DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

PROCEEDINGS OF THE NATIONAL EARTHQUAKE PREDICTION EVALUATION COUNCIL

MAY 7 and 8, 1992

PORTLAND, OREGON

by

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Open-File Report 93 - 333

This report is preliminary and has not been edited or reviewed for conformity with U.S.G.S. publication standards.

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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 United States Geological Survey (USGS) about issuing any formal predictions or other information pertinent to the potential for the occurrence of a significant earthquake. The Director of the USGS is responsible for deciding whether and/or when to issue predictions or other information pertinent to a prediction.

A prediction is defined as a statement on the time of occurrence, location, and magnitude of a future significant earthquake including an analysis of the uncertainty of those factors. NEPEC advises the Director concerning the completeness and scientific validity of the available data and on related matters. Duties include the evaluation of predictions made by other scientists, from within or outside of government, rather than issuance of predictions based on data gathered by NEPEC itself.

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

NEPEC generally functions through the use of working groups organized by the USGS at the request of NEPEC. Working groups often include representatives from private industry, academia, and the USGS. Members of NEPEC who participate in a working group do not vote during NEPEC's evaluation of the results of the working group. After concluding its evaluation, NEPEC presents its recommendations to the Director, who bears ultimate responsibility for a decision concerning issuance of a prediction or other information.

The USGS has published the proceedings of previous NEPEC meetings as open-file reports; these reports, listed on the following pages, are available from the USGS Open-File Distribution Center in Denver, Colorado.

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ANNOTATED LIST OF NEPEC PROCEEDINGS VOLUMES
(Starting with most recent meeting)

Frizzell, V.A., Jr., 1992, Proceedings of the National Earthquake Prediction Evaluation Council: June 11-12, 1991, Alta, Utah: U.S. Geological Survey Open-File Report 92-249, 35 p., plus appendices.

Contains materials presented during an extensive review of the state of knowledge of the Intermountain Seismic Belt, as well as shorter discussions concerning the Parkfield Prediction Experiment, probabilistic prediction methods, the status of research in the Pacific Northwest, and probabilities in Southern California.

Updike, R.G., 1990, Proceedings of the National Earthquake Prediction Evaluation Council: U.S. Geological Survey Open-File Report 90-722, 36 p., plus appendices.

Contains proceedings from three Council meetings:

The January 11-12, 1990 meeting in Berkeley, California, contains discussions concerning the scope, focus, and future strategy of the Council with both proactive and reactive functions in mind, and several presentations, including an alleged prediction of the Loma Prieta earthquake, VLF observations before that event, the status of the report on San Francisco Bay area earthquake probabilities, and statistical models for aftershock probabilities.

The April 30 to May 1, 1990, meeting in Menlo Park, California, addressed the report being prepared by the Working Group on Bay Area Earthquake Probabilities, including discussions on changes for the 1988 probabilities, methodology, logic tree, and resolution of points of contention, a report on short-term earthquake alerts for the southern San Andreas fault, and aftershock probabilities.

The June 6, 1990, meeting in Menlo Park, California, involved preparation of final recommendations regarding the newly completed report by the Working Group on Bay Area Earthquake Probabilities, released as U.S.G.S. circular 1053, entitled "Probabilities of Large Earthquakes in the San Francisco Bay Region, California."

Updike, R.G., 1989, Proceedings of the National Earthquake Prediction Evaluation Council, June 6-7, 1988, Reston, Virginia: U.S. Geological Survey Open-File Report 89-144, 25 p., plus appendices.

Contains materials related to two Soviet algorithms of earthquake prediction (CN and M8) by determining patterns to diagnose "times of increased probability". Also includes discussion of the final report by the Working Group in California Earthquake Probabilities.

Updike, R.G., 1988, Proceedings of the National Earthquake Prediction Evaluation Council, February 1-2, 1988, Menlo Park, California: U.S. Geological Survey Open-File Report 88-438, 21 p., plus appendices.

Contains presentation of report by Working Group on California Earthquake Probabilities that resulted in 1988 USGS Open-File Report 88-398 entitled "Probability of Large Earthquakes Occurring in California or the San Andreas Fault." Also contains shorter discussions of seismicity in Alaska, planning for future meetings, and the status of predictions based upon pattern recognition methodology.

Shearer, C.F., 1988, Minutes of the National Earthquake Prediction Evaluation Council: April 2 and 3, 1987, Seattle, Washington: U.S. Geological Survey Open-File Report 88-37, 332 p., plus appendices.

Contains a review of the long-term earthquake potential of subduction zone earthquakes in the Pacific Northwest, reports on a field review and the response plan for Parkfield, and a discussion concerning expanding a working group to assess the likelihood of a great earthquake in Southern California in the next few decades.

Shearer, C.F., 1987, Minutes of the National Earthquake Prediction Evaluation Council, November 17-18, 1986, Monterey, California: U.S. Geological Survey Open-File Report 87-361, 69 p., plus appendices.

Contains a review of central San Andreas fault predictions, a review of the Parkfield plans, a discussion of the intermediate-term earthquake prediction conference, and future activities.

Shearer, C.F., 1986, Minutes of the National Earthquake Prediction Evaluation Council and the San Francisco Bay Region Special Study Areas Workshop: February 26 - March 1, 1986, Menlo Park, California: U.S. Geological Survey Open-File Report 86-630, 299 p., plus appendices.

Contains the proceedings of the Council and a summary of the San Francisco Bay Region Workshop convened to consider the requirements and potential locations for detailed earthquake prediction studies. The Council discussed the workshop, Parkfield Prediction scenarios and response plans, a proposed red book on intermediate term precursors, reports on the Mojave, San Jacinto, and Indio segments, and an assessment of the Wyss-Burford prediction.

Shearer, C.F., 1986, Minutes of the National Earthquake Prediction Evaluation Council: September 8 & 9, 1985, Anchorage, Alaska: U.S. Geological Survey Open-File Report 86-92, 268 p., plus appendices.

Contains discussions of the potential for an earthquake on the Calaveras fault, Alaskan seismicity, several seismic gaps in Alaska, the Parkfield Prediction Experiment, probabilistic estimates for great earthquakes, and intermediate-term precursors and predictions.

Shearer, C.F., 1985, Minutes of the National Earthquake Prediction Evaluation Council: July 26-27, 1985, Menlo Park, California: U.S. Geological Survey Open-File Report 85-754, 445 p., plus appendices.

Contains a review of research activities at Parkfield, California, a discussion of seismicity and geodetic research and faults in the southern San Francisco Bay area, reviews of earthquake prediction near San Juan Bautista, California, and legal liability.

Shearer, C.F., 1985, Minutes of the National Earthquake Prediction Evaluation Council: March 29-30, 1985, Pasadena, California: U.S. Geological Survey Open-File Report 85-507, 193 p., plus appendices.

Contains a review of the San Andreas and San Jacinto faults in southern California, a discussion of instituting a short-term prediction capability at Parkfield, and a discussion of southern California probability estimates.

Shearer, C.F., 1986, National Earthquake Prediction Evaluation Council Special Report I: Workshop on Special Study Areas in Southern California, San Diego, California, February 28 - March 2, 1985: U.S. Geological Survey Open-File Report 86-580, 239 p., plus appendices.

Following a review of the Parkfield Prediction Experiment, and using it as a conceptual model, the workshop considered the possibility of identifying a 30-km long segment of the San Andreas and San Jacinto fault zones for detailed earthquake predictions studies.

Shearer, C.F., 1985, November 16-17, 1984, Menlo Park, California: U.S. Geological Survey Open-File Report 85-201, 81 p., plus appendices.

The first routinely published proceedings of the Council, contains discussion on the scope and future strategy of the Council, a review of areas that might be studied, a discussion of the Parkfield Prediction Experiment, and a discussion of an earthquake strategy for southern California.

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NATIONAL EARTHQUAKE PREDICTION EVALUATION COUNCIL
MAY, 1992

Thomas V. McEvilly, Chair
University of California

Robert L. Wesson, Vice-Chair
USGS, Reston

Keiiti Aki
University of Southern California

William H. Bakun
USGS, Menlo Park

John N. Davies
University of Alaska

James F. Davis
California Division of Mines and Geology

James H. Dieterich
USGS, Menlo Park

Thomas H. Heaton
USGS, Pasadena

Arch C. Johnston
Memphis State University

Hiroo Kanamori
California Institute of Technology

William H. Prescott
USGS, Menlo Park

Kaye M. Shedlock
USGS, Golden

Joann M. Stock
California Institute of Technology

Ray J. Weldon
University of Oregon

Virgil A. Frizzell, Jr., Executive Secretary
USGS, Reston

NATIONAL EARTHQUAKE PREDICTION EVALUATION COUNCIL
PROCEEDINGS OF THE MEETING OF MAY 7 & 8, 1992
Portland, Oregon

Council Members Present

Thomas McEvilly, Chair	University of California
Robert Wesson, Vice-Chair	USGS, Reston
Keiiti Aki	University of Southern California
William Bakun	USGS, Menlo Park
James Davis	California Division of Mines and Geology
James Dieterich	USGS, Menlo Park
Thomas Heaton	USGS, Pasadena
Arch Johnston	Memphis State University
Hiroo Kanamori	California Institute of Technology
William Prescott	USGS, Menlo Park
Kaye Shedlock	USGS, Golden
Joann Stock	California Institute of Technology
Ray Weldon	Oregon State University
Virgil Frizzell, Executive Secretary	USGS, Reston

Guests

John Beaulieu	Oregon Department of Geology and Mineral Industries
Marvin Beeson	Portland State University
Eddie Bernard	National Oceanic and Atmospheric Administration, Seattle
Bob Bucknam	USGS, Denver
Gary Carver	Humboldt State University
Ron Cease	Oregon State Senate
Sam Clarke	USGS, Menlo Park
Carl Cook	Federal Emergency Management Agency, Seattle
Rod Copmebellick	Alaska Geological Survey, Fairbanks
Brian Cowan	Federal Emergency Management Agency, Washington DC
Jim Devine	USGS, Reston
Jim Dewey	USGS, Denver
Dan Dzurisin	USGS, Vancouver
Chris Goldfinger	Oregon State University
Jack Healy	USGS, Menlo Park
Vern Kulm	Oregon State Unviersity
John Langbein	USGS, Menlo Park
Al Lindh	USGS, Menlo Park
Michael Lisowski	USGS, Menlo Park
Curt Peterson	Portland State University
Matthew Mabey,	Oregon Department of Geology and Mineral Industries
Steve Malone	University of Washington
Ian Madin	Oregon Department of Geology and Mineral Industries
Richard McCarthy	California Seismic Safety Commission, Sacramento
Paul McGarrigle	Seismic Safety Commission, Portland
Alan Nelson	USGS, Denver
David Oppenheimer	USGS, Menlo Park
Terry Tolan	Portland State University
Paul Somerville	Woodward-Clyde Consultants, Pasadena
Anne Trehu	Oregon State University
Randall Updike	USGS, Reston
Tim Walsh	Washington Division of Geology and Earth Resources, Olympia
Ray Wells	USGS, Menlo Park
Dick Wells	Geomatrix Consultants, San Francisco
Bob Yates	Oregon State Univesity
Tom Yelin	USGS, Seattle
Craig Weaver	USGS, Seattle

MAY 7, 1992
Morning Session

T.McEVILLY, Chairman of the National Earthquake Prediction Evaluation Council (NEPEC) opened the Council meeting by asking Council Members, participants, and guests to introduce themselves. All Members were in attendance except J. Davies. McEvilly presented the Agenda (Appendix A) and asked C. Weaver to start the meeting.

C.WEAVER of the U.S. Geological Survey (USGS) in Seattle, Washington, and USGS Team Leader for the Pacific Northwest (PNW) welcomed NEPEC and presented an overview of both the USGS program in the PNW and of the day's presentation, which he characterized as a "short course" on the PNW.

At a meeting held in Seattle in 1987 (Shearer, 1988), six seismologists presented NEPEC with the same complaint about the paucity of data. Indeed, data for M4 and larger events from the National Oceanic and Atmospheric Administration (NOAA) catalogs for the area north of Cape Mendocino shows little seismicity in Oregon or Washington (Figure 1). The activity that is shown are concentrations at Mt. St. Helens and in the Mt. St. Helens seismic zone, as well as the sites of the 1949 and 1965 earthquakes in the Puget Sound region, each of which killed eight people and produced 50 to 100 million dollars in damage.

In 1975, T.Algermissen of the USGS in Denver analyzed the seismic hazards of the region (Algermissen, 1988) using the 1949 event as a design earthquake and produced an outline of the effects of a repeat of that earthquake on the urban counties of Puget Sound. Other than the seismic network at the University of Washington (UW) and occasional studies funded by the National Science Foundation or the USGS, few additional studies had been done before 1986. Beginning about 1986, the USGS, under the aegis of the National Earthquake Hazards Reduction Program (NEHRP), initiated a study of the urban areas in the PNW in order to better understand the hazards associated with earthquakes such as the 1949 and 1965 events.

C.WEAVER presented highlights to emphasize the strengths of the ongoing earthquake hazards reduction program, as well as outlined some of its weaknesses. Between 1986 and 1989, while the effort was largely aimed at redoing the hazards assessment of the urban areas of the Puget Sound and Portland basins, a curious disconnect existed between the advances that workers such as B.Atwater, A.Nelson, and G.Carver were making along the coast and the work in these urban areas. Beginning in about 1989, K.Shedlock outlined a framework for studies in the PNW, producing a more unified scientific program (modified and released by Shedlock and Weaver, 1991) that addressed a wide range of problems relating, for instance, the subduction interface, estimates of hazards in the urban areas, and the tectonic setting. Since 1991, the program has continued as one of the four USGS regional foci. The individuals presenting materials to NEPEC at this Portland meeting represent the program's strengths.

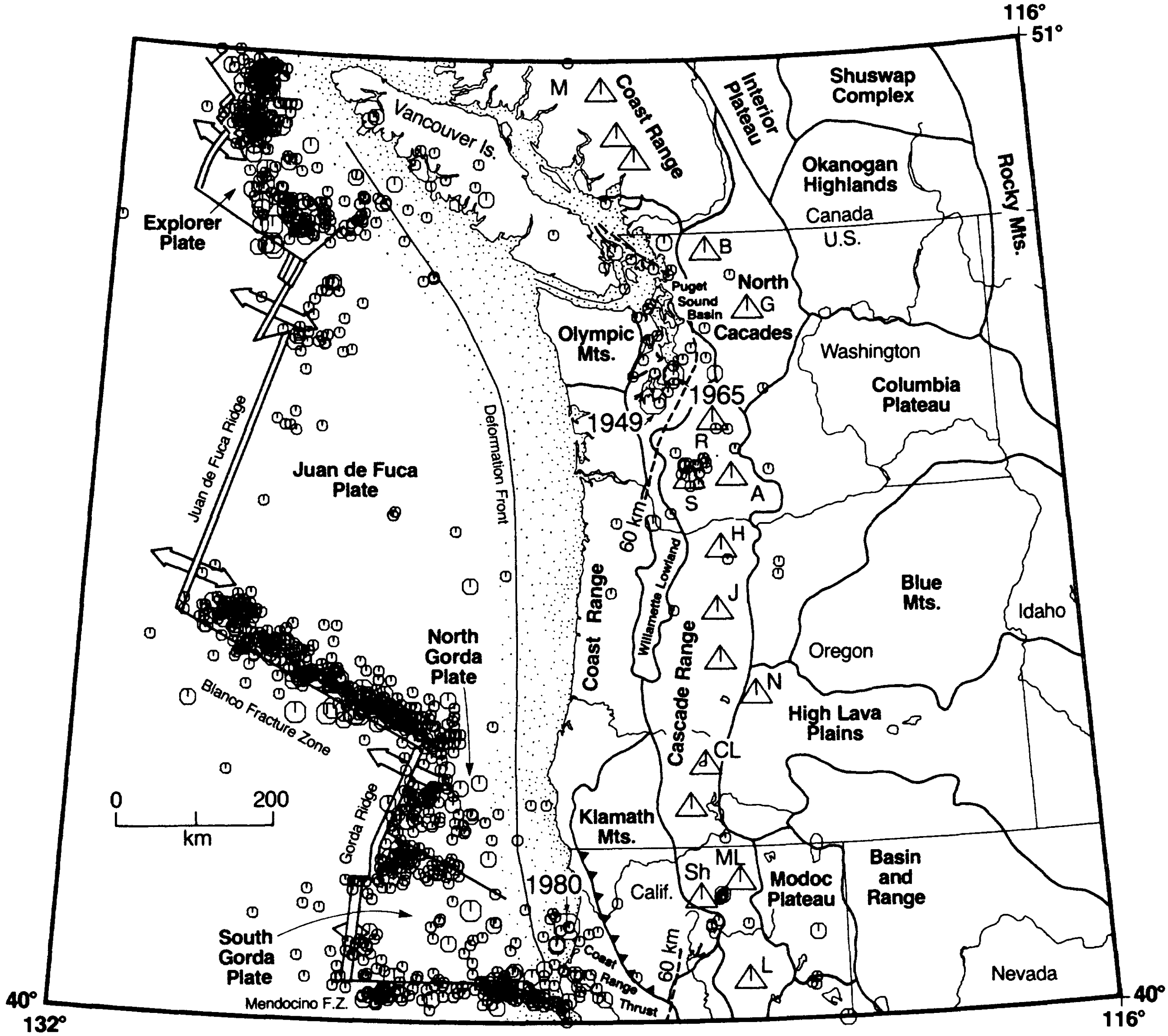


Figure 1: Map showing plate boundaries and physiographic provinces of the Pacific Northwest region. Octagons denote M≥4 earthquakes listed in the National Oceanic and Atmospheric Administration catalog through 1985, and 1949 and 1965 denote the locations of M7.1 and M6.5 events, respectively. From Shedlock and Weaver (1991), which includes open triangles representing Quaternary stratovolcanoes from Ludwin and others (1991).

Heaton and Kanamori (1984) suggested that the PNW is a region in which one would expect great subduction zone earthquakes. Paleoseismic work, one of the PNW earthquake program's major components, has confirmed that subduction zone earthquakes have occurred. This work has more recently been carried into the Puget Sound region, where R.Bucknam has found evidence of major crustal faulting, which represents an important part of the seismic hazards in the region.

Studies of crustal structure represent the second component and include everything from the refraction/reflection studies to magnetotelluric probing of the crust. We are now in a position to start to integrate the broad array of geophysical studies that have been undertaken across the region in anticipation of marine reflection or land refraction.

Seismic and geodetic monitoring represent the third area of strength in the program. S.Malone and M.Lisowski will review the progress across the entire region. From the point of view of the seismologists, a break exists at the California/Oregon border, with the network north of the border operated by the UW and that in California operated by the USGS in Menlo Park. Conceptually these networks are linked, but, in terms of real-time "warnings," the linkage is yet to be fully achieved.

The geodetic manifestations of the subduction zone are very subtle over the region. In fact, the Oregon Cascades look very much like the Basin and Range, with big north-south striking normal faults, a lack of seismicity, and lots of basaltic volcanism, almost as if the subduction zone is only very lightly overprinted on the region, except at the subduction interface. R.Wells will present an alternative model, demonstrating the importance of the crustal tectonics in helping us better understand the regional setting. These models form part of the basis of **C.WEAVER's** thoughts that we need broad-scale geodetic monitoring across big pieces of the region rather than small traverses near the coast.

The fourth component is a broad look at the regional tectonics and geologic setting. While it is important to look at the subduction zone, we cannot forget to fully investigate the areas to the east for clues about how the intricacies of the system might unravel. For instance, the Hanford region is of particular interest from a public policy point of view, and the regional setting certainly should include the tectonics of such areas east of the Cascades.

Applications and outreach constitute the final component of the program in the PNW. More than a quarter to a third of the program has involved transfer and mitigation studies, such as focused investigations on the potential of disruption of water systems. The USGS has funded studies by the water departments of Tacoma, Seattle, and Everett on their water systems looking at the vulnerability to large earthquakes. Initially M7.5 events associated with the Juan de Fuca plate were being considered, but more recent studies by the Seattle Water District included M8+ events on the subduction interface in its analysis.

Another example of outreach, the efforts by structural engineers in Oregon and Washington to change the Uniform Building Code to rezone all of the western parts of the States to at least Seismic Zone 3, will be presented as a poster by R.McGarrigle. In fact, some members of the structural engineering community in Washington would try to rezone western Washington into Seismic Zone 4, if we can provide them with the data they need to campaign for such a change. Here in Portland, our colleagues at the Department of Geology and Mineral Industries (DOGAMI) are producing the prototype regional earth hazards map. This may turn into a larger regional effort, perhaps funded by other agencies.

Thus, the five major successful components of the program include paleoseismic studies, crustal studies, seismic and geodetic monitoring, investigations of the regional tectonic and geologic setting, and outreach. Absent from the list are strong ground motion studies which have been addressed only in a more or less spotty fashion. **C.WEAVER** asserted that we owe the structural engineering community more sustained effort. This community has concerns about three aspects of the problem: one, they accept the occurrence of large subduction earthquakes, but are interested in evidence for the shaking that may accompany such events; two, what peak ground motion would accompany these events (some have suggested that the peak might be no more than 0.3 g); and, third, what durations might be associated with the events?

Secondly, we need to learn much more about tsunamis and the potential for runup along the coast and into Puget Sound and other waterways. E.Bernard from NOAA in Seattle, Washington, will help us with this issue this afternoon. Finally, the Cape Mendocino earthquake raises the odd question about jurisdiction. Heretofore, we had included the entire subduction zone in the PNW. In concept that is true, but on the other hand, the southern part really is in California and is monitored from California. The folks in California have a much more succinct and clear way of thinking and talking about earthquakes than the folks further north. A big education gap starts at California's northern boundary.

R.WESSON asked about the convergence rate between the Juan de Fuca plate and the North American plate as well as the evidence for that rate.

C.WEAVER answered that published data derived from offshore magnetic stripes indicate that convergence varies between 2 and 4 cm/yr, depending upon the geometry.

A.JOHNSTON asked about seismicity of the Gorda plate.

C.WEAVER answered that the usual interpretation is that the seismicity is due, in large part, to the break up of the plate in response to the North American margin. While that may be true, it may have no impact on great subduction zone events.

E.BERNARD asked whether the spreading was like a conveyor belt with systematic or episodic spreading taking place over a few days or over ten years.

C.WEAVER answered that it is not really evident how the conveyor belt works, but that strain release may be averaged over cycles of 300 years or so. We can clearly obtain convergence and strain accumulation consistent with numbers not far off 2 to 4 cm.

M.LISOWSKI interjected that good agreement exists between rates of plate motion over the last two million years and over the last ten years, as determined from space geodesy. This argues for constant overall plate motion.

A.NELSON of the USGS in Denver, presented an overview of Holocene paleoseismology along the outer coast of Oregon and Washington (Figure 2), highlighted some of the problems interpreting the geologic record, and summarized some of the ongoing work that may help solve these problems.

Geologic features produced in broad zones of regional deformation during historic great subduction zone earthquakes provide a guide to the kinds of evidence for past subduction zone earthquakes that we search for in the PNW.

Profiles (Figure 3) of coseismic deformation during the largest earthquakes in Alaska, Chile, and Japan show a zone of coseismic uplift in the trench-ward part of the overriding plate and a parallel zone of coseismic subsidence arc-ward of the zone of uplift. Thus, during great Cascadia earthquakes, regional uplift might be expected along the coasts of northern California and southern Oregon. However, parts of these coasts are also in part of the active fold-and-thrust belt of the overriding North American plate, so local uplift or subsidence due to deformation on faults or folds in the upper plate would also be expected. The northern Oregon and Washington coasts are farther from the trench; they might show evidence of regional subsidence during great earthquakes on the plate interface.

Along a subduction zone coast, one might find raised marine terraces indicating either regional uplift or surface deformation from coseismic growth of thrusts or folds in the zone of uplift, surface ruptures from thrust faults, sand blows and other

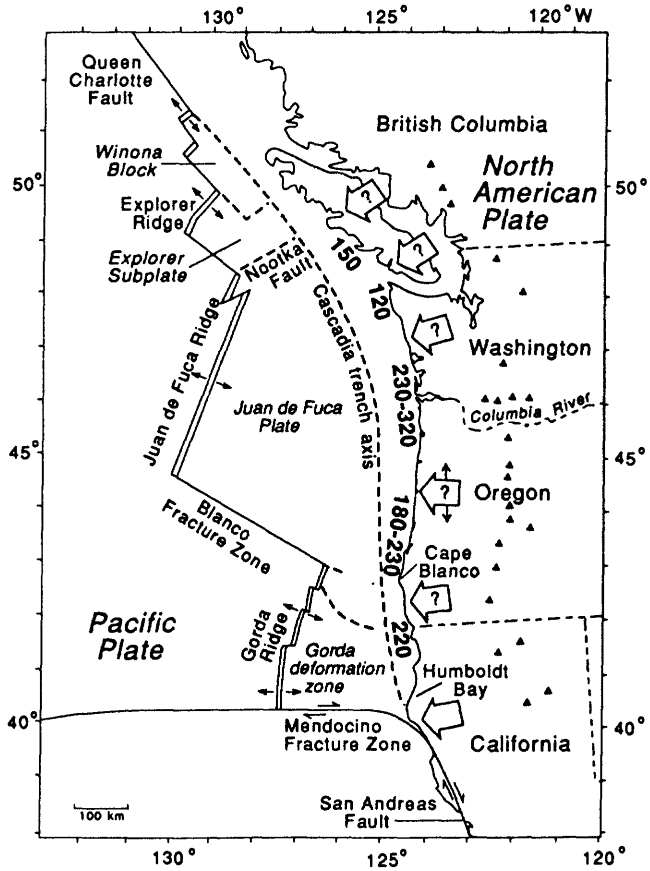


Figure 2: Major features of the Cascadia subduction zone (CSZ) in the northwestern United States and southwestern Canada. The large arrows mark generalized areas along the coast that coincide with boundaries between tectonic subplates, projections of boundaries between volcanic segments of the Cascade Range, or other areas where seismicity and subducting plate parameters may change, and so could correspond with the boundaries between segments of the subducting-plate as outlined by Nelson and Personius (1991). No query is shown at the Mendocino fracture zone boundary because the location of this feature is accurately known. Distances between boundaries are shown only to suggest a range of possible segment lengths. The range of distances shown for segments north and south of 44.5° N reflects several locations for a possible boundary along this part of the coast. We do not know whether most Holocene ruptures along the CSZ have been influenced by these postulated boundaries. Small black triangles mark volcanoes in the Cascade Range.

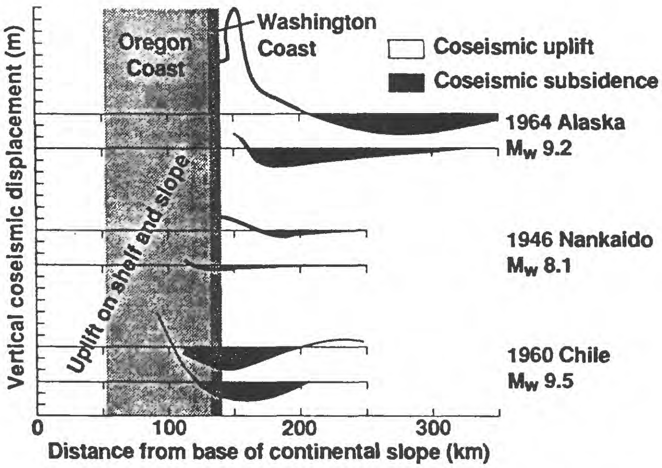


Figure 3. Profiles of vertical coseismic displacement of the land surface along transects perpendicular to subduction zone trenches during great earthquakes in Alaska, Japan, and Chile (from Atwater, 1987). Two profiles are shown for each earthquake. Subsidence is highlighted by shading; displacement equals zero where profile line intersects horizontal line. Light shaded areas show the position of the Oregon and Washington coasts relative to the Cascadia trench compared with the positions of the profiles relative to the trenches in Alaska, Japan, and Chile. Coseismic uplift on the continental slope and shelf is inferred.

types of liquefaction features produced by strong ground motion in saturated sediments, anomalous sand beds deposited by tsunamis that were produced by coseismic uplift of the continental shelf, or, in small localized areas in the zone of coseismic uplift and throughout the zone of subsidence, deposits indicative of sudden coseismic subsidence of coastal lowlands.

