes in the terms and criteria do not entail or imply any changes to the procedures the U.S. Geological Survey uses to notify State and local governments, other Federal agencies, the public, or the news agencies and services.

SUPPLEMENTARY INFORMATION: The Federal Register of April 12, 1977, Vol. 42, No. 70, pages 19292 to 19296 describes the previous terminology as well as the U.S. Geological Survey's authority to issue warnings of geologic-related hazards, capabilities to predict hazardous events, and provisional procedures to report hazardous conditions.

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