Paleoseismologists have been searching for evidence of this sort along the coasts of Oregon and Washington, but some have not been easy to find. In order to generate a little controversy right from the start, **A.NELSON** compiled sites that have been investigated that show probable and possible evidence for late Holocene coseismic earth movements (Figure 4).

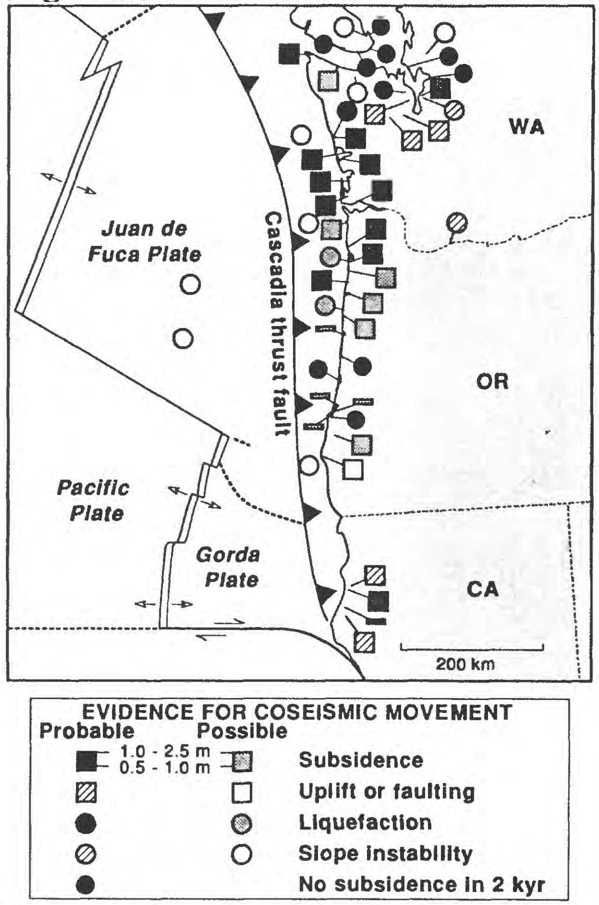


Figure 4. Sites in the Cascadia subduction zone which show probable and possible evidence for late Holocene coseismic earth movements as of March, 1992. Judgment about the documentation of evidence at each site is subjective and incomplete because most of this work is unpublished. Probable evidence of coseismic subsidence is best documented in northern Oregon and southern Washington.

Estuarine stratigraphic sequences containing the buried peaty soils of tidal marshes and swamps have been studied by many paleoseismologists over the past five years. These buried peaty soils are widespread and have the potential for providing evidence of both the magnitude and recurrence of coseismic deformation along much of the Cascadia zone.

Work along the outer coast allows us to conclude that at least two plate-interface earthquakes of M8 or larger have probably occurred in the Cascadia subduction zone in the past 2000 years. At some sites, evidence exists for tsunami deposition at the time of at least one of these events. At two sites 55 km apart in southern Washington, the most recent submergence event occurred between AD 1680 and 1720, about 300 years ago.

We do not know, however, what percentage of reported buried peaty soils at different sites were submerged and buried by aseismic rather that coseismic processes. Nor do we know the coastal extent of submergence events. The times of submergence events at the majority of sites are not known with a precision better than a few hundred years. Finally, it is not known whether strong ground shaking accompanied submergence events.

As many as 11 buried peaty marsh soils dating from the past 5000 years have been described by workers (Atwater, 1987; Peterson and Darienzo, 1991). Two of the peaty soils correlate along at least 100 km and probably 200 km of coastline. A plate-interface earthquake of at least M8 would be needed to produce this much coseismic subsidence along this extent of coastline.

Thinner, fainter, less laterally extensive buried peaty soils have also been suggested as having been produced by coseismic subsidence of former tidal marshes, but they may not have been buried in the same way. At least some of the less prominent and less well exposed soils may have nontectonic origins.

A consensus exists that as one progresses south along the coast of Oregon, the character of the marsh stratigraphic sequences changes. In the northern third of the Oregon and in southern Washington, the two most prominent abruptly buried peaty soils contain the rooted stumps of Sitka spruce and are capped by anomalous sand beds. Estimates of the amounts of sudden submergence represented by the transgressive contacts of the tops of these two prominent soils range from 1 m to 2.5 m. In southern Oregon, abruptly buried soils are less prominent, much less extensive, and more closely spaced in vertical sequence. Most sites show no more than one abruptly buried soil, rooted tree stumps are small and rare, and possible tsunami sand beds have not been well documented. Estimates of the amount of submergence at abrupt transgressive contacts at the tops of the soils range from a few tenths of a meter to a meter.

Some of the differences in the characteristics of buried peaty soils both at the same outcrops and from site to site might be due to different soils having been buried at different times during different kinds of earthquakes. For example, at least in southern Oregon, buried soils may have been submerged by sudden coastal subsidence during deformation by shallow faults and folds in the overriding North America plate, either during great earthquakes on the plate interface or during small earthquakes on structures in the overriding plate that occurred independently of plate-interface events.

Alternatively, many of the thinner, less extensive peaty soils and those exhibiting submergence of less than a meter may have been submerged and buried by aseismic processes. Very similar peaty soils are commonly interbedded with mud in the intertidal sequences of mid-latitude passive continental margins, for example, the U.S. east coast and northwest Europe. Examples of non-tectonic processes that can produce such sequences include rapid changes in the rate of regional sea-level rise, changes in sedimentation rates, or changes in the configuration of bars and channels in tidal inlets that led to local changes in tidal range.

In the PNW, very rapid changes in the rate of regional sea level rise seem unlikely during the late Holocene. Continuous sections of tidal marsh peat in the Siuslaw River estuary of central Oregon and in Puget Sound suggest no sudden changes of more than 0.5 m. However, barrier bar formation and subsequent breaching seems a likely explanation for the abrupt burial of some peaty units in the narrow arms of estuaries, particularly those that do not contain major rivers.

Four aspects of coastal marsh stratigraphy help distinguish between these different processes of submergence: the suddenness of submergence, the amount of submergence, the local and regional stratigraphic extent of submergence, and the degree of synchroneity of the events from site to site. Fossil plants that have rooted in the tops of buried peaty soils and that extend upward into overlying mud or sand offer the best clues to the suddenness of submergence. The stems and leaves of delicate fossil marsh plants would be expected to have been removed by tidal currents or compacted into the upper part of the peaty soil unless the burial occurred within a few years.

Ghost forests of fossil trees in the buried peaty soils of the spruce or cedar swamps offer the most dramatic evidence of sudden submergence and burial. Such forests are found only in southern Washington, however, and spruce stumps rooted in the soils are common only in northern Oregon and Washington. Since tree stumps are common in the intertidal areas of submerging coasts, only where the trees have been shown to have died quickly at about the same time is sudden submergence indicated.

Probably tsunami sands that lie directly on the surface of buried peaty soils and that are overlain by at least a few tenths of a meter of mud offer another indication of the suddenness of submergence.

Fossils are also important in determining the amount of peaty soil submergence. In good outcrops, macrofossils, like rooted tree stumps, may indicate the approximate amount of submergence. However, to estimate the amount of submergence across the upper contacts of deeper peaty units in Washington and all but the 1 or 2 younger soils in Oregon, microfossils from cores must be studied.

Local processes, such as erosion by tidal channels, can produce abrupt contacts. Therefore, an abrupt contact must be traced across two or more subenvironments for hundreds of meters, to determine the local stratigraphic extent of submergence.

Similar sequences of abruptly buried marsh soils from one estuary to another are required for determination of a regional submergence event.

The most precise method of determining the synchroneity of events is by the use of tree-ring chronologies between fossil trees in buried soils and living trees. Yamaguchi and others (1989) have shown that western red cedars at four sites around Willipa Bay all died after AD 1618 to 1684. Because the outermost rings have weathered away, these determinations represent only close maximum ages for the time of tree death.

Radiocarbon dating of plants rooted in the buried soils can constrain plausible mechanisms for the submergence events, depending on whether the ages of the soils of widely separated soils are either consistent or inconsistent with ages for soils at other sites. If the time intervals spanned by calibrated radiocarbon ages of widely separated sites overlap, two types of earthquakes are possible. Soils may have been submerged by regional subsidence during great earthquakes that ruptured at least the distance between the correlative sites. Another possibility is that local subsidence may have been produced by upper plate deformation during plate interface earthquakes. If the time intervals spanned do not overlap, then great plate-interface earthquakes larger than M8 seem unlikely.

Correlation of soils using conventional radiocarbon ages in coastal PNW has not been particularly successful. Studies in southern Washington and northern Oregon show that soils have to be spaced at least 800 years apart to be distinguished solely by conventional radiocarbon ages.

Two methods of high-precision radiocarbon dating are being applied to significantly improve the precision of estimates of the times of submergence events. Both rely on ^{14}C ages from fossil trees and plants rooted in the tops of buried soils. Stratigraphic relations and the thickness of the outermost ring of the fossil trees suggest both types of fossils were killed when the soils were suddenly submerged and buried. High-precision conventional radiocarbon methods yield ages with standard deviations of 10 to 30 years compared to deviations of 60 to 80 years reported by most conventional radiocarbon labs. Using this method, Atwater and others (1991) have shown that trees in the youngest buried soil at two sites 55 km apart in southern Washington died within a decade or two of AD 1700. Accelerator mass spectrometer radiocarbon dating is being used to date 5 to 8 rooted fossil marsh plants from the youngest soil at seven sites. Preliminary results indicate that averaging 5 to 8 samples will produce standard deviations of 20 to 40 years.

A.NELSON concluded that at least two great earthquakes have occurred in the CSZ in the past 2000 years, but few sites have been studied in enough detail to rule out localized subsidence or aseismic processes as the burial mechanism for many peaty soils. Much work needs to be done before the magnitude and recurrence of past plate interface earthquakes on the CSZ can be considered well constrained.

J.DIETERICH asked about rates of aseismic subsidence along the coast.

A.NELSON answered that no aseismic rates are known because of the difficulty distinguishing seismic from nonseismic changes in sea level.

T.McEVILLY noted Nelson's seeming confidence about the event 300 years ago and asked what is known about the older event.

A.NELSON said that the two most prominent events share very similar characteristics. Both contain rooted trees, are very peaty, found at most sites, and occur in approximately the same position, but varying numbers of faint soils may occur between these two bold soils at various sites. The younger soil is about 1700 AD and the older one is about 1700 BP, or 300 AD.

R.BUCKNAM of the USGS in Denver, presented the results of a series of studies from the Puget Sound region (Figure 5) all investigating features that formed in the past two thousand years and all of which may be related to a single event, possibly at about 1000 or 1100 years ago, although it would be difficult to unequivocally assign them to such a single event.

The most conspicuous and dramatic evidence of tectonic deformation in the last 2000 years is well expressed at Restoration Point and less obviously expressed at Alki Point in West Seattle. At Restoration Point, an intertidal platform, inferred to have been formed suddenly in association with an earthquake, has been raised 7 m above present high tide. Marsh deposits behind a gravel beach bar record the history of the preceding few thousand years. The record is as old as 7500 years BP because it includes ash from Mt. Mazama; peat contains charcoal that indicates the uplift occurred after 1300 to 1500 years BP.

Five km north of Restoration Point at Winslow, several meters of peat underlies a salt marsh. The Winslow locality went slightly down or was stable at the time the Restoration Point locality was uplifted 7 m, implying a 7 m gradient in 5 km. Plotted on a regional map, the Restoration Point and Alki Point localities are seen to be regionally unique outcrops of bedrock and appear to be on an axis of uplift near a fault that may have slipped during the event that caused uplift 1000 to 1100 years ago (Bucknam and others, 1992), although there appears to have been no surface rupture at that time.

Evidence preserved in bays in southwest Puget Sound and the landward end of Hood Canal consists of uplifted tidal mudflats overlain by fresh-water peats. Atwater and Moore (1992) have studied a sand layer within the salt marsh at Cultus Bay and a similar feature at West Point which date to the interval of time during which the 7 m of uplift occurred and which may be due to a tsunami generated by that sudden uplift.

Drowned forests are present on large landslides studied by Jacoby and others (1992). The trees provide precise dates for the occurrence of the slides into Lake Washington at the same time as the features described above.

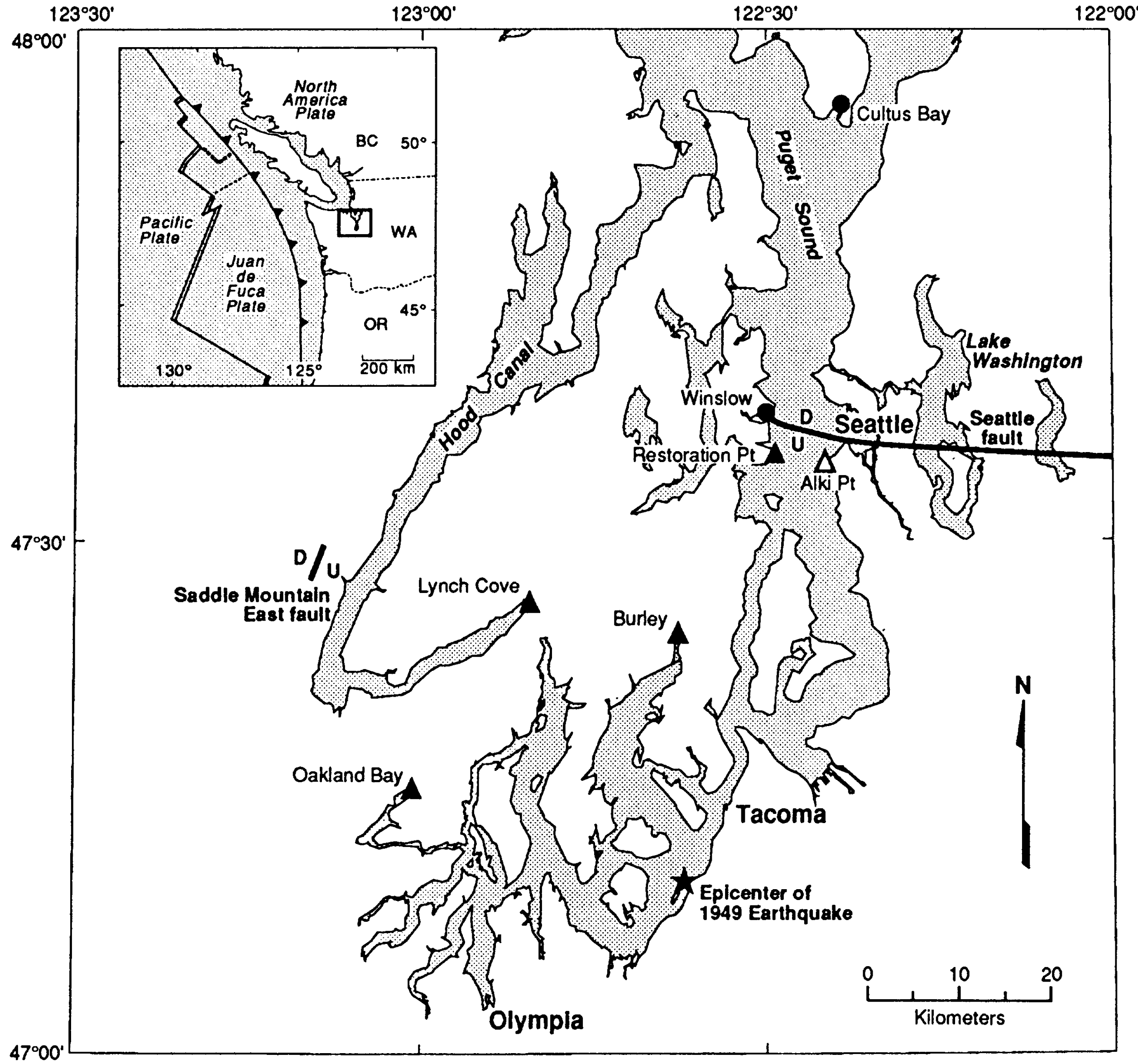


Figure 5. Selected Puget Sound locations and features.

Several sites exhibit similar features and timing, but occur in totally separated areas. The marsh at Lynch Cove is unique for its large size and minimal modification by diking for agricultural purposes. A 2-m-thick fresh water peat is over- and underlain by tidal mudflat deposits. The contact with underlying deposit is sharp and implies sudden uplift of the area, about 1100 years ago, based upon dates from wood at the base of the peat, and slow rise of relative sea level of 2 m since that time.

A fault scarp with nearly 4 m of displacement at Saddle Mountain at the eastern foot of the Olympic Mountains has been described by Wilson and others (1979). The activity on this fault was dated at 1200 BP. Jacoby and others (1992) found trees drowned by the rise of water level in a nearby lake that yielded dates of about

1000 years BP. Schuster and others (1992) have found several lakes in this area in which the trees were killed abruptly about 1100 years ago.

This data collectively suggests that one or two major events have produced broad uplift in the Puget Sound region in the past 900 to 1500 years. This event produced widespread landsliding and deposition of tsunami sands. This suggests that structures in the North American plate are capable of producing damaging earthquakes.

W.BAKUN asked if the 900 to 1500 year BP events correlated with the 1700 year BP event described by Nelson.

R.BUCKNAM thought not. The ages presented don't overlap the older determinations. Interestingly, Atwater (1992) has described evidence for subsidence 90 km to the west that is inferred to be associated with large subduction zone earthquakes about 300 and about 1400 to 1700 years ago. He finds no evidence for subsidence in that area for the period of time 1000 to 1100 years BP.

R.WELLS, of the USGS, Menlo Park, has been interested in the broad-scale aspects of Cenozoic deformation in the PNW coastal regions of the Cordillera. He and C.Weaver have been investigating possible correlations between late Cenozoic geology and seismicity in western Oregon and Washington. They suggest that the pattern of late Cenozoic northward transport and clockwise tectonic rotation of mafic basement blocks in the forearc may provide a model for understanding the present day seismotectonics.

The Eocene tholeiitic crust of the Coast Range appears to be oceanic crust trapped inside the Columbia River embayment, a reentrant in the Mesozoic orogenic belt. Positive isostatic residual gravity anomalies and aeromagnetic highs in the Coast Range correlate with outcrops of this pillow basalt basement and define boundaries of tectonic blocks in the forearc (Figure 6). The thick, cold, Eocene tholeiitic crustal blocks that constitute the forearc region of Oregon and Washington may be relatively strong, with seismicity concentrated along the boundaries of the blocks, especially along their eastern boundary with the relatively weak, hotter continental crust beneath the arc.

Abundant paleomagnetic data indicate that the coastal blocks are rotated up to 70^{o}, with areas east of the Cascade arc rotated less. Plotted on an east-west profile, the slope indicates smoothly increasing rotation toward the coast; this has been interpreted as the result of coupling of the forearc with the obliquely subducting oceanic plates. Using this data, one can calculate a northward transport of about 6 mm per year for the coastal region in the last 15 million years. Presumably, this is accommodated by the observed right-lateral faults in the forearc and arc. In addition to dextral shear in the forearc, north-south shortening of the Coast Range has occurred within the Columbia embayment. This deformation is similar to the east-west trending structures of the late Cenozoic Yakima fold-and-thrust belt east of the Cascade arc.

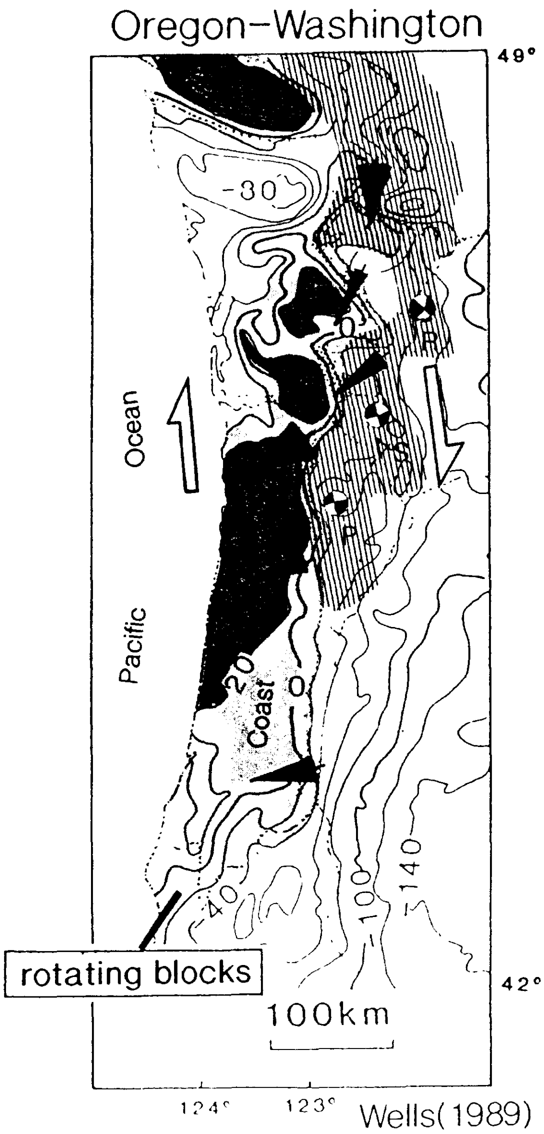


Figure 6. Bouguer gravity map of western Oregon and Washington showing coastal gravity highs that correlate with strong, relatively aseismic mafic basement blocks in the forearc. Blocks are moving north and rotating clockwise in dextral shear couple along the convergent margin (white arrows); pie-shaped wedges indicate paleomagnetically-determined clockwise rotation and their uncertainties with respect to north. Seismicity forms several northwest trending, en echelon zones inboard of northward moving blocks (lined pattern with selected focal mechanisms: P = Portland, S = St. Helens, R = Rainier zones). See Wells (1989) for details.

Present day seismicity mirrors this pattern of deformation. Several northwest-trending dextral-shear zones form a right-stepping, en echelon pattern of seismicity along the Puget-Willamette lowland and western Cascades (Figure 6). They include the Portland seismic zone, the St. Helens seismic zone, a zone west of Mt. Rainier following a Cenozoic fold-and-thrust belt, a North Cascades foothills zone, and the Darrington-Devil's Mountain fault zone. East-west seismic zones locally contain thrust mechanisms, including the Greenwater, Seattle, and Darrington-Devils Mountain, which appear to form the boundaries for the individual right-lateral segments (Figure 7). The seismicity parallels steps in the Coast Range gravity gradient which may reflect basement contrast between the Coast Range and Cascades. As previously suggested, the St. Helens zone may reflect the boundary at depth between the basalts of the Coast Range and the rest of the continent. The right lateral strike-slip seismicity is concentrated in the continental crust, whereas basalts of the Coast Range are relatively aseismic, particularly in Oregon where the basalt is relatively thick and little broken up. In Washington, coastal blocks are smaller, and seismicity is widespread where northward-moving blocks pile up against the Vancouver Island buttress of preTertiary continental crust.

The regional picture, then, is one of northward-moving coastal blocks, rotating clockwise in a dextral-shear couple driven by oblique subduction. East-west structures, basins, and uplifts bounded by high-angle reverse or thrust faults accommodate north-south shortening in the northern

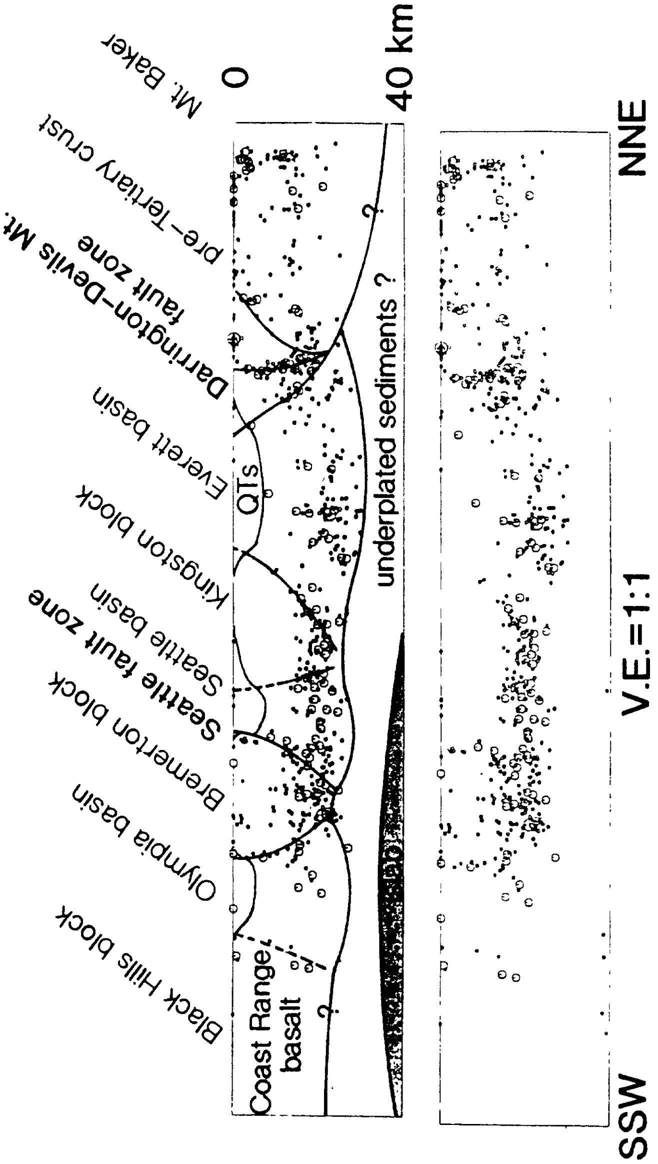


Figure 7. Seismic cross section of the Puget lowland oriented SSW-NNE, 1970-1992; magnitude > 1.5, z<40 km. Uplifted basalt basement blocks are bounded by reverse faults in upper interpretative cross section.

Coast Range, as blocks impinge upon Vancouver Island (Figure 7). Underplated sediments from the accretionary wedge, thicker in the northern part of the region, may significantly influence the size of blocks of the Eocene basalt and the amount of coupling with the downgoing slab. The rotating forearc blocks of thick basaltic crust may be coupled with the subducted slab and may represent asperities for large subduction zone earthquakes, as has been suggested for the western Aleutian Islands.

S.MALONE of the University of Washington (UW) presented an overview of the seismicity in the PNW (Appendix B). The moderately robust UW seismic monitoring effort has been crucial for investigating the distribution and patterns of earthquakes and has allowed us to develop a basic understanding of earthquake hazards in the region.

Eleven different organizations operate about 190 nonuniformly distributed seismograph stations, predominantly narrow-band, high-frequency, single-component instruments. These comprise the regional networks from western Montana to northern California (Figure 8). The rather enlarged PNW encompassed by these networks emphasizes the importance of the more isolated networks in terms of earthquake hazards with relation to growing populations. Cooperation and sharing of data amongst the various organizations is increasing.

Although not as seismically active as California, significant activity is concentrated in several different areas which have a variety of characteristics (Figure 9). In the east, in 1983, Idaho experienced one of the largest events for the continent in the past several decades. Activity in the Cape Mendocino area will be addressed later today. The area (Figure 10) covered by the Washington Regional Seismograph Network for the last 20 years includes rather shallow events within the

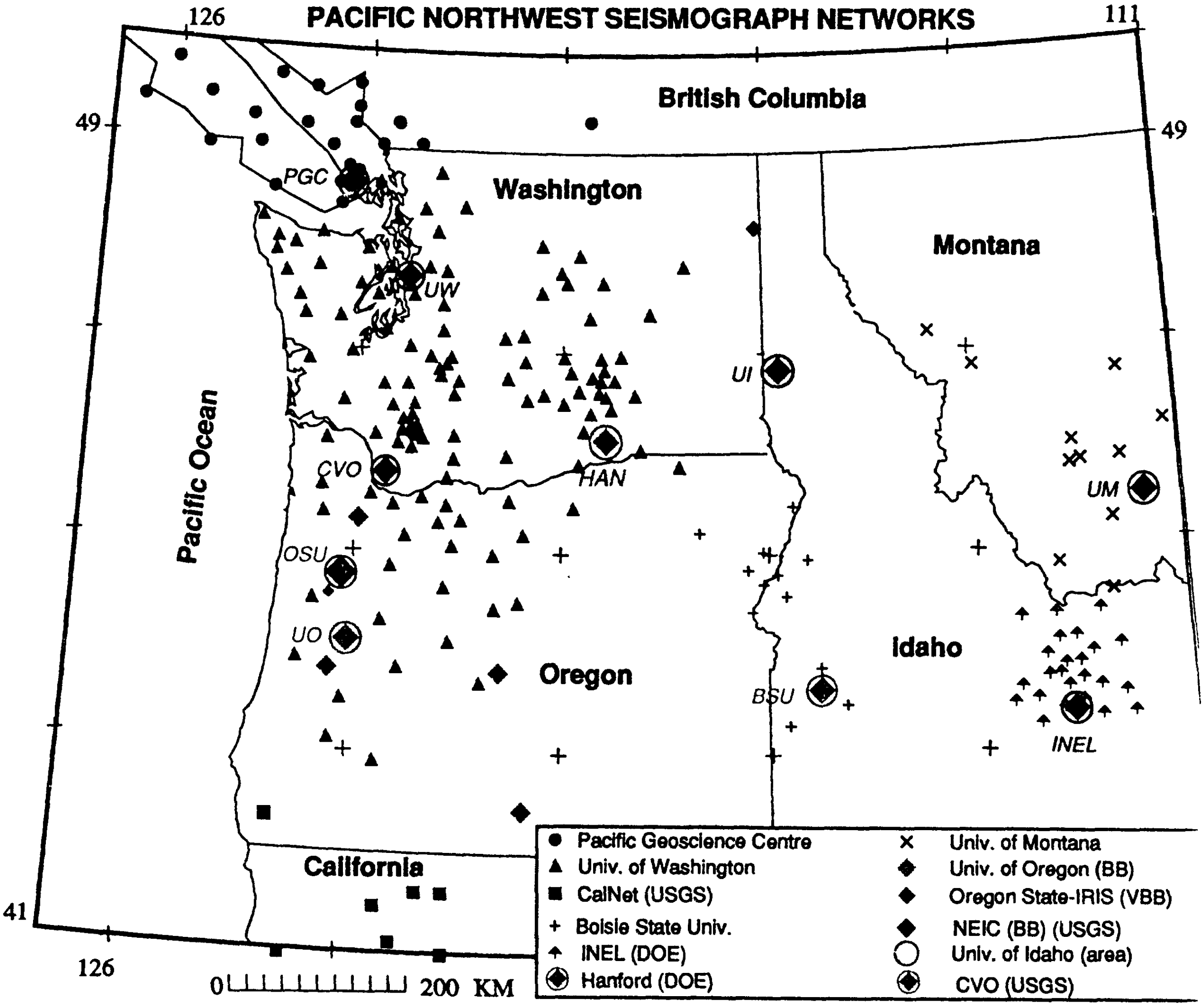


Figure 8. Map of the Pacific Northwest showing location of some 190 seismic stations operated by 11 organizations noted in inset. See Appendix B for additional information concerning networks.

Columbia River basalts in eastern Washington, zones of earthquakes on the west flank of the Cascades and the Puget Sound area from the deeper crust, and subcrustal events from southern Vancouver Island to the Portland, Oregon, area. North-south cross sections of this data show the distribution of these events from west to east (Figure 11).

If only the last 100 years of record were available, one would underestimate earthquake hazards (See Appendix B). One would assume that the seismic hazard was low for many areas of the PNW, including areas that will be impacted by subduction interface events. Areas with moderate seismicity and medium-sized events, but without major thoroughgoing structures or longer trends of seismicity, wouldn't seem to be at risk from large events. Larger types of events could be assumed as likely in zones with moderate seismicity and medium-sized events combined with the thoroughgoing structures. Areas with the most probability of future damaging events would be those areas that have been struck by

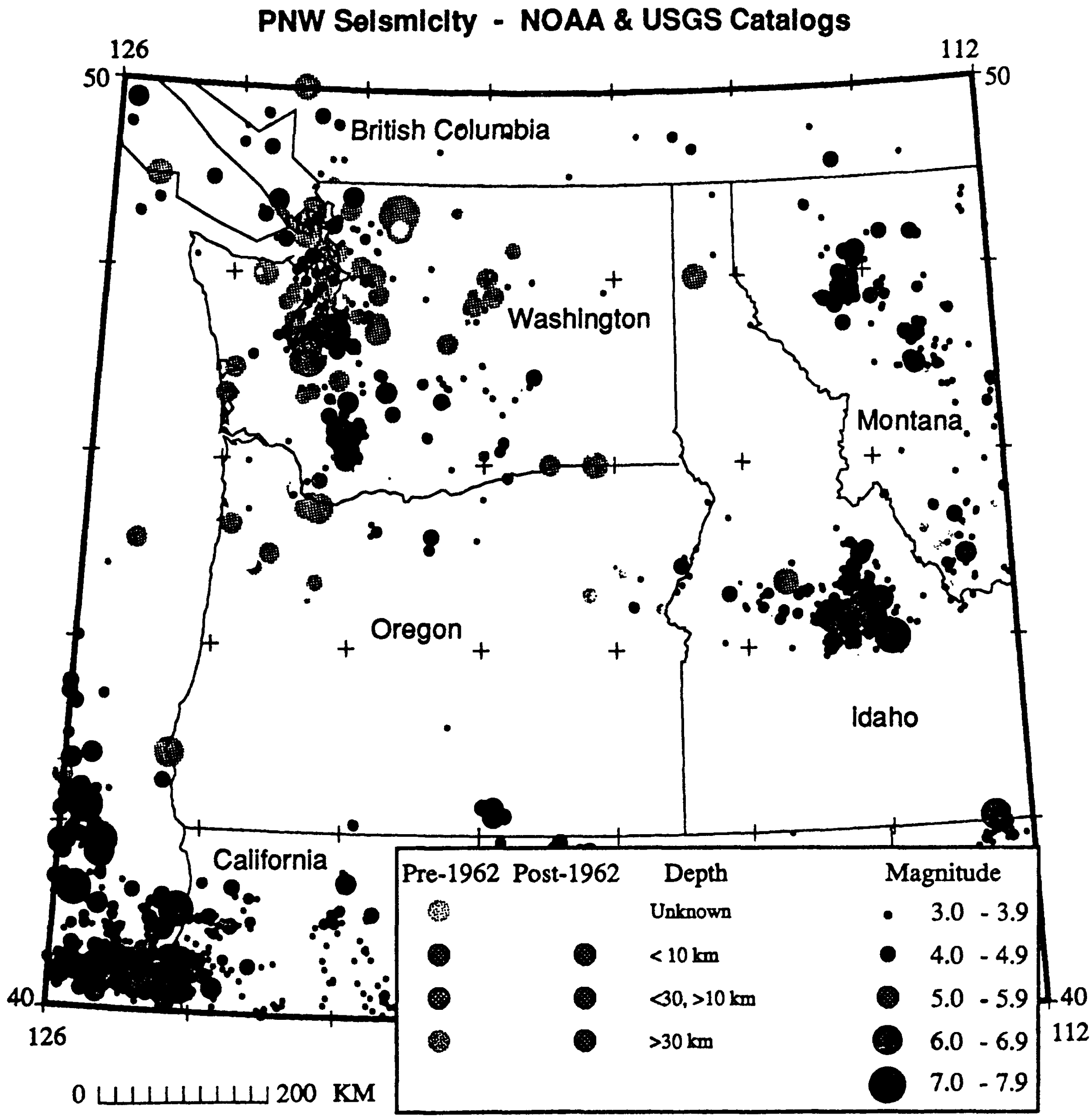


Figure 9. Black and white reproduction of color map of seismicity in the Pacific Northwest (NOAA and USGS sources).

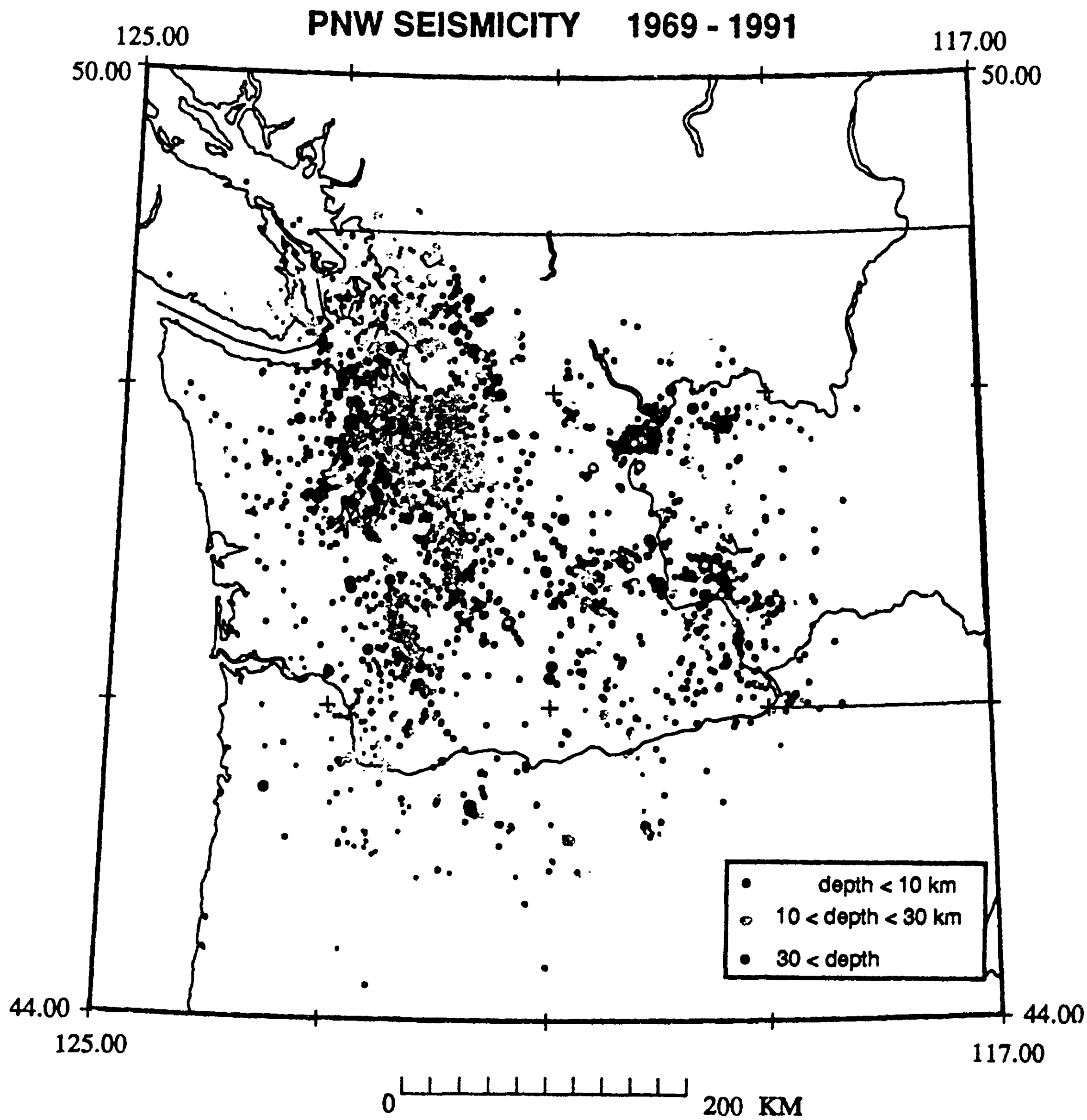
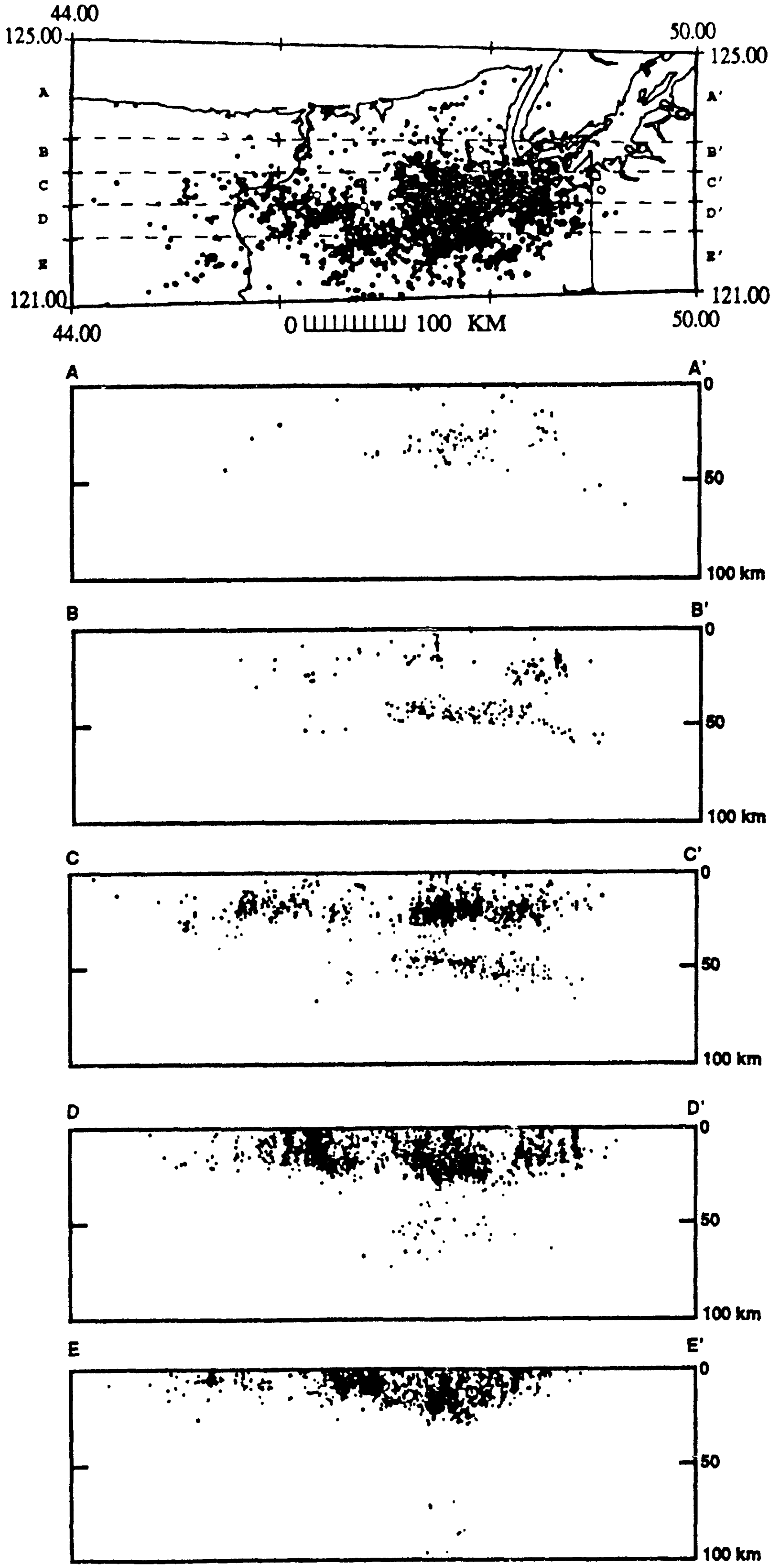


Figure 10. Black and white reproduction of color map of seismicity of Washington and northern Oregon from the Washington Regional Seismograph Network catalog. Small symbols represent $2.5 \leq M \geq 3.5$ events, and larger symbols represent $3.5 \leq M \geq 5.5$ events.



damaging events, which probably occur within the slab as it bends to a steeper dip . These slab-bending events have traditionally been the main source of concern.

The 1872 crustal event, one of the largest events in the PNW with an estimated magnitude of a little over 7, is perhaps one of the least well understood. A causative structure has not been identified. Minor crustal zones exist is several parts of the region. In eastern Washington, in particular, some concern exists about an extension of the fold belt across the Columbia River Plateau, which does have a modest amount of seismicity, including earthquakes up to M5.

Figure 11. North-south cross sections showing distribution of earthquakes with depth in western Washington and northern Oregon in slices from the coast (A-A') to the Cascades (E-E').

M.LISOWSKI of the USGS in Menlo Park, while concentrating on the Olympic Peninsula and Cape Mendocino areas, presented evidence from geodetic measurements made over the last century that support a model for seismic subduction in the Cascadia zone (Savage and Lisowski, 1991; See Figure 12). As the oceanic crust is subducted, a locked zone in the interface produces buckling of the crust that is observable at the earth's surface.

Initial work was undertaken in the Seattle area in the early 1970's to better understand the shallow seismicity described today by S.Malone. The network was expanded to the Olympic Peninsula in the early 1980's. In 1986, the first global positioning systems (GPS) measurements were made while recovering a triangulation network across the Straits of Juan de Fuca.

Both the Olympic Peninsula and Seattle areas exhibited relatively low rates of strain accumulation, contraction on the order of 0.1 ppm, for the periods 1982 to 1990 and 1972 to 1979, respectively. More recently, the Seattle area has exhibited rates of 0.3 ppm for the period 1979 to 1990. Likewise the northern San Andreas area and southern part of the Cascadia zone exhibited northeast directed contraction on the order of 0.2 ppm. Using deviatoric rates, east-northeast or northeast directions of contraction seem to be indicated in the vicinity of the subduction zone. In the Mt. St. Helens area, the deformation is not well defined, but it does appear to include north-south extension concentrated near the volcano. In the backarc near Hanford, no significant strain accumulation exists.

A 43 mm/yr convergence of the Juan de Fuca plate with North America directed in N68^{o}E direction is indicated by a uniform strain model for the Olympic Peninsula region. Tide gages in the region also seem to indicate deformation. Rates of strain accumulation in the network appear to be uniform in time. Investigations of vertical deformation by Holdahl and others (1989) indicate that the coast is variably going up at a rate of 3 mm/yr, relative to the Puget Sound trough, with a tilting towards the arc.

A simple dislocation model (Figure 13) proposed by Savage and others (1991) would have the interface locked down to about 20 km in depth. At 20 km, the crust has heated up enough so that it can flow plastically, with a zone over which slip occurs at some intermediate rate transitional to the freely slipping part of the interface below about 35 km. For much of the offshore region, the slip deficit is accumulating at the subduction interface. Strain rates predicted for the Olympic Peninsula are those observed. The observed data in the Olympic Peninsula-Seattle area fit the locked subduction zone model, but this doesn't prove the model. The model is 2-D in an elastic half-space and doesn't account for observations in several other parts of the region which need to be investigated further.

The direction of the principal contraction (Figure 12) is similar in all networks and is approximately aligned with the direction that the Juan de Fuca plate is converging upon the North American plate. The strain rates are highest in the fore arc region and very low in the back

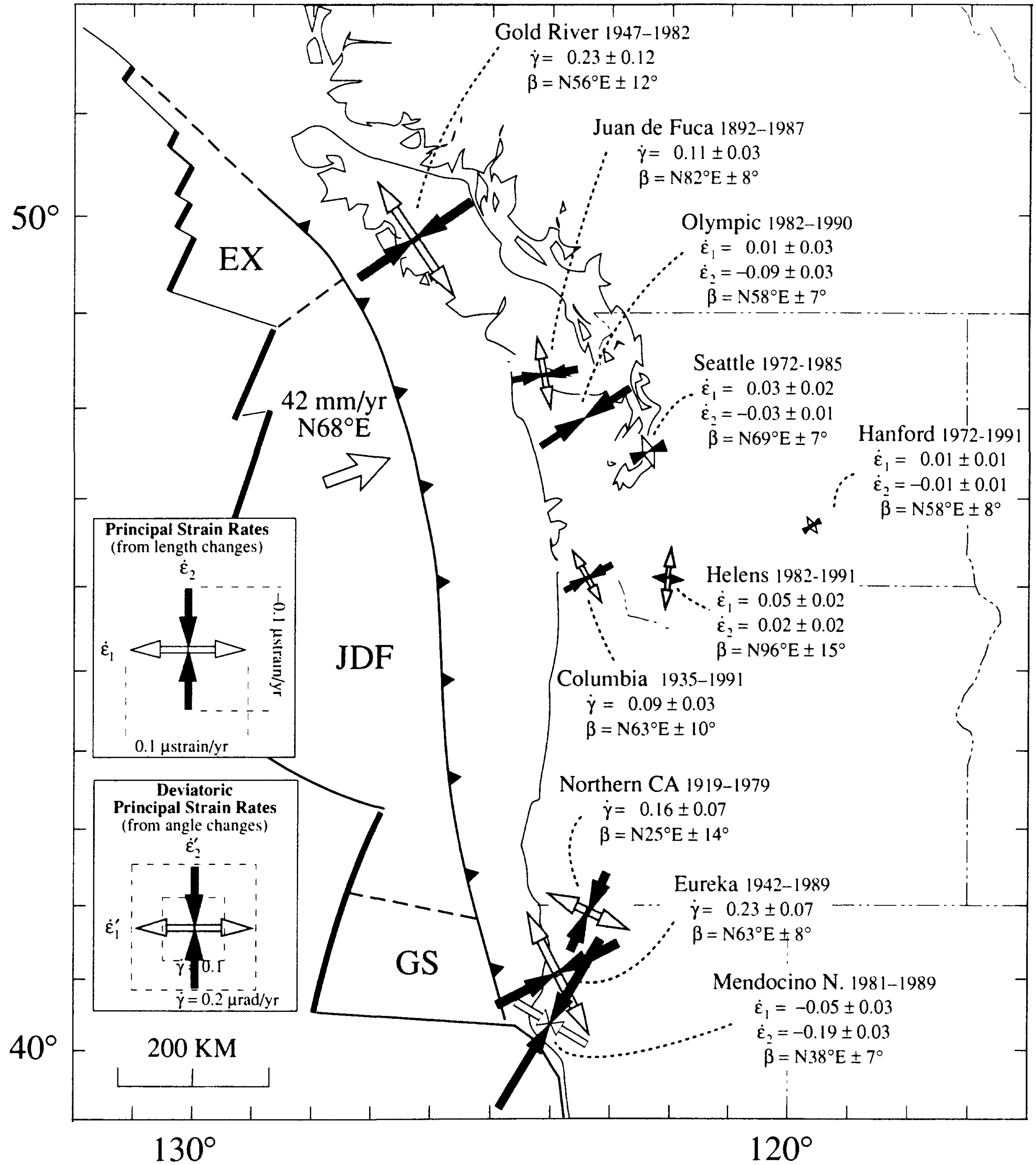


Figure 12. Map showing the average strain accumulation rates (ppm/yr) along the Cascadia subduction zone inferred from repeated geodetic surveys. Areas covered by geodetic networks are shaded, and the magnitude and directions of the deviatoric or principal strain rates are represented with arrows. The network labels give the times of the initial and final surveys, the principal strain rates (e_1 and e_2), the total shear (g $_1$ = e_1 - e_2; deduced from angle changes), and the direction of maximum contraction (b). The convergence rate and direction of the Juan de Fuca plate (JDF), relative to North America (DeMets and others, 1990), is shown on the JDF. The dashed lines in the JDF mark the boundaries of the Explorer (EX) and Gorda South (GS) subplates (Riddihough, 1984). The strain rate for northern California is from Drew and Snay (1989). Savage and others (1991) and Savage and Lisowski (1991) present a discussion of strain accumulation in the Olympic and Seattle networks along with a dislocation model for the Cascadia subduction; other strain accumulation rates are from unpublished Canadian Geological Survey and USGS data.

arc region. Locking of the shallow interface between the subducting Juan de Fuca plate and the overriding North American plate could produce the observed surface deformation. If the observed strain is a result of the elastic deformation of the Earth's crust from stuck plates, then the strain accumulated over hundreds of years might some day be released by one or more large earthquakes.

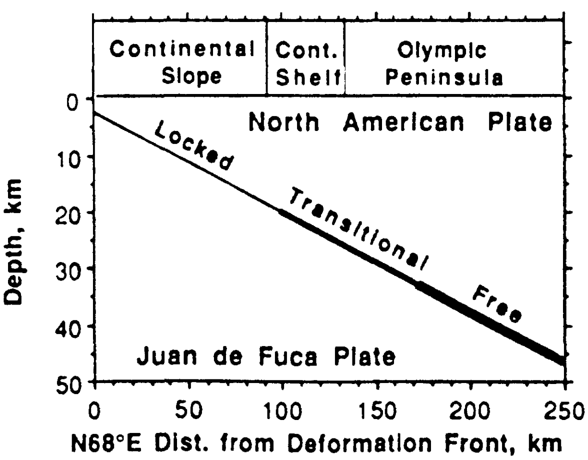


Figure 13. Simple dislocation of the Cascadia subduction zone through the Olympic Mountains along a trend N68oE (A-A' in Savage and others, 1991, fig. 1). The plate interface is divided into locked, transitional, and freely slipping zones. From Savage and others (1991, fig. 10).

At Cape Mendocino, a clear transition separates right-lateral shear on the order of 20 mm/yr south of the Cape to northeast directed contraction at rates of about 0.2 ppm. G.Carver says that this area has been contracting at this rate since the late Pleistocene. The Cape Mendocino event occurred in the zone of transition. Deviatoric principal strains from triangulation in the Eureka basin the show eastnortheast axes of principal contraction for the period 1940's through 1989.

P.SOMERVILLE, of Woodward-Clyde Consultants, Pasadena, California, discussed the process of modeling strong ground motion (Appendix C) and introduced the rationale for some recent changes in the Uniform Building Code seismic zonation map in the western part of Oregon, and a likely similar change in coastal Washington, from Seismic Zone 2B to zone 3. The change to zone 3 requires more accounting for ductility for long-duration motion and enhances survivability of structures during subduction-earthquake-type motions.

The three seismic sources present in the Pacific Northwest include events on the plate interface, deep, Wadati-Benioff zone events, and shallow crustal events. The depth at which the plate interface can no longer be a seismic source is important and **P.SOMERVILLE** would place it at about 40 km, but acknowledges that M.Lisowski just depicted the position further west at a shallower depth. Thus, for modeling, one needs to consider the slip occurring on deep, intermediate, or shallow parts of the interface.

Strong motion data from two M8 events give us some idea of possible strong ground motion (Somerville and others, 1991). The shallow dip (about 10^{o}) of the zone at Michoacan, Mexico, and the position of the shoreline make that 1988 event an appropriate model for events in the Washington state part of the PNW (Figure 14), and the 1985 Valparaiso, Chile, event presents a good model for Oregon, where the dip is about 20^{o}.

Two empirical attenuation relationships for a M8 subduction

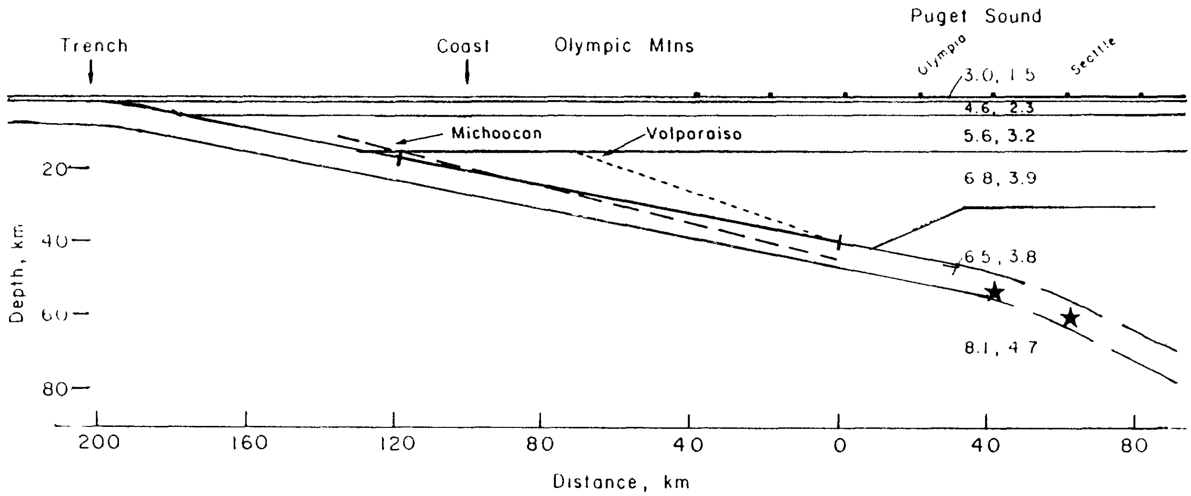


Figure 14. Vertical section through the western Washington zone showing the location of the plate interface. The rupture zones of the 1985 Michoacan and Valparaiso earthquakes are superimposed for comparison. The 1949 Olympia (54 km depth) and 1965 Seattle (60 km depth) earthquakes in the Wadati-Benioff zone are shown by stars. Figure from Cohee and others (1991, Figure 3).

event that incorporate recordings of these events by Youngs and others (1988) and Crouse (1991) are compared (Figure 15) with our (Cohee and others, 1991) numerical modeling results, calibrated against this data and using the specifics of the geometry of the CSZ. The peak accelerations reach about 0.3 g for rock and about 0.6 g for coastal soil site about 20 or 25 km above the subduction zone. Due to the greater width of the fault zone and greater depth of the source, these motions are slightly larger than the peak accelerations of a M8 crustal event.

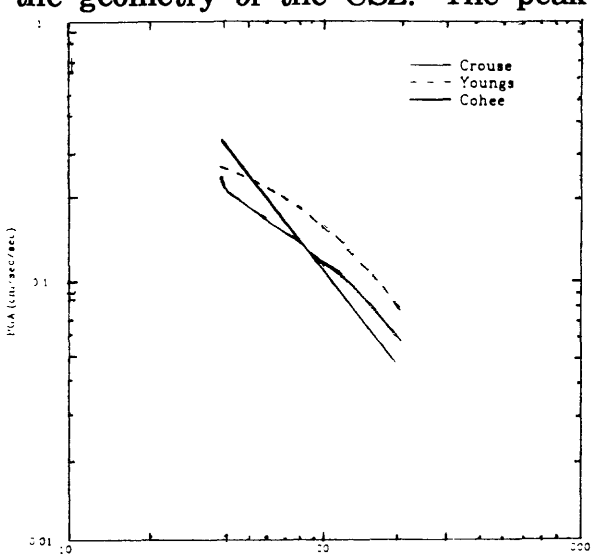


Figure 15. Attenuation of peak acceleration on stiff soil for a M8 subduction earthquake for three models: one from numerical modeling (Cohee and others, 1991) and two from regression of recorded data (Crouse, 1991; Youngs and others, 1988).

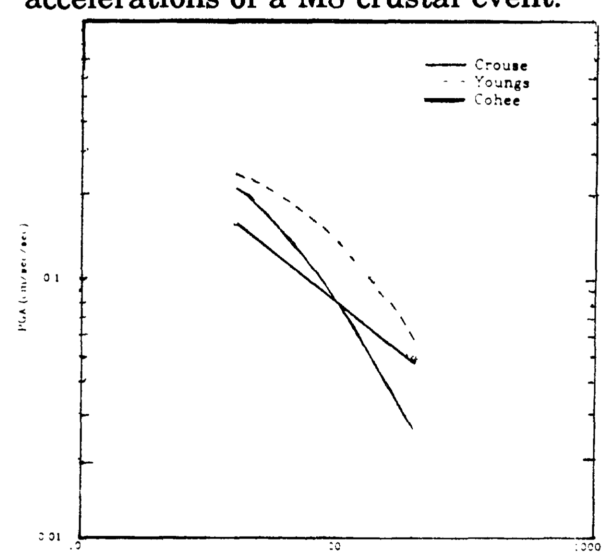


Figure 16. Attenuation of peak acceleration on stiff soil for a M6.75 Wadati-Benioff zone earthquake for three models: one from numerical modeling (Somerville and others, 1992) and two from regression of recorded data (Crouse, 1991; Youngs and others, 1988).

The results of the Cape Mendocino events will be studied carefully because they may be the first local records for subduction-type events in the PNW. Preliminary analysis of an instrument at a soil site near Petrolia reveals a very large motion (0.7 g) at a period of about one second; a record on bedrock at Cape Mendocino shows so far inexplicably large spikes.

Models of attenuation for the Wadati-Benioff zone events with a M6.75 (similar in size to the 1949 and 1965 events) show slower attenuation compared to crustal events of the same size his is due to the greater depth of the intraplate events in the subducting plate.

A subduction zone event, M8, would produce spectral accelerations with a factor of about 2 larger than those recorded for the 1949 and 1965 events at a period of about one second. For longer period motions, local geometry and conditions significantly influence response spectra. For instance, using the San Fernando event as a model, waves from the west would be trapped by critical angle phenomena in the thickening basin edge, producing large motions in the deep part of the Portland basin, and escape out the thinning edge of the basin. This might result in a much longer duration of shaking and shows most dramatically using a 3-D finite difference model. It is particularly critical that we improve our understanding about how these long period motions will be influenced by the local basin fill and how they will interact with existing structures that may not have adequate ductility and with newer, larger structures that may be built in the urban areas of the PNW.

T.HEATON commented that several events the size of the Valparaiso or Michoacan events, which are on the low end of the size of the earthquakes that might be possible in the PNW, would be needed to fill the CSZ region and that perhaps it would be interesting to model the results of a single event rupturing the whole CSZ.

P.SOMERVILLE stated that predicting effects from M8 events was reasonably well known, but predicting the effects of larger events was more problematical. He agreed that the duration would be longer for the larger event, and, for events larger than M8, shaking might go on for several minutes in some of the taller buildings in Seattle, but that the high frequency motions wouldn't necessarily be larger.

R.WELDON briefly summarized recent attempts to understand the overall pattern of ground motion using a geographic information system (GIS) data base involving various sources, various attenuation relationships, local strain, and local basin fill and geometry in order to determine regional differences in ground acceleration or velocity (Figure 17). Possible seismic sources include a locked portion of the CSZ as defined from the geodetic data, the 1949 and 1965 crustal events in the downgoing slab, and several Holocene basin and range faults (Pezzopane and Weldon, 1993) that may produce events in the M6-7 range.

The combination of these data with any one of several empirical relationships can be used to model earthquakes and derive maps depicting peak basement acceleration (Figure 18), peak velocity maps (Figure 19), peak duration maps (Figure 20), and probabilistic hazard (Figure 21) and risk maps (Figure 22). The models can be improved as new data become available.

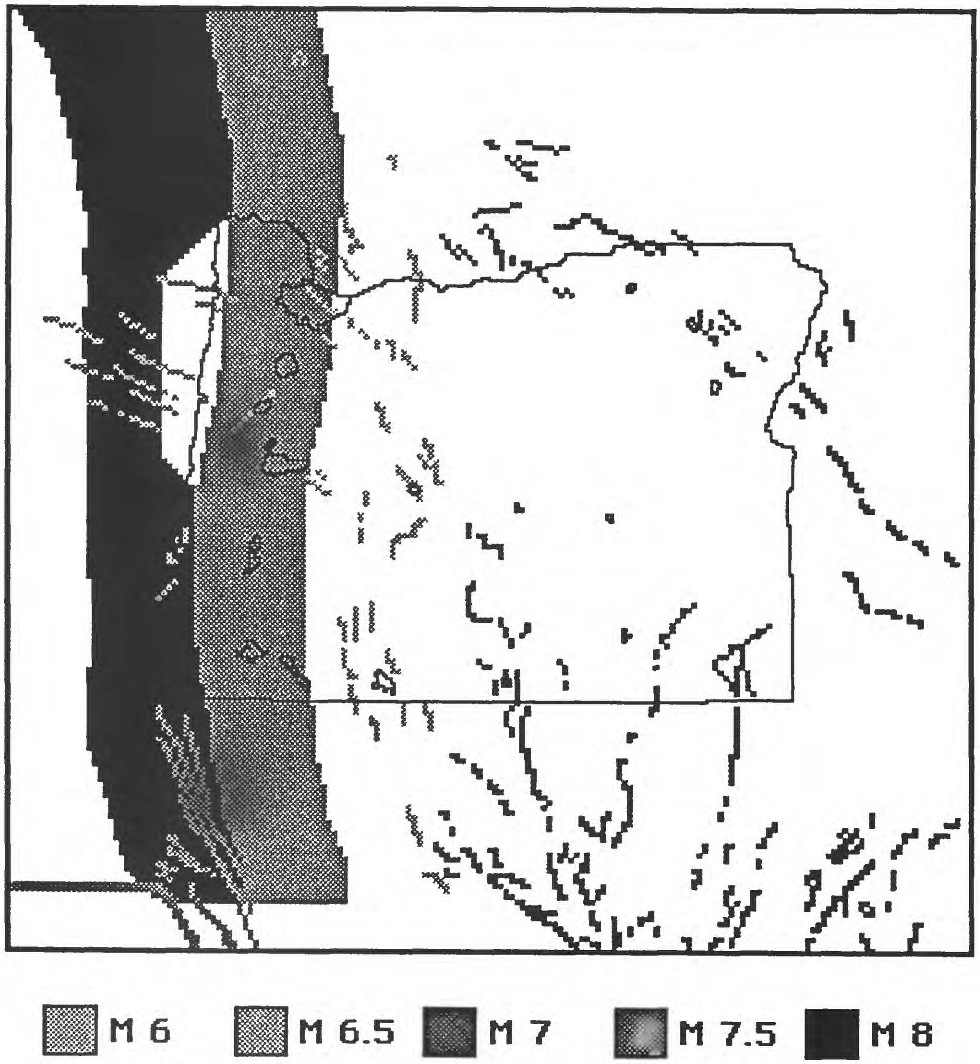


Figure 17. Map of earthquake source zones and expected magnitudes from geographic information system data base showing the spatial distribution of map elements considered as potential sources of large-magnitude earthquakes. Sources in the Willamette Valley and the Cascades are characterized by M6 events, the coastal and offshore faults are thought to be sources for M6.5 events, whereas all active faults in the eastern half of the State are considered sources for M7 events. The San Andreas fault zone and slab-bending zone are considered sources for M7.5 earthquakes, whereas the subduction zone accommodates M8 events. The long-term slip rate for each source zone is estimated from a kinematic model that partitions the strain associated with motion of the Pacific, North America, and Juan de Fuca plates onto the zones. The contour of >200 persons/km^2 is shown for selected population centers.

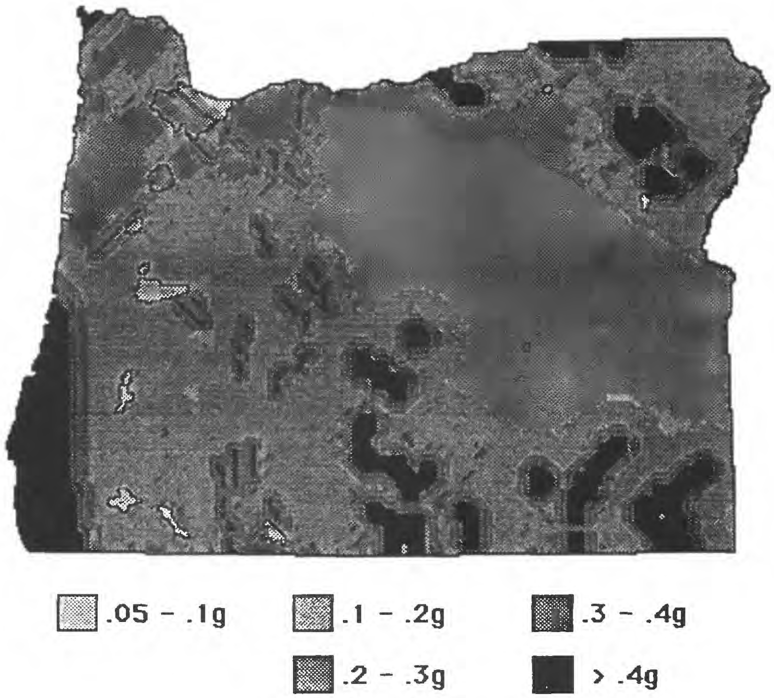


Figure 18. Contour map of the randomly oriented horizontal component of peak acceleration at bedrock sites in Oregon, exceeded at the 5% probability level during any 100-yr period including historic seismicity. Acceleration values are based on the lengths and slip rates of active faults, magnitude-frequency data from historical seismicity, and the predictive equations of Joyner and Fumal (1985). A background of accelerations due to probability levels estimated from the b-value of historic seismicity is used where it exceeds the levels of shaking as a result of mapped faults.

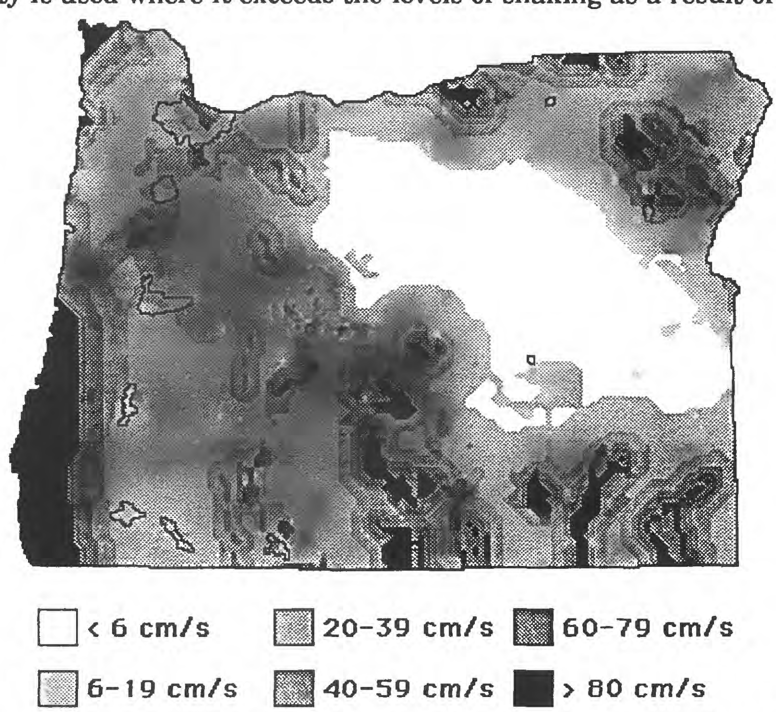


Figure 19. Contour map of the randomly oriented horizontal component of peak velocity including amplification, exceeded at the 5% probability level during any 100-yr interval. Velocity values are based on the lengths and slip rates of active faults and the predictive equations of Joyner and Fumal (1985).

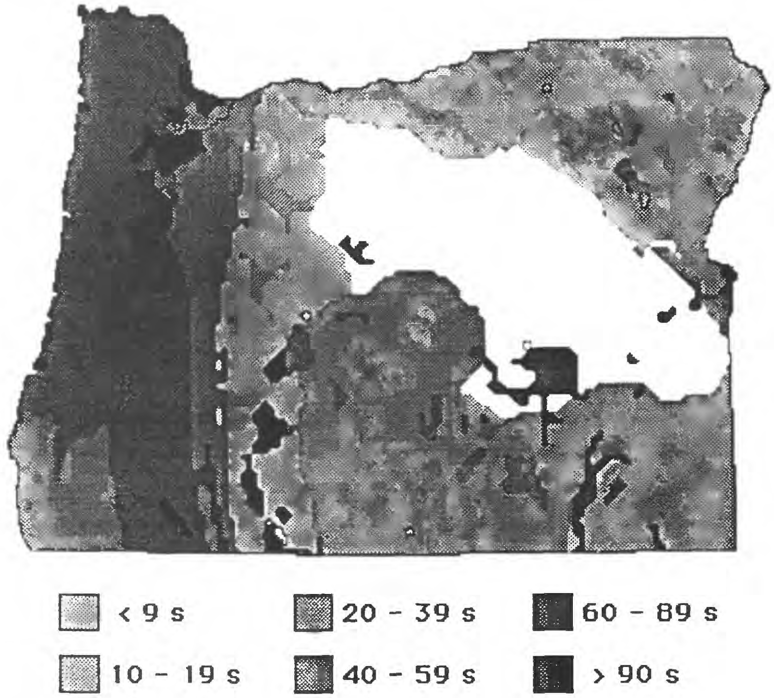


Figure 20. Duration of shaking at sites with >6 cm/s peak velocity including amplification. These values are assumed to be amplified by geological units. Duration is described as the sum of the earthquake rupture duration (a function of magnitude and fault dimensions) and the difference between the fastest and slowest waves arriving at a site ({1/Vs-1/Vp} multiplied by source to site distance). Shaking would exceed 60 s in and near most populated areas of Oregon.

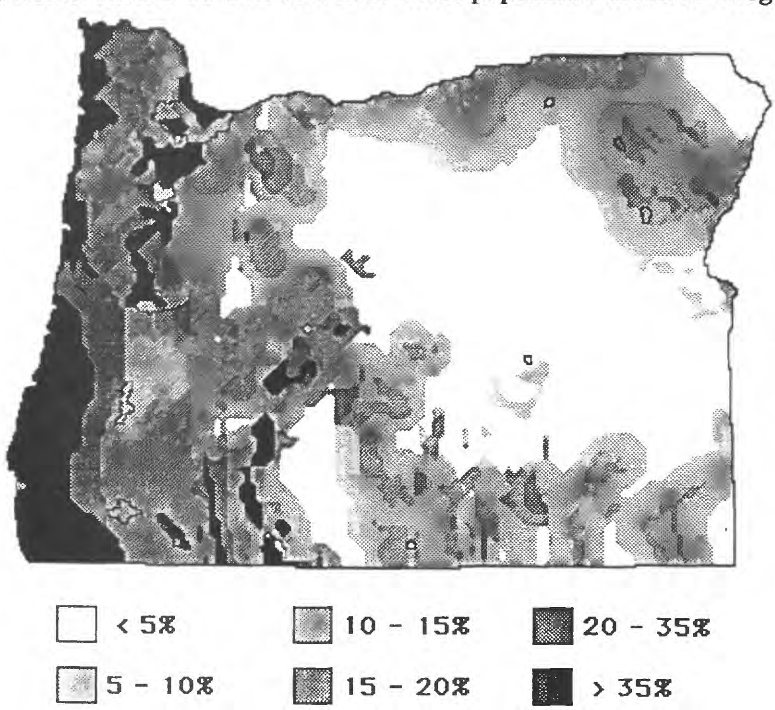


Figure 21. Map of probability in any 100-yr interval that earthquakes in Oregon will produce peak horizontal velocities that exceed 20 cm/s taking into account amplification by geologic units, fault sources, and regional strain model. Forty percent of Oregon has >10 percent chance of peak horizontal velocity >20 cm/s.

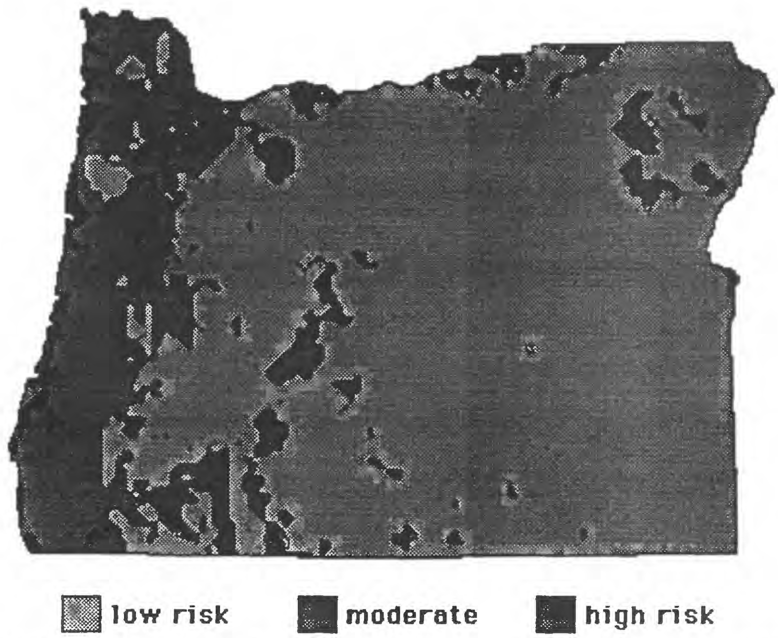


Figure 22. Map of the potential risk from strong ground shaking as a result of earthquakes associated with active faults in Oregon. Population density was multiplied by the probability of exceeding 20 cm/s peak velocity including amplification. High risk areas have probability values >15 percent and population density>200 persons/km^2 and probabilities >20 percent and population density of 1 to 200 persons/km^2. Roughly 80 percent of population resides within a high risk area.

I.MADIN of DOGAMI in Portland presented an overview of seismic hazards in Portland and the rationale for the first generation of hazards maps for the area. Both the public and the policy makers are sufficiently aware of the work done over the past decade and they have reached a consensus that something must be done to address the hazard. Although many uncertainties exist, we are using compilations of existing and new information to provide the basis for a rational start to mitigation activities.

Most of the earthquakes that have been felt in Oregon have occurred in the Portland area. Although many faults have been mapped there, none are known to have been the source of any of these crustal earthquakes. In fact, because we have been unable to prove that any of these faults have moved in recent times, it is difficult to differentiate which areas are most at risk within the Portland urban region. Therefore, the approach has been to look at local soil conditions as a predictor of potential damage during future earthquakes.

Several maps have been produced during this investigation. One depicts areas underlain by 30 feet or more of unconsolidated sand, silt, or clay. Another shows the distribution of saturated Holocene and Quaternary alluvium that may be a potential liquefaction hazard; still another shows moderately steep slopes with a significant cover of loess.

In order to better communicate with the planning community, we are producing a relative earthquake hazard map. We are fairly confident that we can obtain a good generalization of the local conditions in order to produce a detailed, three-dimensional geological, geotechnical model using these and additional data. The map will present the relative probability of amplification, liquefaction, and production of landslides on a 90 m grid cell. This will give our local planners the basis with which to determine how to concentrate their resources, where to prioritize retrofit activities, and where to avoid siting of critical structures, as well as to make other decisions about mitigation.

R.YEATS from Oregon State University briefly presented the results of recent investigations delineating possible seismic sources in the northern Willamette Valley. These include: a major structure that trends northeast from the Coast Ranges, through Corvallis, across the Salem Hills, into the frontal part of the Waldo Hills to the northeast; a series of faults east of Corvallis that show Holocene displacement; and the Mount Angle structural zone, which produced earthquakes near Woodburn in 1990. Seismic, aeromagnetic, and gravity data from the Tualatin basin just west of the Portland Hills indicate the presence of two major structures, the Beaverton and Helvecia fault zones, in the most rapidly growing urban area in the State. Slip rates will be relatively low on these structures, however, and we have no evidence that they affect Holocene units. While the PNW has three types of earthquake sources, careful investigations can significantly improve our understanding of possible local seismic sources.

J.BEAULIEU of DOGAMI presented NEPEC with his perspective as a science manager in a State agency. In simple terms, the State wants to define the risk in a manner that the nontechnical community can understand so that individuals in that community can make rational personal and communal decisions about how to address the risk. In other words, how would the information presented to NEPEC get translated into positive action? (See Appendix D)

Several important events have occurred in Oregon during the last few years. In 1990, an Executive Order created the Seismic Safety Policy Advisory Commission, and Senate Bill 96 put the Executive Order into law. This advisory commission presents advice to key policy makers and legislators; its outreach and education effort is long-term in nature. The first White Paper from the Commission addressed research needs for the State of Oregon.

In spite of the relative youthfulness of the State's earthquake program, we probably have one of the best frameworks for using the results of earthquake hazards research in the country. One major State planning goal mandates that all jurisdictions in the State must identify and plan for geologic hazards.

You have heard today about the change from seismic zone 2B to zone 3 for many parts of the State. In addition, within any seismic zone in the State, the Building Code Commission has additional directives that require specialized seismic protection for critical facilities or high occupancy structures.

In response to a question concerning the possible tsunami hazard from **T.HEATON, J.BEAULIEU** indicated that the Department was trying to find federal funding to undertake a credible investigation of the problem, including modeling, planning, education, zonation, and warning systems.

- PAGE 33 FOLLOWS -

May 7, 1992
Afternoon Session

Presentation of the following posters started the session:

Beeson, M., Tolan, T.L., and Madin, I.P., Structure of the Tualatin Mountains.

Carver, G.A., Paleoseismicity of the Gorda Segment of the Cascadia Subduction Zone.

Lisowski, M., Savage, J.C., and Prescott, W.H., Geodetic Studies of the Cascadia Subduction Zone.

Madin, I.P. and Mabey, M.A., Seismic Hazard Mapping in the Portland Metropolitan Area.

Malone, S., Pacific Northwest Earthquake Hazards Based on Historical Seismicity.

Nelson, A.R., Jennings, A.E., and Kashima, K., Coastal Paleoseismicity Studies in the Coos Bay Area of Southern Oregon.

Trehu, A.M. et al, Crustal Structure of the Cascadia Subduction Zone Beneath Western Oregon.

Wells, R.E., Snavely, P.D., Jr., and Neim, A.R., Quaternary Thrust Faulting at Netarts Bay, Northern Oregon.

Yeats, R.S., Geologic Map of the Willamette Valley.

Yelin, T.S., Seismicity, Seismic Hazards, and Tectonics of the Portland, Oregon - Vancouver, Washington Region.

T.WALSH of the Washington Division of Geology and Earth Resources presented the framework for seismic hazards mitigation by the State in Washington (Appendix E). In 1990, the legislature passed the Growth Management Act which requires that rapidly growing jurisdictions, or those with large populations, prepare comprehensive plans and fit zoning patterns to those plans. Protection of sensitive areas is one of the required elements for the plan, and this includes seismic hazard protection. In 1991, the legislature amended the Growth Management Act and extended the hazards mapping requirement to all counties and cities.

In 1990, the legislature also established the Seismic Safety Advisory Committee which was to examine the preparedness of the State and present a plan for reduction of earthquake risk in December, 1991. The Committee completed a package that was sent to the legislature, but the tight fiscal situation precluded consideration of any of the recommendations. Some of the recommendations can be addressed, at least in part, with existing revenue.

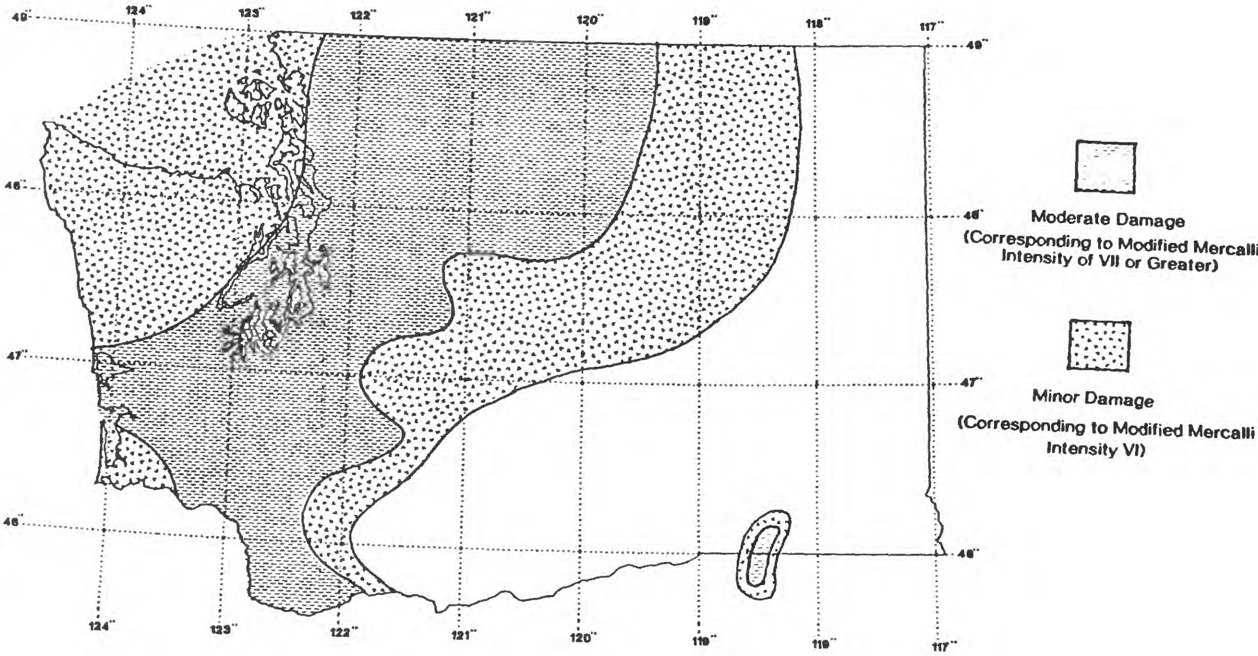
In particular, the Puget Sound Region Instrumentation Advisory Committee Study (USGS, 1989) included a plan for strong motion instrumentation at free-field sites and in buildings. This was not funded, but it is one of the recommendations of the Seismic Safety Advisory Committee plan, and we have been able to cooperatively fund instrumentation at a site in Olympia, Washington.

The State of Washington is coordinating with Oregon's modification of the Uniform Building Code seismic zone boundaries (which Oregon promulgated by the use of an administrative rule). All of western Washington and part of eastern Washington (to include the probable site of the 1872 earthquake) will be placed in Seismic Zone 3. The new zone boundaries have not been drawn, but they will have been in time for submission to International Conference of Building Officials. Washington has no intent to use an administrative rule to modify the zonation. Instead, the application will proceed as a joint proposal with the State of Oregon and will be implemented, if it is implemented, in the 1994 Uniform Building Code.

Several types of information supplied evidence for proposing the change in seismic zonation. Compilation of intensity data for six well-studied damaging earthquakes (Table 1) shows that all of western Washington (Figure 23a) has been subject to at least MMI VI damage and most of the state, in fact, has been subjected to MMI VII. We then postulated a M8.5 subduction zone earthquake and used an attenuation model (Crouse, 1991) to project accelerations and obtain damage zones from that event (MMI VII and above or 0.1 g zone) (Figure 23b). This material was recently adopted by the Structural

Table 1. Six damaging Washington earthquakes.

Earthquake	Location	Maximum MMI	Magnitude	References
1872	North Cascades	IX	7.0-7.5	Malone and Bor, 1979
1936	Milton-Freewater	VII	5.7-6.4	Neuman, 1938
1945	North Bend	VII	5.5-6.0	Bodle and Murphy, 1947
1946	Vancouver Island	VIII; VI in Washington	7.3	Rogers and Hasegawa, 1978
1949	Olympia	VIII	7.1	Murphy and Ulrich, 1951
1965	Seattle-Tacoma	VIII	6.5	Von Hake and Cloud, 1967



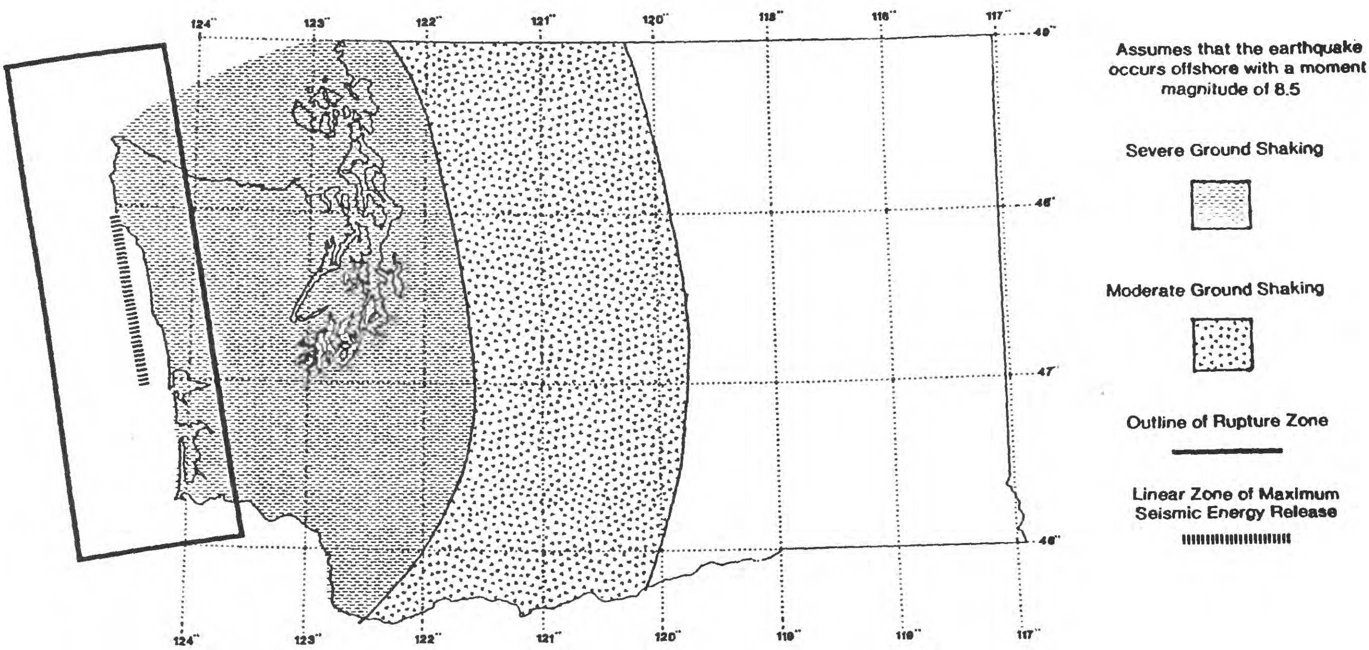


Figure 23. A. Areas damaged by six historic Washington earthquakes between 1872 and 1965. See Table 1 for events used for map compilation. B. Area exposed to strong ground shaking from a scenario Cascadia subduction zone earthquake, assuming a M_W 8.5 event located along bold dashed line using attenuation relation of Crouse (1991). Note different use of patterns in A and B.

Engineers Association of Washington to initiate the process of amending the building codes.

Support and coordination of the mapping of sensitive areas is another important activity. This supports the Growth Management Act and allows us to interact more closely with the Department Natural Resources and the growth management people and in cooperation with the USGS.

In support of this effort, we have produced small-area zonation mapping. For instance, the City of Puyallup (Palmer and others, 1991) is upstream from Tacoma on the Puyallup River, which drains Mount Rainier. During the 1949 earthquake, many localities underwent liquefaction; many of the houses reported basements filled with black sand. We have drilled numerous boreholes to determine liquefaction susceptibility. We also are producing a liquefaction susceptibility map of the Renton quadrangle.

In response to a question from **T.HEATON** concerning the possible tsunami hazard, **T.WALSH** indicated that no plan yet existed. Washington's Seismic Safety Plan delegated tsunami hazard activities to the Division of Emergency Management. No mapping scheme exists, but the State has discussed a proposal with the Federal Emergency Management Administration.

G.CARVER of Humboldt State University presented an update of research on the Gorda plate and introduced the three earthquakes that occurred near Cape Mendocino on April 25 and 26, 1992.

About half-way between Crescent City and Eureka, the fold-and-thrust belt of the subduction zone comes ashore (Figure 24). As one progresses south, one crosses a number of very large thrusts before the belt dies out at the Eel River. South of the Eel, these structures are no longer expressed in the large area of increasing uplift of the very thick sequence of the late Pliocene or earliest Pleistocene shallow marine Wildcat Group, which is about 4 km thick. These sedimentary rocks overlie melanges of the False Cape shear zone (sensu lato) which contain very young blocks of material, perhaps as young as late Pliocene or early Pleistocene. These melanges were subducted and deformed by Juan de Fuca-Gorda plate subduction before the arrival of the triple junction and have been uplifted and exposed in the last million years.

Uplift rates, based on marine terraces, fluctuate as one traverses the fold-and-thrust belt, with subsidence stratigraphy in the cores of the synclines. South of the Eel River, uplift has been relatively continuous until one gets south of the King Range. Sparse age determinations from the youngest emergent terrace at Cape Mendocino indicate that they are less than about 3,000 to 4,000 years old. Individual strand lines that may indicate significant subduction zone earthquakes in the region are overlain by debris fans that have yielded determinations of about 300, 1100, and 1700 years, ages not dissimilar to those on the Oregon and Washington coast. Buried forests from the Eel River basin also yield dates indistinguishable from those on the southern coast of Washington.

Background seismicity, available from a network of 16 stations operated along the coast between 1974 and 1984, has helped define the plate boundaries and geometry. (Figure 25) This data allows us to see the top of the Gorda plate in cross section, as well a double layer of events that may indicate the Gorda plate is stacked or doubled.

As shown in this somewhat interpretive crustal cross section (Figure 26) based in part on the long-

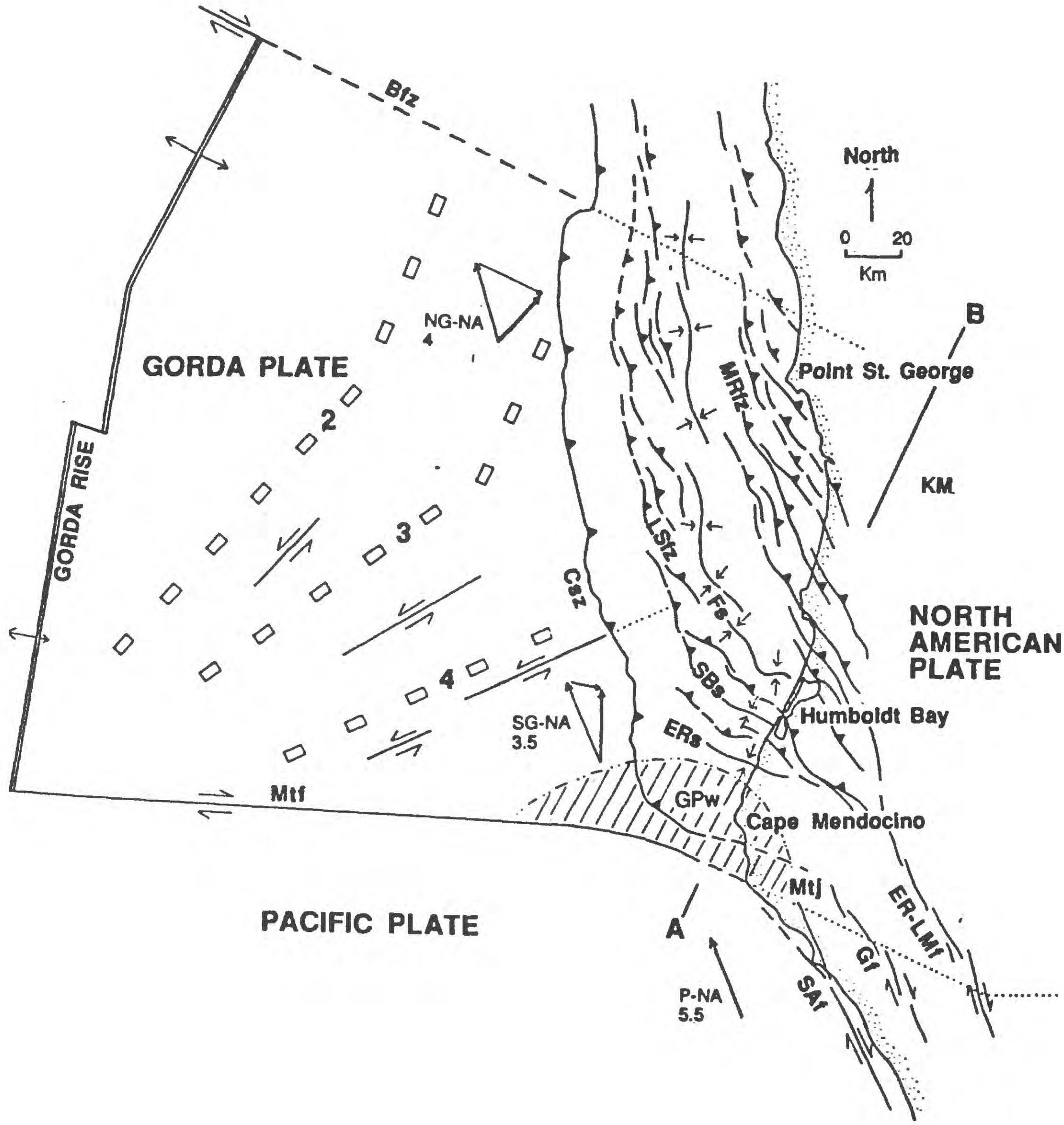


Figure 24. Plate tectonics map of the Gorda plate and segment of the Cascadia subduction zone. Lines of open rectangles indicate the position of sea floor magnetic anomalies which show rotation of the southern part of the plate and decreased spreading at the south end of the Gorda rise. These internal plate motions have resulted in decreased convergence at the south end of the subduction zone as shown by the vector-rate diagrams depicting northern Gorda (NG-NA), southern Gorda (SG-NA) and Pacific (P-NA) motions relative to a fixed North American plate. Convergence between the Gorda and Pacific plates results in compression and thickening of the southeast edge of the subducting oceanic slab and generated the Gorda-Pacific wedge. Symbols: Bfz-Blanco fracture zone, Mtf-Mendocino transform fault, Csz-Cascadia subduction zone, MRfz-Mad River fault zone, LSfz-Little Salmon fault zone, Fs-Freshwater syncline, SBs-South Bay syncline, ERs-Eel River syncline, Mtj-Mendocino triple junction, SAf-San Andreas fault, Gf-Garberville fault, ER-LMf-Eaton Rough-Lake Mountain fault, GPw-Gorda-Pacific wedge, KM-Klamath Mountains.

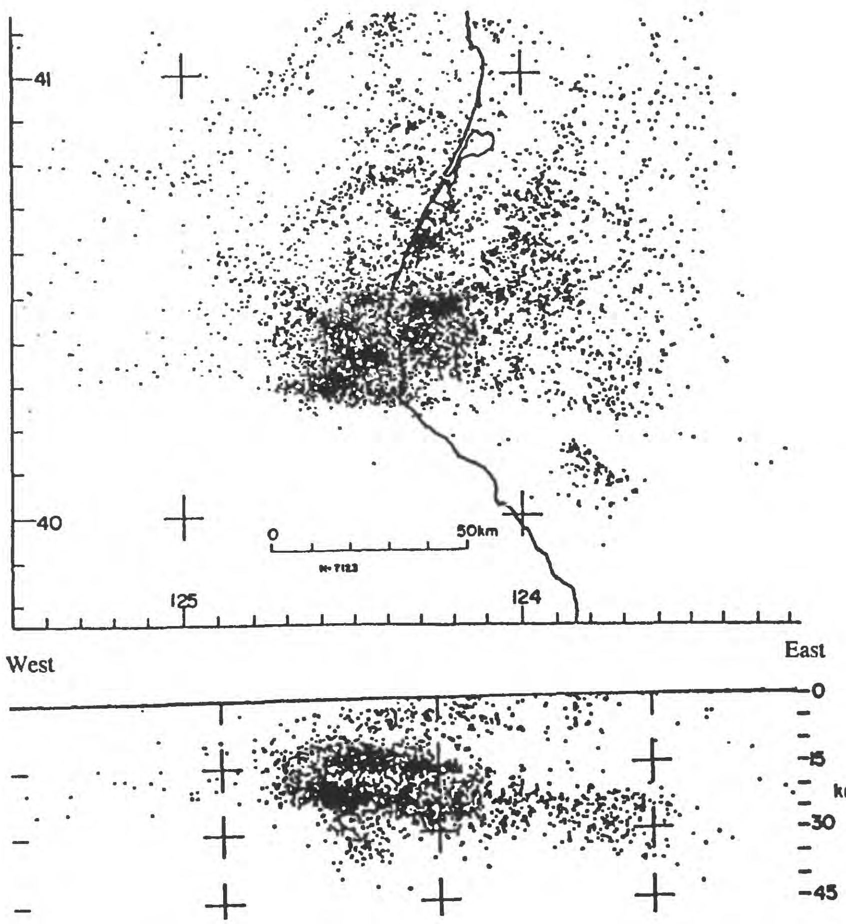


Figure 25. Gorda plate seismicity in the Cape Mendocino region 1974-84 (McPherson, 1989). Earthquakes recorded by the 16 station Humboldt net define the plate geometry near the triple junction. The map shows Gorda plate seismicity extending inland more than 75 km., with a concentration of many epicenters in the region around Cape Mendocino. The April 25, 1992, earthquake was located in this region of high seismicity. The Mendocino fault between the Pacific and Gorda plates is well defined by many earthquakes. In the east-west cross section the oceanic plate with the double seismic layers can be seen dipping at a shallow angle to the east. The upper bound of seismicity in the subducted slab in sharp and the dense Gorda plate seismicity contrasts with the more scattered activity in the accretionary wedge of the North American plate.

term seismicity and surface geology along the coast, the Gorda plate thickens somewhat at its southern end, as it buttresses against the Pacific plate. It looks as if the M6.9 earthquake of April 25, 1992, occurred along the bottom of the thickened ramp. Slip appears to have occurred along the plate boundary or close to it, where the boundary is a bit steeper than we normally think, somewhere between 20^{0} to 25^{0} instead of 10^{0} to 12^{0}.

The event occurred at or near the megathrust boundary about 10 to 15 km north of the junction. Rupture originated onland at a depth of about 15 km and surfaced partially offshore and partially onshore, and aftershocks formed a nearly square

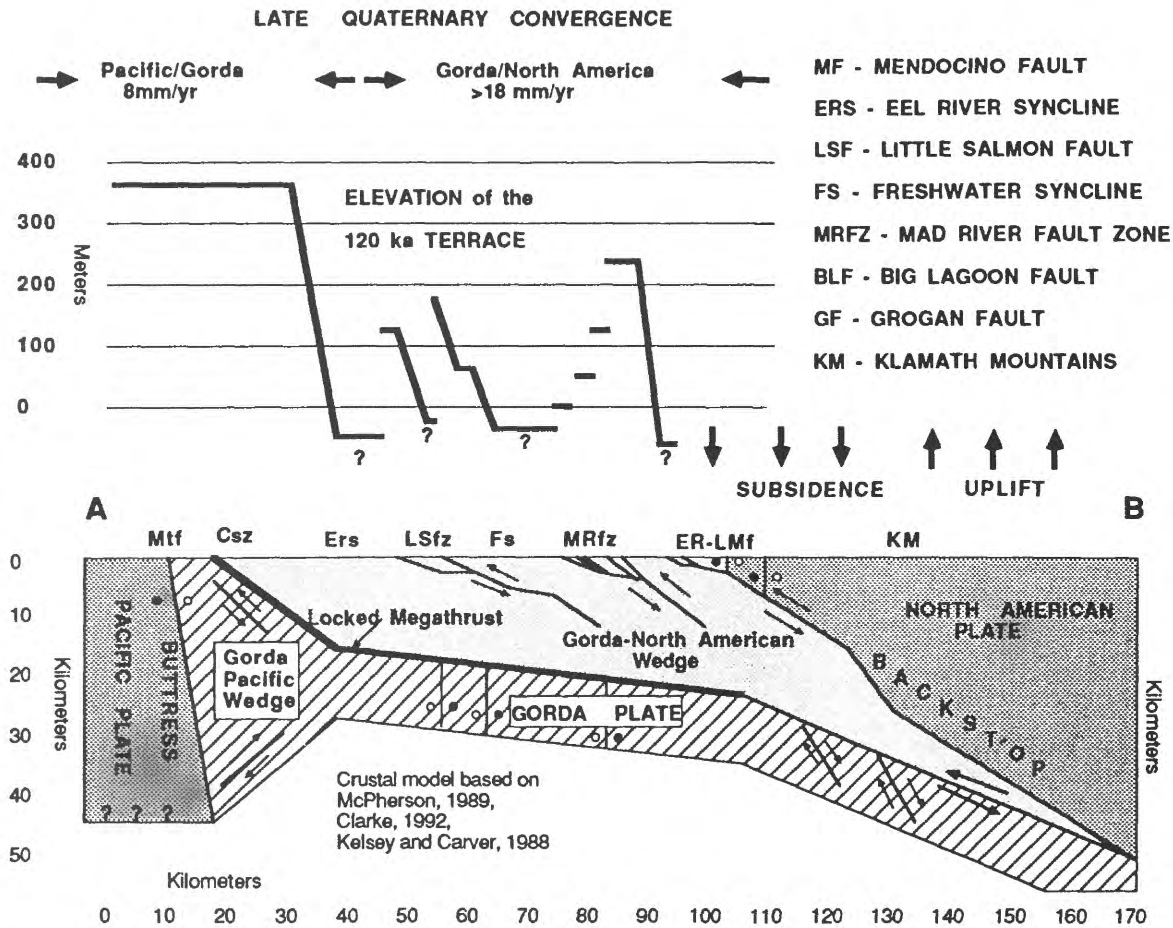


Figure 26. Interpretive cross section showing possible plate geometry and crustal structures across the southern end of the subduction zone (A-B on Figure 24). Internal deformation of the southern end of the Gorda plate where it is buttressed against the Pacific plate has resulted in thickening and produced the Gorda-Pacific wedge. Uplift above the thickened subducting slab is the highest in the region. North of the triple junction region, thrusting and folding in the overriding North American plate (Gorda-North American wedge) has elevated and deformed glacio-eustatic marine terraces, allowing estimation of late Pleistocene convergence rates

pattern at the top of the plate. We looked for high intensity shaking effects along the trend on which the steeper of the two planes of the focal mechanism might daylight. Since we found no evidence for such shaking, the geologic evidence supports the occurrence of the event on the shallow, east-dipping plane.

The M6.5 and M6.7 events occurred within four hours of one another in the Gorda plate very close to the boundary between that plate and the Pacific plate, along a fault that does not cross the plate boundary. The aftershock sequence formed a broad area in the subducting slab.

Preliminary impressions from field work immediately after the recent earthquakes allowed **G.CARVER** to present a general assessment of isoseismal effects (Figure 27). Effects were rather uniform over a very large area. Quite strong ground motions affected the region from the Eel River valley to south of Petrolia. Significant landsliding occurred; many landslides were small, but large

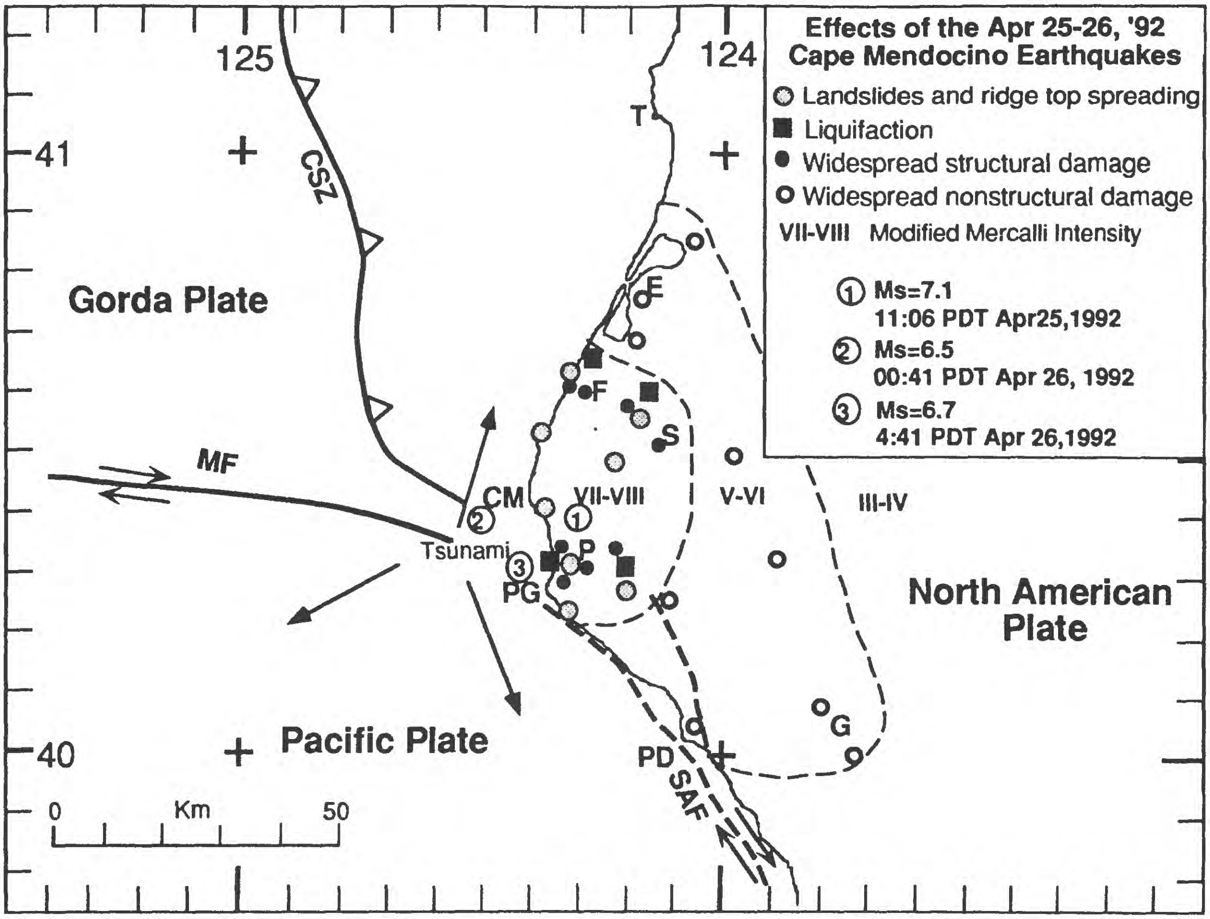


Figure 27. Isoseismal effects of the Cape Mendocino earthquakes. Geologic effects of the earthquakes included numerous landslides, ground cracks, and ridge top failures. Liquefaction was common along the lower Mattole and Eel Rivers and in the Eel River valley. Many structures were damaged or destroyed at Ferndale (F), Scotia (S), and in the Petrolia (P) area. Non-structural damage was common from Eureka (E) south to Garberville (G) and Point Delgada (PD) on the coast. Structures in Trinidad (T) sustained no damage. Maximum MM intensity was about VII to VIII over a large area between Ferndale and Petrolia. A small tsunami was generated along the coast in the vicinity of Cape Mendocino (CM) to Punta Gorda (PG).

failures occurred in the sea cliffs along the coast, especially near Ferndale and Centerville Beach, as well as in "native" slopes that had not been logged or disturbed in the center of the isoseismal region. Liquefaction was generally restricted to small sand blows and minor spread failures, but, where it occurred, these features were numerous. Throughout the Eel River valley, the occurrence of these effects was widespread.

While virtually no structures exist in the large central region of the event, significant structural damage occurred along the south edge of the Eel River valley and in the Petrolia area. A somewhat larger area yielded less damage, including common reports of items toppling from shelves and windows breaking. On this basis, we have assigned preliminary MMI intensities of about VII to VIII for the large central area and V to VI for the more extensive surrounding area.

D.OPPENHEIMER, of the USGS in Menlo Park, presented a preliminary interpretation of the Cape Mendocino earthquake sequence. The network in northern California consists of stations operated by the USGS and the Terra Corporation (1974 to 1983) (McPherson, 1989). Most well-located events (Figure 28) prior to the April 25th earthquake occurred offshore. These events may be less-well located than those onshore because all the seismic stations are sited onshore. The Mendocino triple junction has one of the highest densities of earthquakes in California. The seismicity terminates abruptly south of the Mendocino fracture zone in the Pacific plate. This pattern reflects the relative component of convergence between the Gorda and Pacific plates such that east of the triple junction the stress is relieved and the seismicity within the subducting Gorda plate terminates. In terms of spatial density, arguably more large earthquakes have occurred here than any other locale in California, with 9 events greater than M5, not including the three under discussion, occurring here since 1979. The map view is somewhat misleading because it depicts seismicity in the North American plate as well as seismicity due to internal deformation in the Gorda plate.

Four cross sections (Figure 28b) show earthquakes relocated using data from the regional network and clearly depict the subducting Gorda plate. The width is about 10 to 15 km, and the plate has a shallow dip of about 10^0. Since the width of the shallow portion of the Gorda plate is about 150 km, we can get some idea of the area that might be involved in a subduction zone earthquake. Events become sparse where the dip of the plate increases, reaching depths of about 75 km below the Central Valley. A north-south section would show the plate thickening at the triple junction.

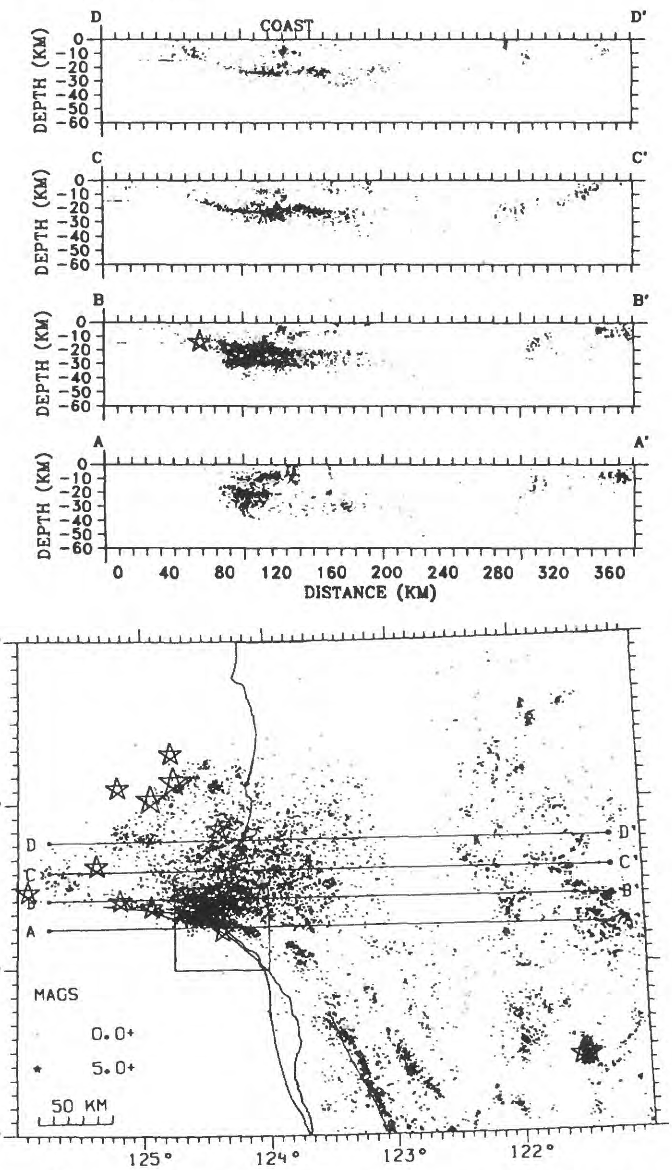


Figure 28. Maps and cross-sections of seismicity at the Mendocino triple junction and northern California since 1974 (but preceding the Cape Mendocino earthquake sequence) located from data recorded by stations of the USGS Northern California Seismic Network and the Terra Corporation. Cross section endpoints are depicted in map view. Width of cross-sections is ± 10 km. The small box depicts the boundaries of Figures 29 and 30.

A few selected focal mechanisms, from P-wave first motions, for large events in the region (Figure 29) reveal some of the complications endemic to the region. A focal mechanism for the December 21, 1986, M5.2 event indicates right-lateral motion on a vertical structure subparallel to and north of the Mendocino fracture zone. In addition, a nearby M5.7 event on July 3, 1987, indicates a source with left-lateral motion parallel to a lineation of earthquakes, similar to the mechanism of the Eureka earthquake of 1980. These events are thought to occur because of a component of relative convergence between the Pacific and Gorda plates that results in north-south compression within the Gorda plate. This compression is relieved in left-lateral rather than right-lateral faulting because of preferred zones of weakness inherited from the spreading ridge. In contrast, the M6 Honeydew earthquake, which occurred on August 17, 1991, at a depth of 11 km south of the junction of the Mendocino fracture zone had a focal mechanism indicating reverse faulting oriented parallel to the coast. These mechanisms illustrate the complex deformation taking place at the triple junction.

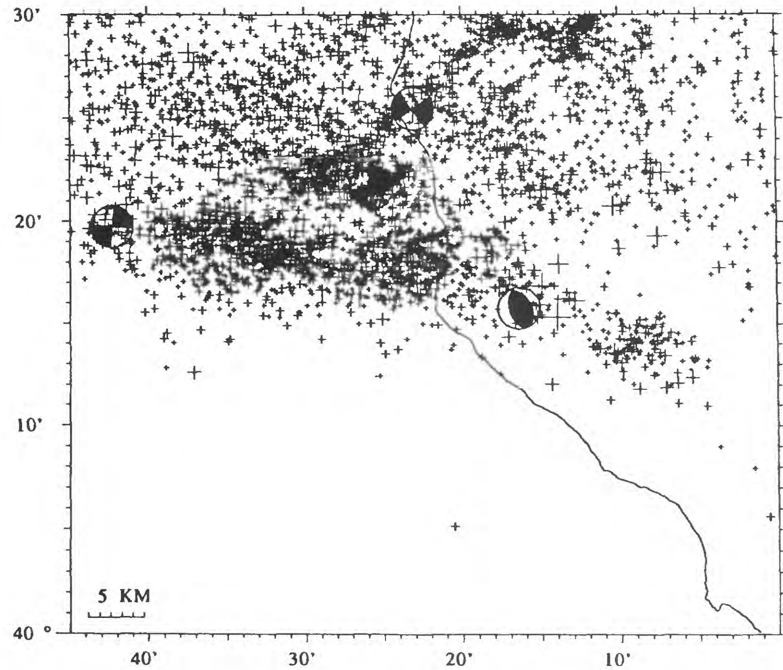


Figure 29. Map of seismicity in the vicinity of the Mendocino triple junction. Lower-Hemisphere, equal-area, fault-plane solutions are shown for the 12/21/86, 7/31/87, 9/21/89, and 8/17/91 earthquakes. Note that the seismicity trends define the slip planes of the focal mechanisms for the 11/21/86, 7/31/87, and 9/21/89 events. Sources same as Figure 28.

Using centroid moment tensor solutions from Caltech, the first earthquake had a reverse mechanism on a plane dipping about 23^o to the northeast and an auxiliary plane dipping steeply to the southwest (Figure 30). The Harvard solution for the main shock has a solution with a shallower dip, about 10^o. The two after shocks have left-lateral motion on northeast planes or right-lateral motion on northwest planes.

The main shock occurred at a depth of about 10.6 km, apparently at the interface between the North American and Gorda plates. Most of the aftershocks occur offshore. The depths of the two large aftershock are approximately 20 km, indicating that they occurred within the Gorda plate. The aftershocks are bounded on the south by the Mendocino fracture zone, on the east by the main shock epicenter, on the north by a northwest trending band of seismicity, and on the west by the two large aftershocks.

Aftershocks clearly delineate the shallow dipping thrust plane of the mainshock as well as the northwest striking plane of the second large aftershock. No appreciable seismicity that would define the slip plane is associated with the first large aftershock.

With the exception of the two big events, the temporal aspects of the aftershock sequence appear to be normal. The patterns for the second day appeared to be very similar to the first, but the third shows decay in seismicity. The aftershock rate actually falls off a little more rapidly compared to other main shock sequences in California. Generic aftershock probabilities (Reasonberg and Jones, 1989) for a M7.1 indicate a 95 percent probability for a M5 or greater earthquake within the first week. Based on the decay of aftershocks, we can update the probabilities. As of the date of this presentation, a 20 percent probability exists for the occurrence of a M5 and 3 percent probability exists for a M6.

The waveforms and associated spectra for the mainshock and the two large aftershocks are compared in Figure 31. Because the source-to-station paths are nearly identical for all three events, the extreme variation in spectral content can be attributed to differences in source characteristics, such as directivity. Moreover, the location and mechanism of the two aftershocks are

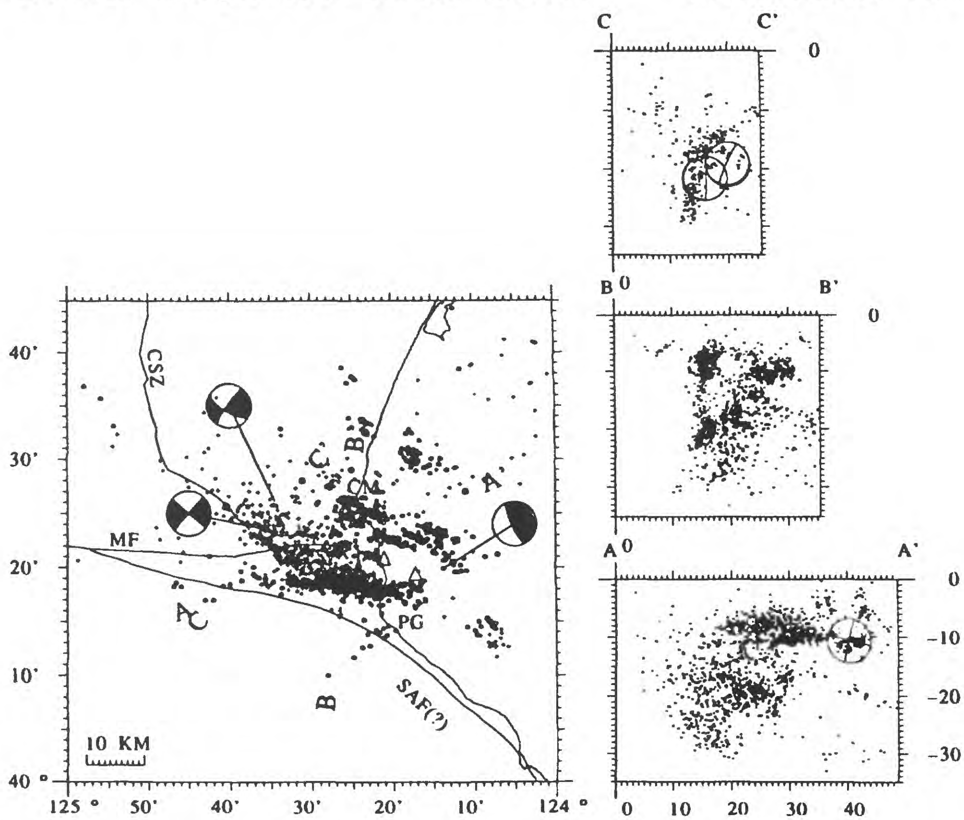


Figure 30: Focal mechanisms of the main shock and two large aftershocks at their epicentral locations, aftershocks for the period 4/25/92 to 9/30/92, and cross sections. Aftershocks in map view are shown as open circles if depth is less than 12 km. Cross section width is 20km for sections A-A' (perpendicular to main shock strike) and B-B' (perpendicular to Mendocino fault), and 9 km for C-C' (perpendicular to strike of Ms 6.7 aftershock). The dilatational quadrant of the focal mechanisms is filled in map view and marked by a "T" in cross sections. The triangles near the main shock epicenter depict the locations of strong ground motion stations maintained by the California Division of Mines and Geology (CDMG). CSZ=Cascadia Subduction Zone, MF=Mendocino fault, SAF=San Andreas fault, PG=Punta Gorda, and CM=Cape Mendocino.

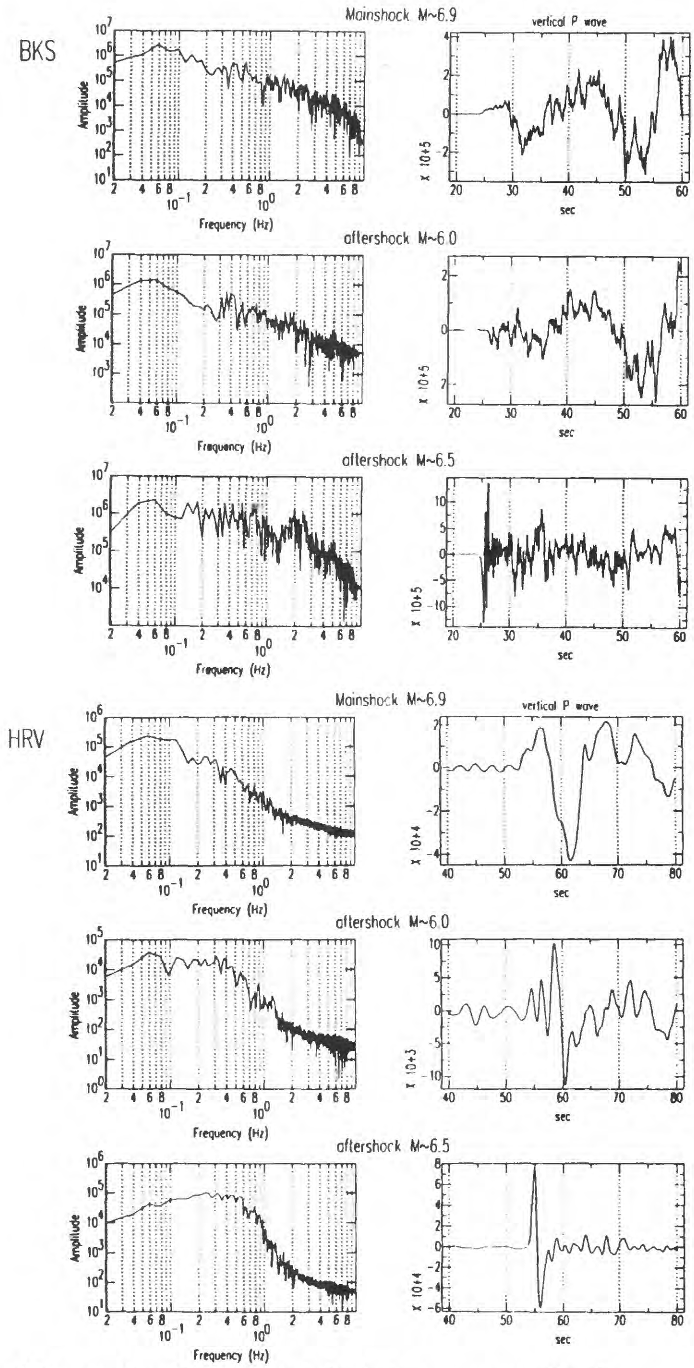
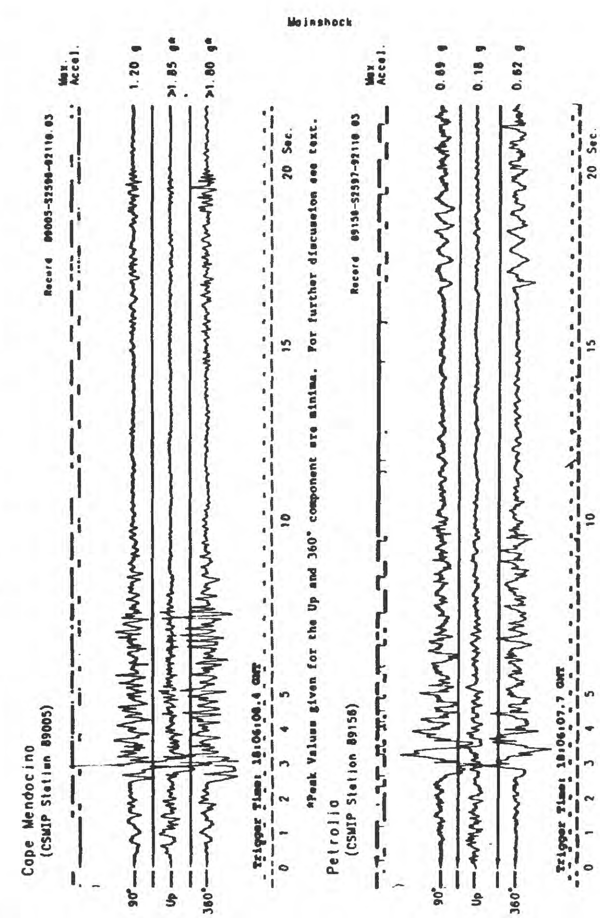


Figure 31. Broadband (written communication, G.C. Beroza, 1992) velocity records and spectra of the main shock and 2 large aftershocks recorded at Berkeley (BKS)(Δ=315 km, azimuth = 150°) and Harvard (HRV) (Δ=4366 km, azimuth = 69°).

similar and the seismic moment of the second aftershock is only a factor of two greater than the first, yet the P-wave amplitudes are nearly 15 times larger and clearly enriched in high frequency energy.



Fourteen State of California strong ground motion sensors within 110 km of the main epicenter were triggered (Shakal and others, 1992). Two sites within 5 km of the main shock recorded very high accelerations (Figure 32). The State's Quick Report indicates maximum accelerations exceeding 1.8 g on all 2 components at Cape Mendocino for a few hundredths of a second. While this high acceleration is of seismological interest, the damage potential of a pulse of such duration is not very great. At Petrolia, 0.7 and 0.8 g horizontal accelerations were recorded, but no evidence of the 1.8g pulse was observed, suggesting that the source of the pulse is local to the Cape Mendocino site.

Figure 32 (opposite page). Strong ground motion accelerograph recordings from CDMG free field sites (Fig. 30) at Cape Mendocino (Δ=10 km) and Petrolia (Δ=5 km) (Shakal and others, 1992). The accelerations recorded at Cape Mendocino exceed the instrument recording limits of about 1.80g.

S.CLARKE, of the USGS in Menlo Park, presented a geologic overview of the southern Cascadia subduction zone and Mendocino triple junction region. This is the only portion of the subduction-zone accretionary fold-and-thrust belt that extends onshore, making it a particularly fruitful study area because the three-dimensional view of offshore structure afforded by seismic-reflection profiling can be combined directly with detailed studies onland of accretionary tectonics and paleoseismicity.

The principal geologic units depicted in an onshore-offshore structural and geologic map (Figure 33) include the Coastal and Central belts of the Franciscan Complex, which form acoustic basement offshore, and the late Cenozoic Wildcat Group and correlative units, which comprise the forearc basin fill.

Offshore seismic-reflection studies show that east- to northeast-dipping thrust faults in the 90- to 100-km-wide accretionary fold-and-thrust belt overlying the southern Cascadia subduction zone have been active during the late Quaternary. These faults merge downward with sole thrusts that can be traced in the seismic data to depths of 13-15 km, near the Gorda-North American plate interface. These faults commonly extend upward to or near the sea floor or terminate in fault-propagation folds that deform late Quaternary and Holocene deposits (Figure 34a). The seawardly-propagating basal thrust of the subduction zone locally cuts Holocene sediment offshore in the Gorda basin (Figure 34a). Collectively, these faults and folds form two or more east-dipping zones of imbricate thrust faulting that express active Gorda-North American plate convergence with strong partial coupling between these plates. The areal pattern of deformation suggests that the Klamath Mountains act as a buttress (or backstop) against which the upper crustal part of the North American plate, west of the Klamath Mountains, is being deformed.

Intensity of deformation, as reflected in background seismicity, late Quaternary uplift rates and geologic structure, increases southward toward the Mendocino triple junction. Principal late Quaternary-Holocene structures include the Little Salmon and Table Bluff thrust-and-fold systems (Figures 33, 34b). The megathrust marking the seaward edge of the subduction zone extends southeastward to within 20 km of the coastline, and is tentatively projected shoreward along Mendocino Canyon to cut the coastline 10-15 km south of Cape Mendocino (Figure 33). Similarly, the Mendocino transform fault system extends eastward along the base of the Gorda Escarpment to near the mouth of Mattole Canyon, and is projected landward along the canyon to cut the coast near Punta Gorda, and to continue eastward along the north flank of the King Range. Both the megathrust and the Mendocino transform are thought to merge with prominent shear zones that intersect onland near the hamlet of Honeydew, the probable upper crustal position of the Mendocino triple junction.

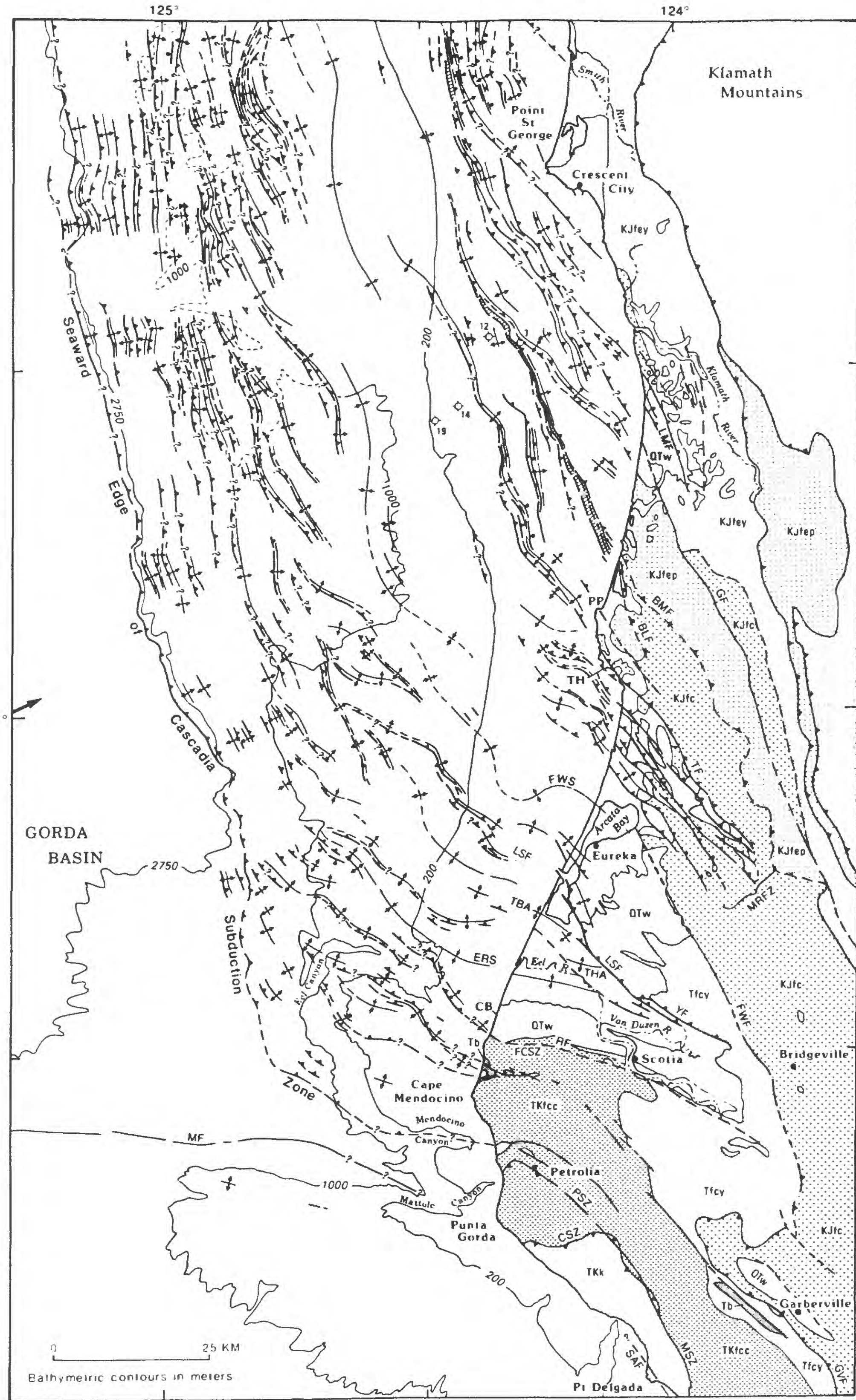


Figure 33. Geologic and structural map of the Eel River basin and adjacent region. Rock units: KJ_{fep}, Cretaceous and Jurassic basement rocks of the Pickett Peak terrane of the Eastern belt, Franciscan Complex; KJ_{fey}, Cretaceous and Jurassic basement rocks of the Yolla Bolly terrane of the Eastern belt, Franciscan Complex; KJ_{fc}, Cretaceous and Jurassic basement rocks of the Central belt, Franciscan Complex; TK_{fcc}, Paleogene and Cretaceous basement rocks of the Coastal terrane of the Coastal belt, Franciscan Complex; T_{fcy}, Paleogene basement rocks of the Yager terrane of the Coastal belt, Franciscan Complex; TK_k, Tertiary and Cretaceous rocks of the King Range terrane; Tb, upper Tertiary rocks of the Bear River beds of Haller (1980) and correlative units; QT_w, Quaternary and upper Tertiary rocks of the Wildcat Group and correlative units; unpatterned, mostly nonmarine, Quaternary, undifferentiated rocks. Structural features: BLF, Big Lagoon fault; BMF, Bald Mountain fault (Bald Mountain-Big Lagoon fault zone offshore); CSZ, Cooskie shear

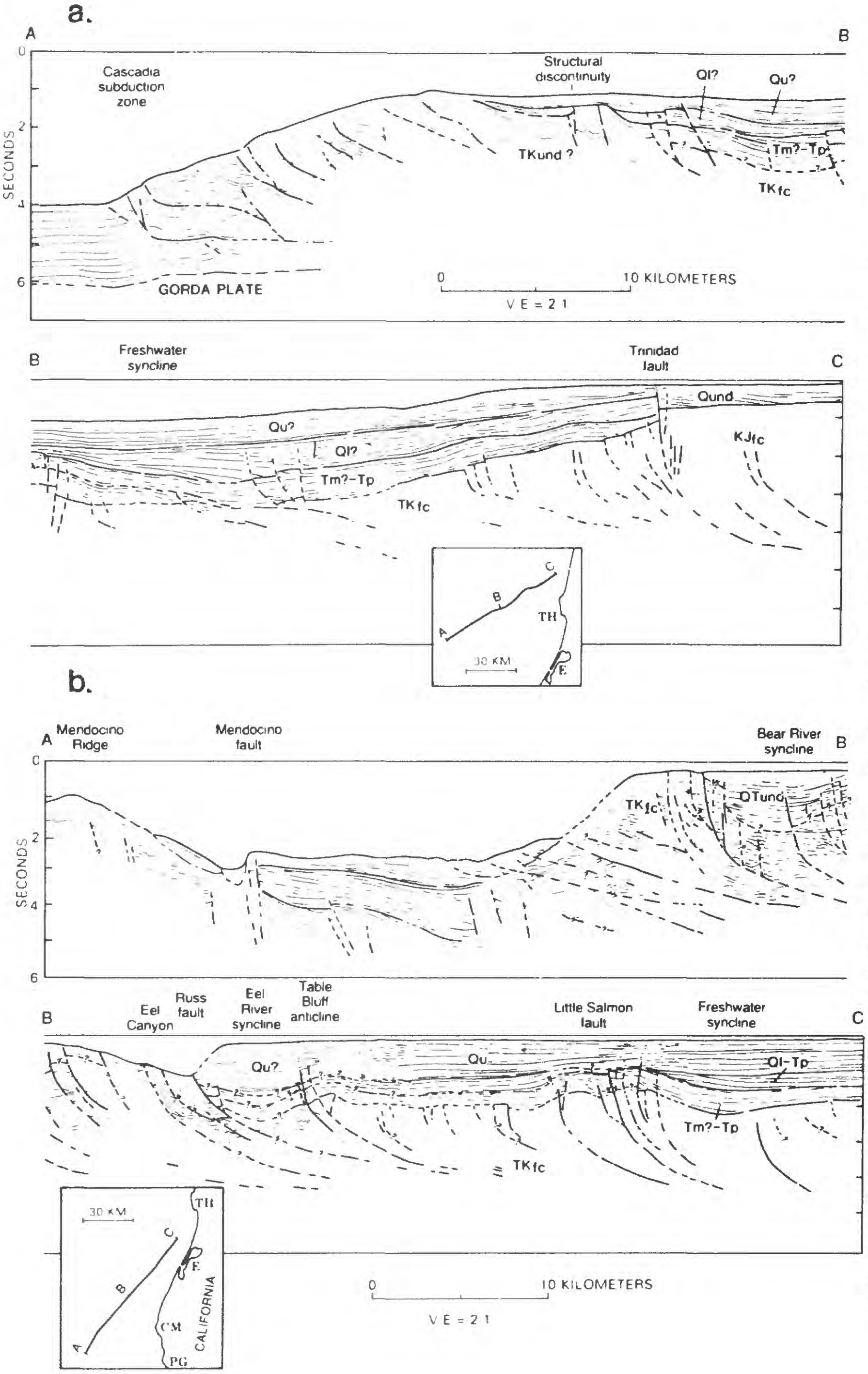


Figure 34. Interpretation of acoustic-reflection profiles (time sections: time in seconds 2-way traveltime) (a) across the central Eel River basin, and (b) from the southern Eel River basin to Mendocino Ridge. Acoustic units: KJfc = Central belt, Cretaceous and Jurassic Franciscan Complex; TKfc = Coastal belt, Tertiary and Cretaceous Franciscan Complex; TKund(?) = Tertiary and Cretaceous strata, undivided, in the seaward part of the accretionary prism; Tm?-Tp = Miocene(?) and Pliocene strata equivalent in age to the lower part of the Wildcat Group; QTund = Quaternary and Tertiary strata, undivided, equivalent to Miocene and younger strata in the Bear River "syncline" on land; Ql-Tp = lower Quaternary and Pliocene strata equivalent in age to the upper part of the Wildcat Group; Ql? = lower(?) Quaternary strata equivalent in age to the upper part of the Wildcat Group; Qu = upper Quaternary strata equivalent to nonmarine deposits that postdate the Wildcat Group onshore; Qund = Quaternary strata, undivided. Locations: CM = Cape Mendocino; E = Eureka; PG = Punta Gorda; TH = Trinidad Head. (Sections reproduced from Clarke, 1992, figs. 6 and 7.)

Figure 33 (opposite,continued): zone; ERS, Eel River syncline; FCSZ, False Cape shear zone; FWF, Freshwater fault; FWS, Freshwater syncline; GF, Grogan fault; GVF, Garberville fault; LMF, Lost Man fault; LSF, Little Salmon fault; MF, Mendocino fault; MRFZ, Mad River fault zone; MSZ, Mattole shear zone; PSZ, Petrolia shear zone; RF, Russ fault; SAF, San Andreas fault; TBA, Table Bluff anticline; TF, Trinidad fault; THA, Tompkins Hill anticline; YF, Yager fault. Locations: CB, Centerville Beach; PP, Patrick's Point; TH, Trinidad Head; 7, 12, 14, and 19 show locations of Exxon P-007-1 and P-012-1, and Shell P-014-1 and P-019-1, exploratory wells. Hachured areas offshore indicate fault zones. Barbs are on upper plate of thrust and reverse faults. (Map reproduced from Clarke, 1992, figure 2.)

S.CLARKE noted that the Humboldt Bay paleoseismic record provides evidence for five seismic events in the past 1,700 years, yielding a recurrence interval of 300 to 400 years. The most recent event occurred 300 years ago, at about 1700 AD according to Clarke and Carver (1992), who consider them to be megathrust, not local, events because (1) the rate of shortening across known major structures is about 11 to 19 mm/yr and, with a convergence rate of 30 to 40 mm/yr, the elastic strain across the subduction boundary cannot be relieved by M7 to M7.5 earthquakes unless such events are numerous, and such activity is not observed; and (2) thrust faults in accretionary prisms elsewhere in the world typically move only in response to displacement on the underlying megathrust. Consequently, the excess strain is probably relieved by periodic displacement on the Cascadia subduction zone megathrust and, using constrained estimates of the area of the rupture surface, the maximum expected magnitudes of such earthquakes can be determined.

In the southern Cascadia subduction zone, a discontinuity in structural trend located about 20 km landward of the deformation front (Clarke, 1992) appears to be the western edge of strong coupling between the Gorda and North American plates, and the east edge of the fold-and-thrust belt, nearly coincident with the bend in the subducting Gorda plate, is thought to be the eastern edge of strong interplate coupling. This suggests a locked zone breadth of 70 to 80 km in this region, a dimension that is also consistent with observed seismicity in the North American plate and upper part of the Gorda plate (Cockerham, 1984; McPherson, 1989). The distribution of subduction-zone seismicity prior to and during the 1986 Andreanof Island, Alaska, (Mw8.0) earthquake, together with the similarities in upper plate structure of the southern Cascadia subduction zone and the Andreanof segment of the Aleutian arc, further supports this model of rupture breadth.

Clarke attempted to determine the shortest length of the Gorda segment that is structurally coherent and characterized by the same style of late Cenozoic deformation, and that might be regarded as a mechanical unit. He concluded that the southern Cascadia subduction zone from Cape Sebastian, Oregon, to Cape Mendocino, California, represents such a unit. The length of this segment is about 240 km, yielding a model rupture area of 17,000 to 19,000 km^2 and a corresponding magnitude of 8.4 (M=log A+4.15; Wyss, 1979).

In the absence of convincing evidence for seismic segmentation along the Cascadia subduction zone and given the correspondence of high-resolution ^{14}C ages for the most recent (ca 1700 AD) event in the northern and southern parts of the subduction zone (Atwater and others, 1991; Carver and others, 1992), one must consider that a source region as large as 75,000 km^2 and yielding M9+ events is also quite plausible.

E.BERNARD, of NOAA in Seattle, Washington, presented an overview of tsunamis on the west coast. Over the last 200 years, tsunamis have caused damage on the west coast several times, and those originating some distance from the coast (Figure 35) have caused the most damage, with some events affecting elevations up to 4.5 m. Tsunamis generated from local earthquakes (Figure 36) include a 3.5 m wave elevation event generated at Santa Barbara in 1812, the largest recorded, and events in 1930, 1912, 1927, and 1989.

Hebenstreit and Murty (1989) constructed a series of subduction related earthquake scenarios, including a Gorda south event. A 5 m uplift offshore of the northern California-southern Oregon region was modeled to generate waves of about 2.5 m in about 50 m of water. Crescent City would receive the peak, which would taper off rapidly in Eureka. Such scenarios provide some understanding about what might happen with these type of events.

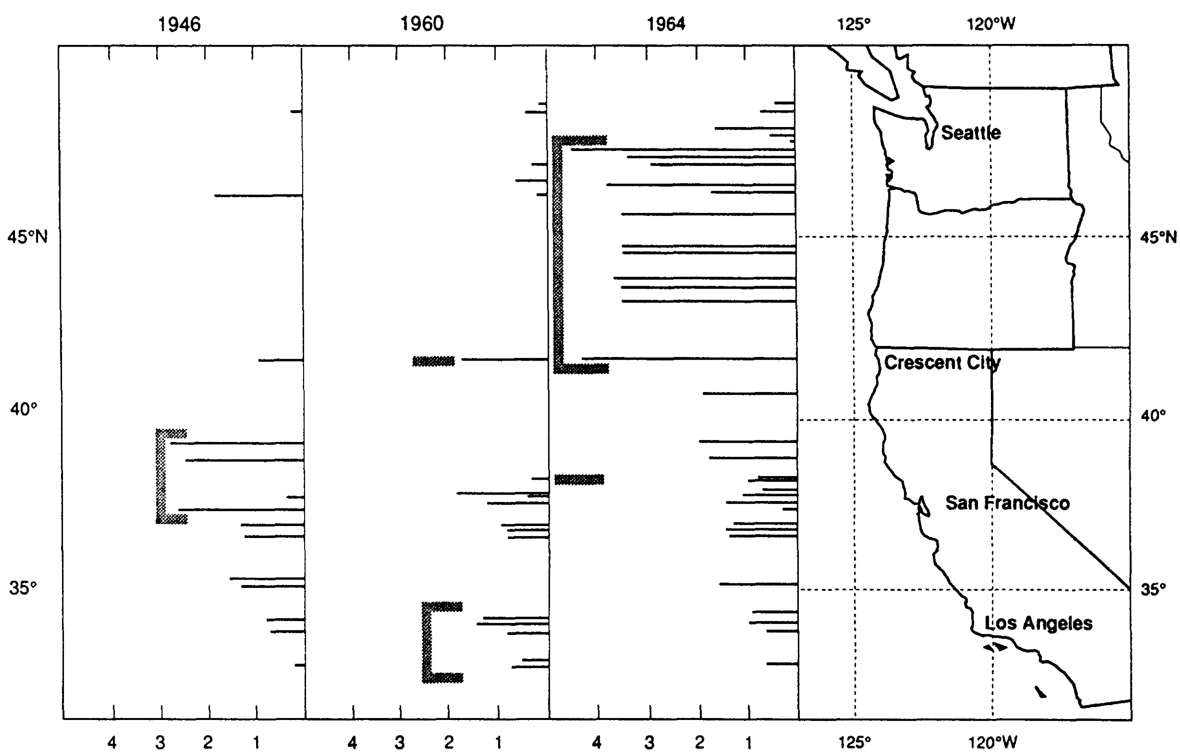


Figure 35. Amplitudes of tsunamis generated by the 1946 Aleutian chain earthquake, the 1960 Chilean earthquake, and the 1964 "Good Friday" earthquake in Alaska, as well as areas of principal damage caused by these events on the west coast of the United States. Horizontal bars indicate amplitudes in meters; shaded brackets indicate areas of principal damage.

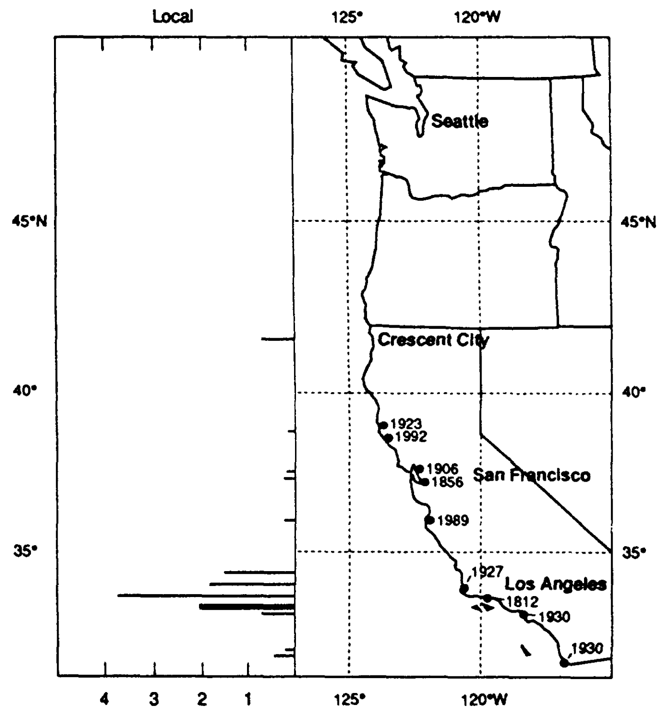


Figure 36. Map showing amplitudes of tsunamis associated with local earthquakes in coastal California, starting with an event in 1812. Horizontal bars indicate amplitudes in meters.

NOAA and the Army Corps of Engineers have funded an observational program in the Pacific. The deep instruments, in 2,000 to 4,000 m of water, can track the tsunamis very accurately in the deep ocean. The coastal stations, operated in about 10 m of water, use pressure gauges to measure the amplitude of the waves. Future phases of this program will transmit the data from stations in the Gulf of Alaska to a buoy and beam the information to GEOS satellites. Unfortunately, two key stations were down on April 25.

The Cape Mendocino earthquake of April 25 , 1992, generated a tsumani recorded by NOAA sea level gauges in California, Oregon, and Hawaii (Figure 37). The tsunami hit Humboldt Bay precisely at low tide (Figure 38a) and produced a 20 cm elevation with oscillations continuing through the tidal cycle. At Arena Cove, to the south, it produced a 10 cm rise at low tide. At Crescent City (Figure 38b), which is a natural trap similar to Hilo, about 40 minutes from the source, the event produced a 1.2 m peak to trough wave with a half amplitude of about 60 cm. The 1992 earthquake at Cape Mendocino is the first local event to have substantial wave elevations on its seaward side at a distance. In Hawaii (Figure 38c), it

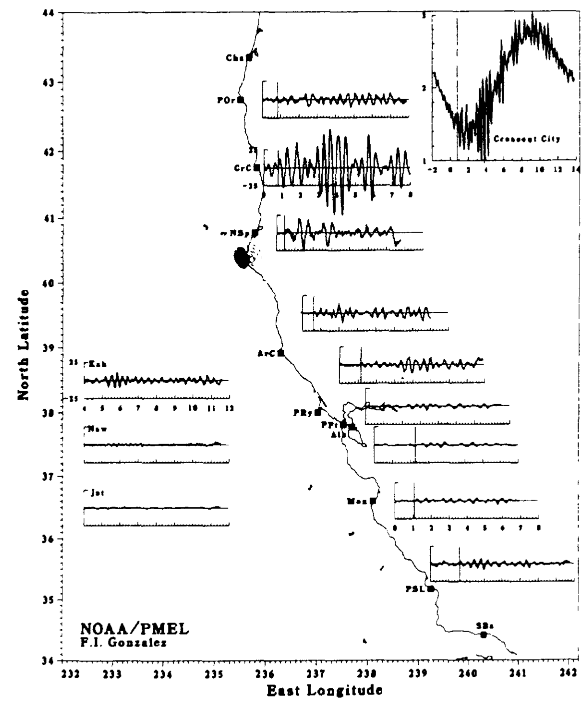


Figure 37. Records of the April 25, 1992, tsunami at selected NOAA sea level stations. Vertical axes range from -25 cm (below) to +25 cm (above) the mean of the record with tidal signals removed from each; horizontal axes represent elapsed time in hours after mainshock; and vertical lines mark expected arrival time. Crescent City record begins 2 hrs before the earthquake, includes the tidal signal, and has the vertical scale in meters. Cha, Charleston; POr, Port Orford, 50 (travel time in minutes); CrC, Crescent City, 47; North Spit NSp, 26; ArC, Arena Cove, 37; PRy, Point Reyes, 69; FPt, Fort Point; Mon, Monterey, 64; PSL, Port San Luis, 97; SBa, Santa Barbara; Kah, Kahului; Naw, Nawiliwili; Jst, Johnston Island. From Gonzalez and Bernard, 1992.

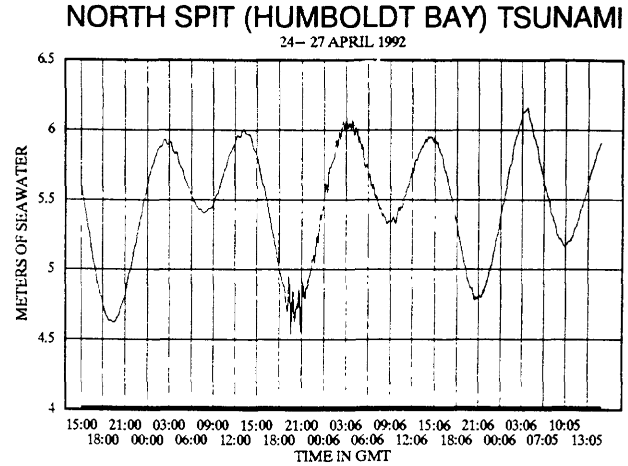
produced 15 cm, peak to trough. In each of these cases, if the tides had been high instead of low, local flooding would have occurred. This also points out that one cannot isolate local tsunamis and say that the largest rise will be closest to the source. Topography, harbor resonance, and other hydrodynamic features tend to amplify tsunamis.

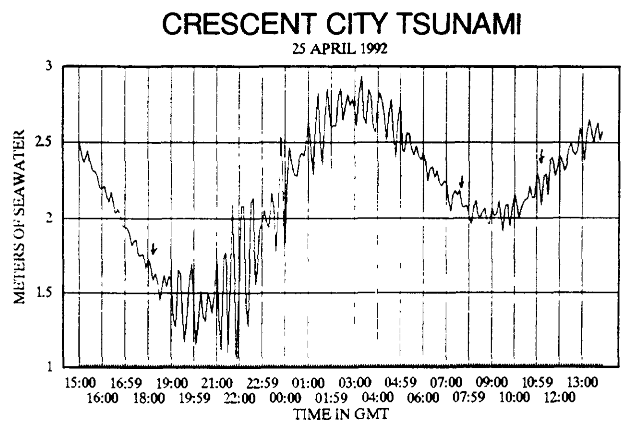
Using the Harvard moment tensor solution for the recent event and removing the tidal cycle, we can estimate a region about 30 km by 30 km with uplift on the landward side and subsidence on the seaward side, but we cannot eliminate a slump as the source. Wave travel times are consistent with this being the source region, but we are dealing with a sampling interval of 6 minutes.

Local tsunamis don't give us much time. We need to do advance planning by producing scenario events to determine areas that could be flooded with different sources and inundation models. We are trying to improve our understanding of the current models and pushing to the next generation, which require the use of supercomputers. Our goal is to start a standardized model within the next two years.

We would like to be able to produce scenario studies that would allow the local populace to take action by evacuating the particular inundation zone without warning. Hilo, the most tsunami-effected zone in the US, has implemented an inundation model based upon the 1946 and 1960 events. Recent changes have moved the evacuation line closer to the shore.

It is important to use the best published data in order to avoid





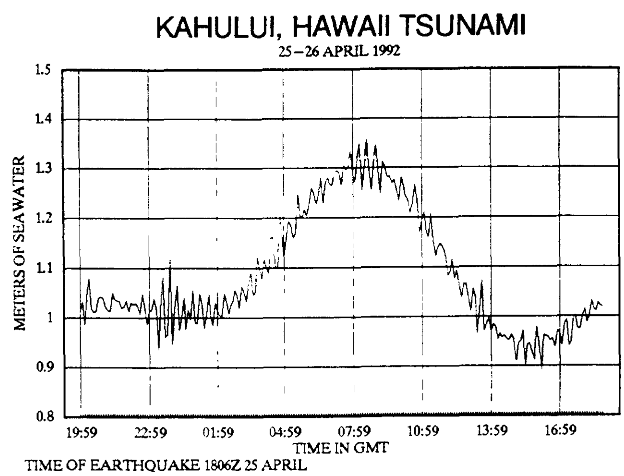


Figure 38. Wave elevation caused by the Cape Mendocino earthquake. a. Humboldt Bay, California. b. Crescent City, California. c. Kahului, Hawaii. At each location, the tide was low when wave elevation occurred. See text for discussion.

overdesign. If the states of California, Oregon, or Washington have any plans to produce inundation models, we certainly should proceed in concert.

T.HEATON asked about the size of an event that might produce 10 m rises of the sort described by Reinhart and Bourgois (1989).

E.BERNARD indicated that he wasn't aware of that study, but that such an event would almost certainly be related to a very large earthquake, but local topography can have large effects. In addition, El Niño can produce sea level changes on the order of 25 to 30 cm, and such changes can have meteorological effects that may be ascribed to tsunamis.

A.LINDH asked the shortest amount of time that residents of Crescent City might have after a large Gorda plate event.

E.BERNARD, using a reasonable model, suggested that people should react by 10 minutes for such an event.

T.McEVILLY initiated a period of discussion by presenting a short draft statement on seismic hazards in the PNW that was prepared by K.Shedlock, C.Weaver, and H.Kanamori and asking these NEPEC members to address the document.

K.SHEDLOCK started by indicating that the draft statement was somewhat stronger than any documents on the PNW that have been made previously by NEPEC. Although the tectonic and geologic setting of the PNW includes an active subduction zone, no subduction zone events have occurred since the arrival of Europeans. Nevertheless, the late Holocene record of buried intertidal marshes and other lines of evidence might lead to the following statement from the draft: "Given the available data, NEPEC concurs that these subduction zone events probably occur on the average of every few centuries and involve lengths of the coast sufficient to produce earthquakes of at least M8.5."

The preliminary draft statement also notes the two other sources of earthquakes in the region: the intraplate sources within the subducting Juan de Fuca plate and Gorda plates, and the crustal earthquakes. For the former, we suggested: "NEPEC concurs with recent studies that have concluded that intraplate earthquakes should be expected anywhere along the subducting plate at depths comparable to those known in this century, in the 40 to 60 km deep range, and that a realistic magnitude for planning purposes for these events is from M7 to 7.5." For the latter, we then addressed the major crustal events in a more general manner: "NEPEC believes that crustal earthquakes may be a major urban hazard in the Puget Sound basin, but considerable additional geologic and geophysical studies are needed on this issue."

Today, after talking further, the three of us would like to offer another sentence along the following lines: "Magnitude 7 and larger crustal earthquakes do occur in similar subduction regimes." This is based on the further evidence that

R.Bucknam and others have presented in the past few months.

W.BAKUN asked about the phrase that "these subduction zone events probably occur on the average of every few centuries." He asked, "didn't we hear about one three hundred years ago and one about 1700 years ago?"

K.SHEDLOCK, answered yes, that is what we've heard today. We were willing to say "every few centuries" because of ambiguities in some of the data, with five possible events in northern California, which would give a shorter recurrence interval, and 1100 year intervals in some of the other tidal marshes.

T.HEATON noted the tendency to downsize the magnitude from M8.5 to M8 when discussing the subduction zone events. The evidence that we have seen indicates that we are looking at several events of at least M8.5, and that if it is not several such events, but a single event, we are really talking about the M9 range.

K.SHEDLOCK agreed and said that this is exactly what has occurred in writing this draft. By addressing the M8 events, the trio felt comfortable talking in terms of "every few centuries;" if addressing M9 events, they would have referred to "every several centuries."

Discussion concerning the relation of magnitude, brittle zones and heat flow ensued. **A.JOHNSTON** summarized the day by stating that nearly everyone seems to accept the concept of large past subduction zone earthquakes and wondered if other workers were opposed to the concept. **R.WELDON** personally supports events greater than M8 based on paleoseismology, but, while such events might be plausible, opposes the concept of M9 events; he is not convinced that the whole zone could be involved in a single event.

T.HEATON pointed out that the Nankai, southwestern Japan trough sometimes releases as a large single event and sometimes as multiple event. **G.CARVER** pointed out that when we start breaking segments down into M8 or about M8 events, we would need to call upon a number of segments for each of the three events. If, for the whole coast we need 5 or 6 M8 events, we would be calling upon 15 M8 events in the last 1700 years, as opposed to three giant events. Much discussion continued. **A.NELSON** opined that the paleoseismic record is undoubtedly incomplete even for M8 events. Identification of PNW subduction zone earthquakes producing tsunamis that might be shown in the Japanese record was discussed.

J.DAVIS asked the group to review what it was trying to accomplish with the statement under discussion: is it directed to the scientific community or the public policy community? If we want the public policy people to take the statement seriously, we must avoid a document about which the scientific community continues to argue, thereby undercutting the impact that we wish to obtain. When one reviews documents that have influenced the public sector over the past five years, one is impressed with the outcome of the working group reports, which build consensus documents by group analysis. The subject under discussion is reaching maturity for such consideration, but not maturity for a two-page statement. **J.DAVIS** suggested that if we want this statement to elicit long-term commitment in the public sector, than a working group evaluation should be considered.

T.McEVILLY reviewed NEPEC's charge from the Director (See Frizzell, 1992, appendix A), which was to "undertake an analysis of the current understanding of the earthquake hazard in the Pacific Northwest, including an assessment of the current consensus view on the potential for future great earthquakes along the Cascadia subduction zone."

R.WESSON recalled that, in about 1987, NEPEC considered the potential for a large subduction zone earthquake, but that analysis resulted in a rather weak statement. Since that time consensus has been developing that the subduction zone is seismic, and at the NEPEC meeting at Alta last year, the council asked this team to prepare a draft statement summarizing issues for which consensus exists and issues that remain unresolved. He noted that J.Davis proposes is an intermediate product that summarizes the evidence for large earthquakes in the PNW and that could be published as a USGS Circular. This would be a big job, but it could be done and might be useful. What has been presented today could be the basis for impaneling a working group.

J.DAVIS agreed and suggested that such a document would be a policy watershed, not only for the working group document and the judgments that come from it, but also for a consensus on what the record says, as well as an enumeration of the remaining questions and their implications.

Discussion ensued concerning the possibility of the formation of a working group. It was suggested that Shedlock and Weaver (1991) answered some of these issues, but most agreed that while the report sets the context for a research plan, it should not be used as the basis for public policy. The next phase should be a broadly based analysis of all aspects of the issue, including tsunamis.

The Council determined that a working group, including both proponents and opponents of the occurrence of large subduction zone earthquakes, should prepare a document summarizing the evidence for such events and other earthquake hazards in the PNW, presenting the implications of these events, and listing the questions that remain to be resolved, including the possible modes of failure of the CSZ, the implications for each mode, and what actually would happen in the built environment struck by a M9 event. This would be an intermediate document presenting a scientific consensus to the scientific community concerning the upper bound of earthquakes and the available evidence concerning their frequency and the implications of the data. This document would be the basis of a public policy document .

The evidence has accumulated to the extent that the hazard is known to range up to the highest ever in this area. As a consequence, NEPEC should compile the information in a collected and systematic fashion for the Director's consideration. The Chairman outlined the elements of the document charging the ad hoc working group that resulted in Appendix F.

May 7, 1992
Evening Session

T.HEATON, of the USGS in Pasadena, California and USGS Team Leader for southern California, started a presentation on the April 22, 1992, Joshua Tree earthquakes with a summary of a method (developed by Agnew and Jones, 1991) of estimating probabilities that earthquakes on the southern San Andreas fault are foreshocks to larger events.

Agnew and Jones determined that foreshocks and main events are nearly always within 10 km of one another, usually within 5 km, and divided the San Andreas into segments surrounded by 10 km envelopes. They argued that since the 1988 NEPEC report (Working Group on California Earthquake Probabilities, 1988) indicated that the probability for a M7 or larger event in the next 30 years is 40 percent and since 50 percent of earthquakes have foreshocks, there is a 20 percent chance of a foreshock for an event M≥7.5. They assumed that foreshocks were just as likely on quiet segments as active segments and concluded that the chance that an event in the quiet segments is a foreshock is relatively large. This work allows estimates to be made of the conditional probabilities for major earthquakes in the three days following a M5 earthquake on different segments of the San Andreas fault (Figure 39).

Jones and others (1991) established various alert levels (Table 2) for four regions of the San Bernardino Mountains and Coachella Valley segments of the southern San Andreas fault using such information and the magnitude of possible foreshock events in those regions (Table 3), with USGS activities suggested for a given specific alert level. This plan, although accepted by NEPEC and the California Earthquake Prediction Evaluation Council (CEPEC), has never been fully instituted by the State of California.

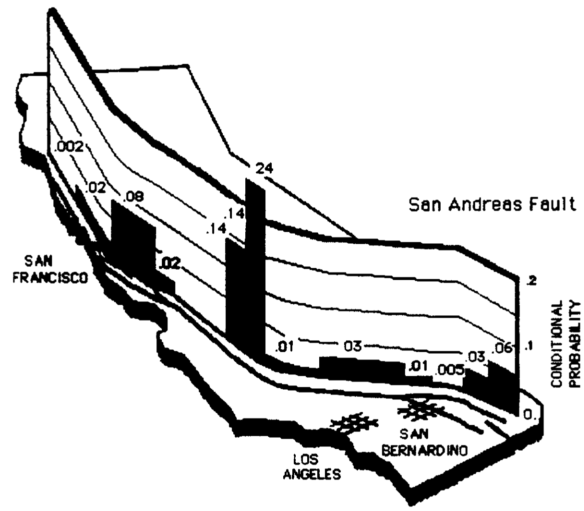


Figure 39. Conditional probabilities of major earthquakes for 3 days following a M5 earthquake on segments of the San Andreas fault. The San Bernardino Valley and Coachella Valley segments of the Working Group on California Probabilities (1988) were divided into smaller regions by Agnew and Jones (1991). (Figure from L.M.Jones, written communication, 1992, after Agnew and Jones, 1991.)

The M4.7 event on April 22, 1992, (Figure 40) indicated a C level of alert and numerous phone calls were made in accordance with this procedure. The M6.1 Joshua Tree earthquake occurred about 2.5 hours later and we elevated the alert level to B. In cooperation with P.Flores, a high-ranking representative of the California Office of Emergency Services (OES), we prepared a hazard advisory for distribution by the OES. Given that Pasadena was not really ready to issue advisories, we felt that

Table 2. Definitions of levels of estimated short-term increases in earthquake hazard for the southern San Andreas fault (from Jones and others, 1991).

Level	Probability of M>7.5 earthquake in next 72 hours	Expected time between occurrences	USGS Action
D	0.1% to 1%	6 months	Notify scientists involved in data collection and OES Ontario office
C	1% to 5%	5 years	As for D, and also notify Comm. Officer of OES in Sacramento and OEVE Chief
B	5% to 25%	28 years	As for C and D, and also notify USGS Director and CDMG State Geologist, and start intensive monitoring

Table 3. Magnitude of possible foreshock needed to reach a specified probability level for four microseismic regions of the San Bernardino Valley and Coachella Valley segments of the southern San Andreas fault (Jones and others, 1991, p. 2).

Level Probability of M>7.5 in next 72 hours	B 5-25%	C 1-5%	D 0.1-1%
San Bernardino	5.8	5.0	3.9
San Gregory	6.1	5.3	4.2
Palm Springs	5.2	4.5	3.4
Mecca Hills	4.9	4.2	3.1

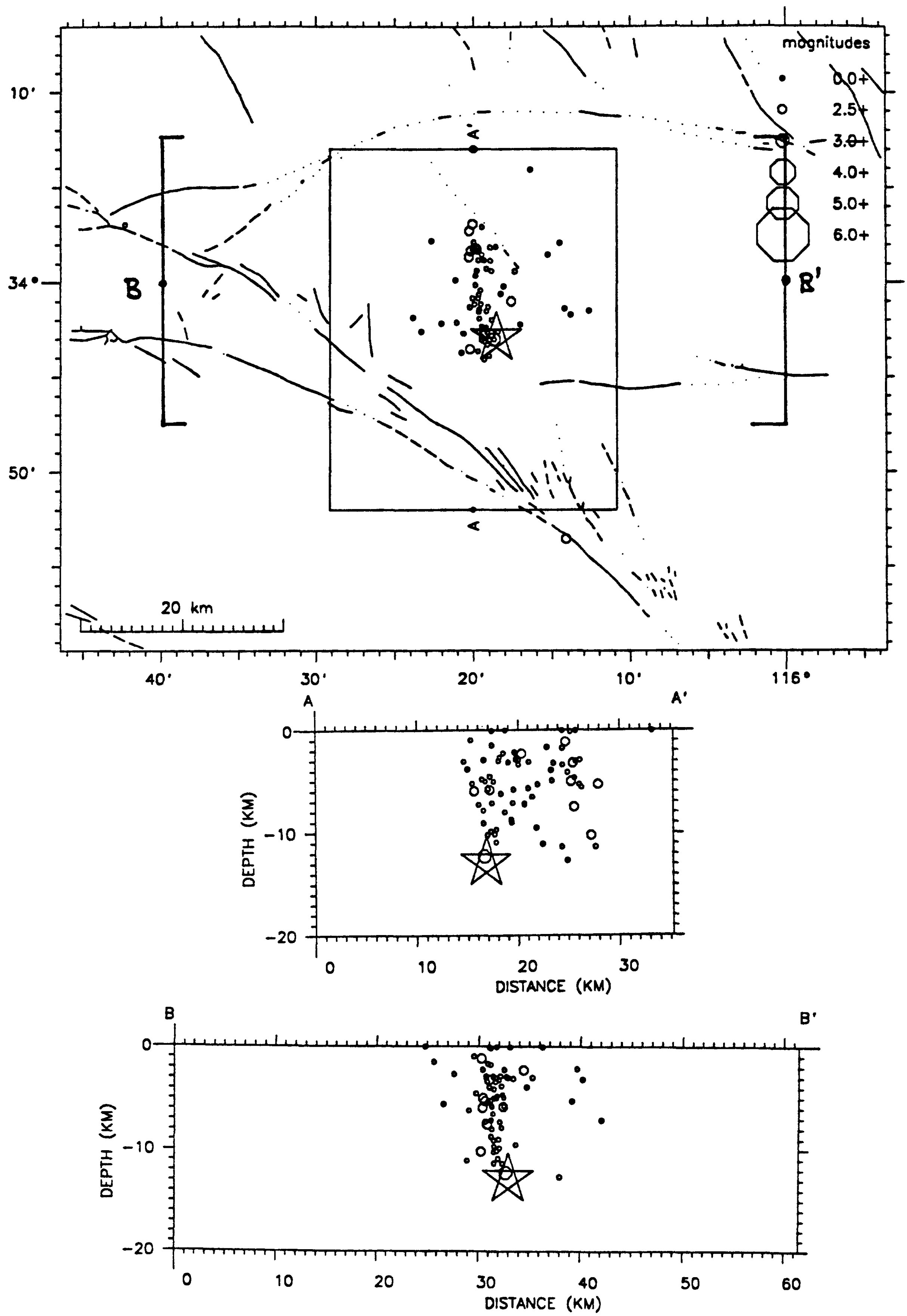
the situation was scientifically serious and that overall the system worked pretty well. Having the apparatus in place proved very convenient.

Earthquakes for the period 1979 to 1992 define several areas of activity preceding the Joshua Tree event. These include the north Palm Springs event, background seismicity, a band of activity in the Mojave desert, and aftershocks to the Homestead Valley sequence of 1978. We think that the San Andreas is essentially trifurcating near the intersection of a structure defined by the Joshua Tree earthquakes and the San Andreas, with the two branches of the San Andreas and a third right-lateral branch trending north into the Mojave desert.

The main, M6.1, Joshua Tree event occurred in the same area as the foreshock, and most of the aftershocks occurred in the same

Figure 40 (opposite page). Map showing the location of events northeast of the Palm Springs region of the Coachella Valley segment of the southern San Andreas fault that were timed during the first day of the April 22, 1992, M6.1 Joshua Tree earthquake sequence. (Figure from E. Hauksson and others, written communication, 1992.)

JOSHUA TREE EARTHQUAKE 1992
Timed locations during first day



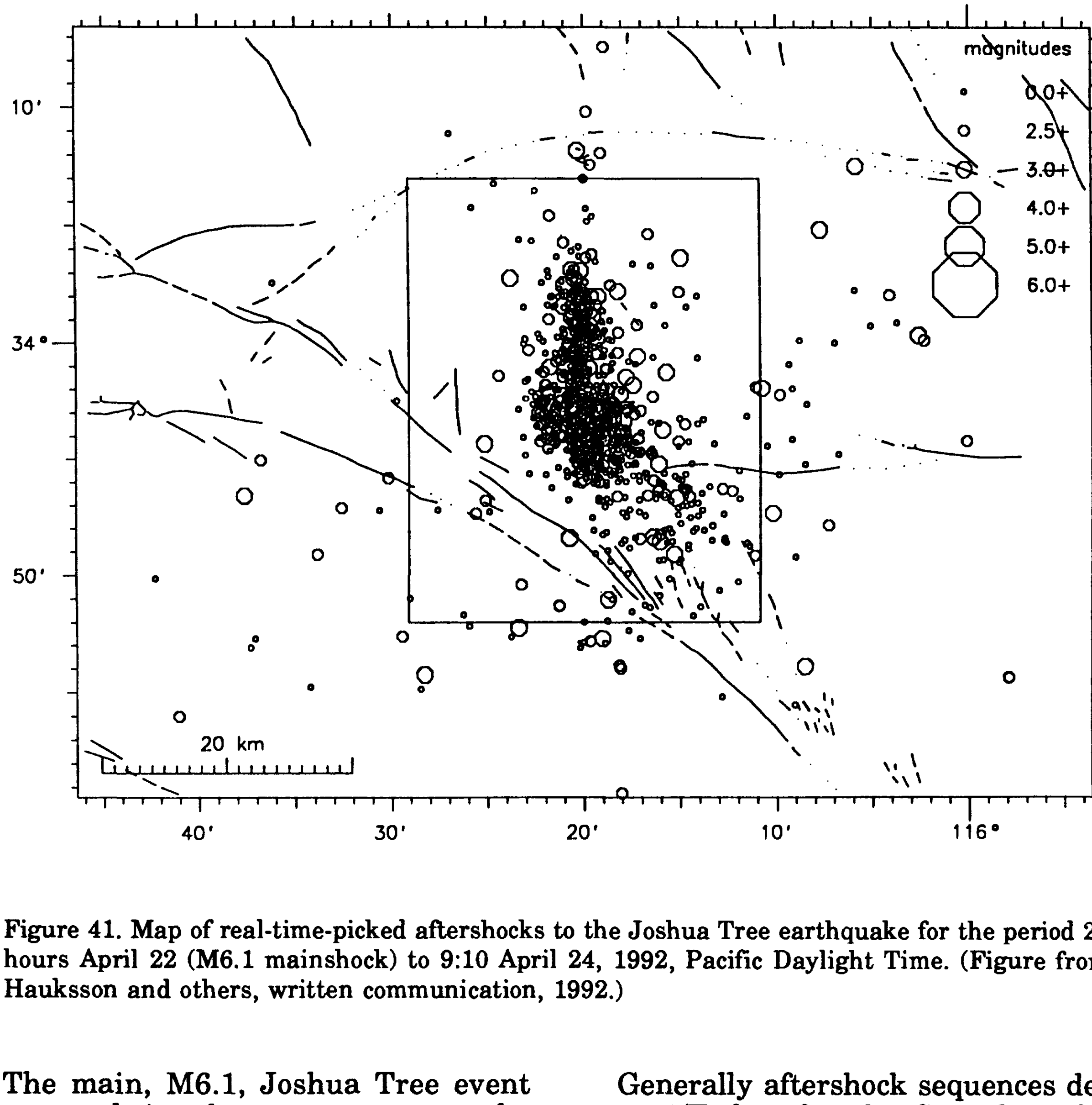


Figure 41. Map of real-time-picked aftershocks to the Joshua Tree earthquake for the period 21:50 hours April 22 (M6.1 mainshock) to 9:10 April 24, 1992, Pacific Daylight Time. (Figure from E. Hauksson and others, written communication, 1992.)

The main, M6.1, Joshua Tree event occurred in the same area as the foreshock, and most of the aftershocks occurred in the same region (Figure 41). The early aftershocks (Figure 40) define a single plane to about 12 km in depth; a subsequent cloud of shallow seismicity may indicate a curving splay. The southernmost aftershocks along this trend occurred in close proximity to the San Andreas and caused us some anxiety.

Generally aftershock sequences decay at 1/T, but for the first day of the Joshua Tree aftershocks the plot did not decay according to this ratio (Figure 42). We found it disconcerting that the number of events were not decaying as a function of time and that a number were occurring near the San Andreas. Of course, the sequence, though healthy, has begun to decay. Now, two weeks after the event, we are officially out of the alert status, but unofficially we will tell people that we are still concerned about the situation.

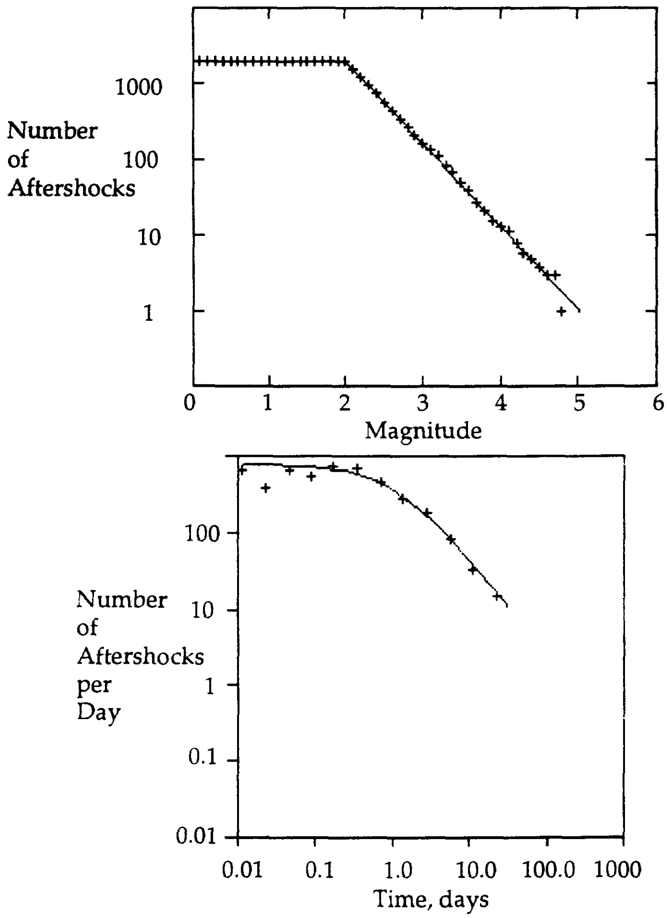


Figure 42. Plots of the aftershock decay sequence following the 1992 Joshua Tree earthquake. Constants include: $p=1.37\pm0.07$, $c=1.37\pm0.23$, $a=-1.35\pm0.12$, and $b=1.10\pm0.02$. (From L.M. Jones, written communication, 1992.)

J.DIETERICH asked, that since more than a dozen events $\geq$ M4 have occurred, if the threshold magnitudes should be reset? **T.HEATON** agreed that this was something that should be addressed.

R.WESSON raised the issue of how to better deal with the still relatively high probabilities after the end of the 72-hour alert. Since the Poisson, background, probabilities are on the order of 0.003 percent, the decayed probabilities in the tails of the curves are still a couple orders of magnitude above the Poisson values, even several weeks after these events. Perhaps we should revisit the issue after a few months of the termination of an alert, maybe with an intermediate-term warning in the form of a reminder. Without addressing the tails to these curves more rigorously, we shouldn't later take "credit," for the "foreshocks" as we did for the two M5 events that preceded the Loma Prieta event. We need to find a better way to express this intermediate-term probability.

R.WELDON of the University of Oregon presented his interpretation of the paleoseismic evidence from Wrightwood, California, and addressed a distribution function that might be used in predictions. In summary for the latter, if one takes a sequence of events on the southern San Andreas, one can ask whether the data fit the probability function that has been used for making the forecasts for the fault (e.g., Working Group on California Earthquake Probabilities, 1988, 1990). **R.WELDON** asserts that the answer is convincingly no.

The stratigraphic record at Wrightwood (Figure 43, 44), which has a Holocene slip rate of about 3 cm/yr, has been detailed from work over the last 6 years. Approximately 50 radiocarbon ages have been determined for the section (Figure 45), mainly from peat which occurs about every 20 years. While some events are well resolved stratigraphically, resolution of actual ages for these events is not as well constrained.

We made incorrect assumptions about clustering of events. We had considered certain events to be a cluster because they were stratigraphically close together. Our dating now indicates that the stratigraphic distance between events has nothing to do with the length of time between events.

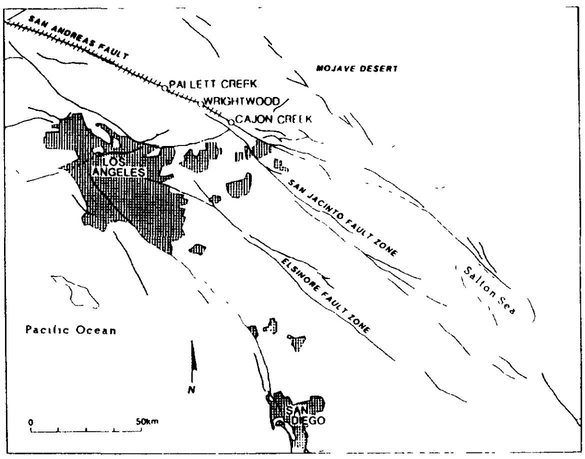


Figure 43. Index map for the southern San Adreas fault, showing the sites discussed during presentation. Hatchers on the fault indicate the extent of the 1857 rupture; the 1812 rupture is inferred to overlap ~20 km and extend to the south, including the San Bernardino region. The extent of other earthquakes discussed are unknown. (From Fumal and others, 1993.)

Using these events with their uncertainty, we can determine that the probability of an earthquake in 30 years is about 40 percent, the value assigned by the 1988 working group (Working Group on California Earthquake Probabilities, 1988). If we combine the record from Wrightwood with a somewhat reinterpreted Pallett Creek record, we still see the clustering that K.Sieh has described (Sieh and others, 1989) and derive a probability function (Figure 45) similar to about 30 percent in 30 years. Closer inspection of these records and investigation of unmatched events, however, indicate that the records are incomplete: "extra" events at Pallett Creek occur during long intervals at Wrightwood, and vice versa (Weldon, 1991).

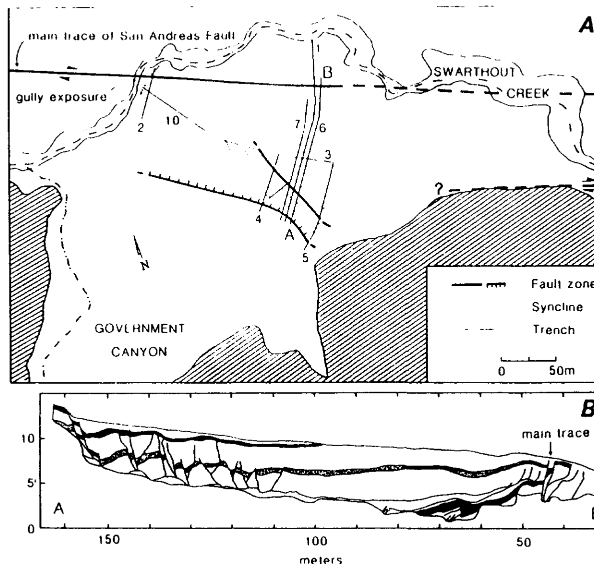


Figure 44. Map and cross section at Wrightwood site, focused on the northwest portion of the site near the "gully." This portion and the secondary zone are connected by a trench, so the exact correlation of the stratigraphy and deformational events is possible. (From Fumal and others, 1993.)

If one reinterprets the records together, one gets a significantly different probability function. If we make no assumptions about rupture models, we can produce a complete record from the two incomplete records. Events at Pallett and Wrightwood that overlap are assumed to be the same event, and nonoverlapping events are counted as an event for the combined record. The resulting distribution function (Figure 46, 47, 48) describes the probability for the southern San Andreas in the vicinity of Pallett Creek and Wrightwood for events that would be important for Los Angeles. The data from the "complete" record described today can be addressed with several different methods which produce recurrence intervals of about

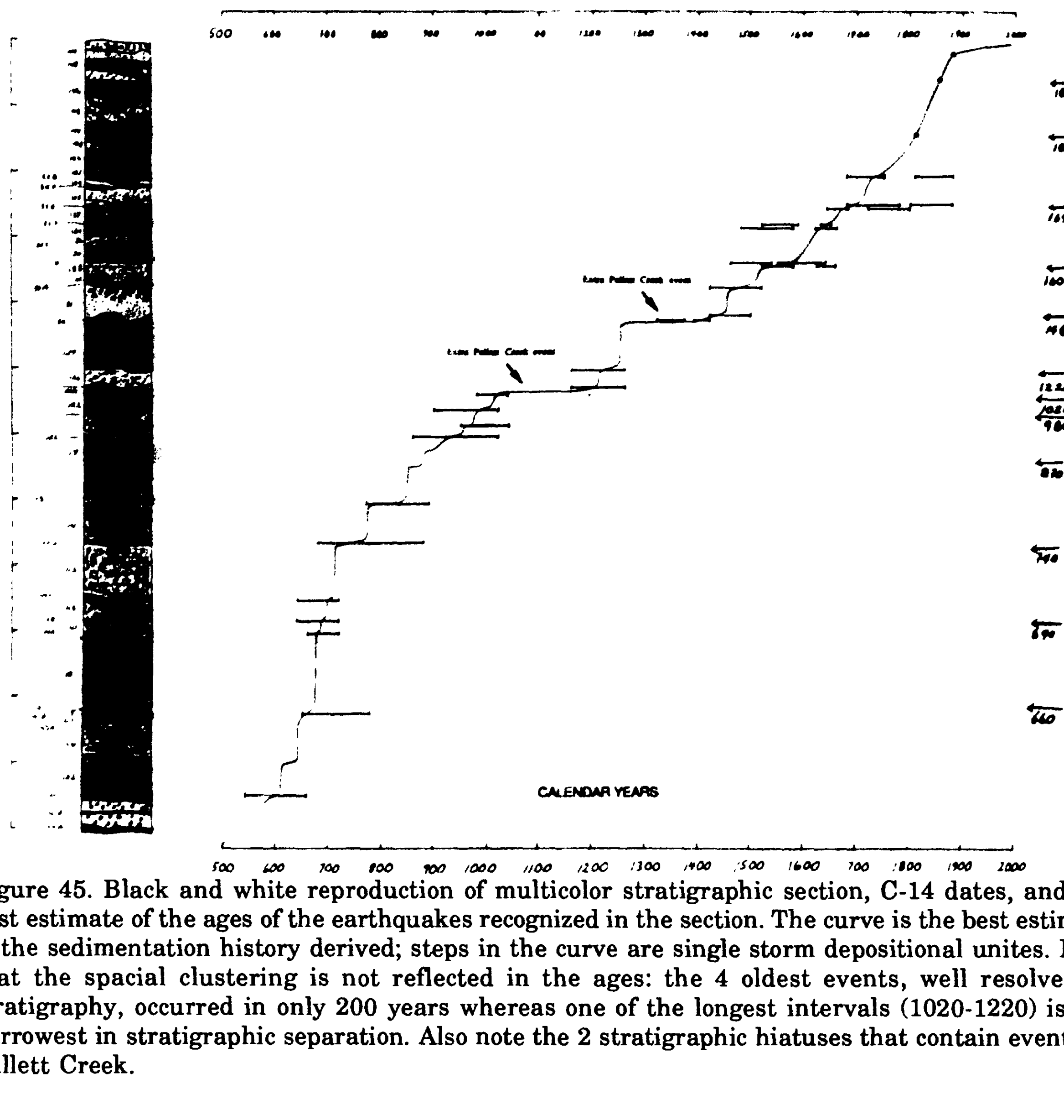


Figure 45. Black and white reproduction of multicolor stratigraphic section, C-14 dates, and the best estimate of the ages of the earthquakes recognized in the section. The curve is the best estimate of the sedimentation history derived; steps in the curve are single storm depositional unites. Note that the spacial clustering is not reflected in the ages: the 4 oldest events, well resolved in stratigraphy, occurred in only 200 years whereas one of the longest intervals (1020-1220) is the narrowest in stratigraphic separation. Also note the 2 stratigraphic hiatuses that contain events at Pallett Creek.

100 years and probabilities of 80 percent in the next 30 years, or twice as high as the probability derived in 1988.

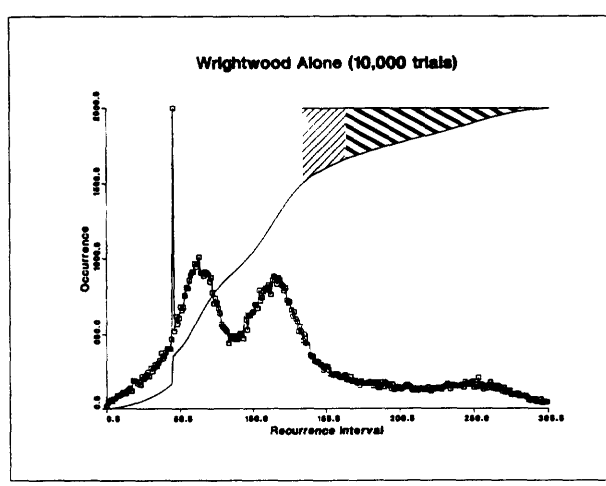


Figure 46. Empirically derived probability function for recurrence at Wrightwood. Irregular curve with points is derived by the Monte Carlo technique. The spike at 45 years is due to the exact interval and is not truncated. The striped regions show the areas used to calculate the 30-yr conditional probability.

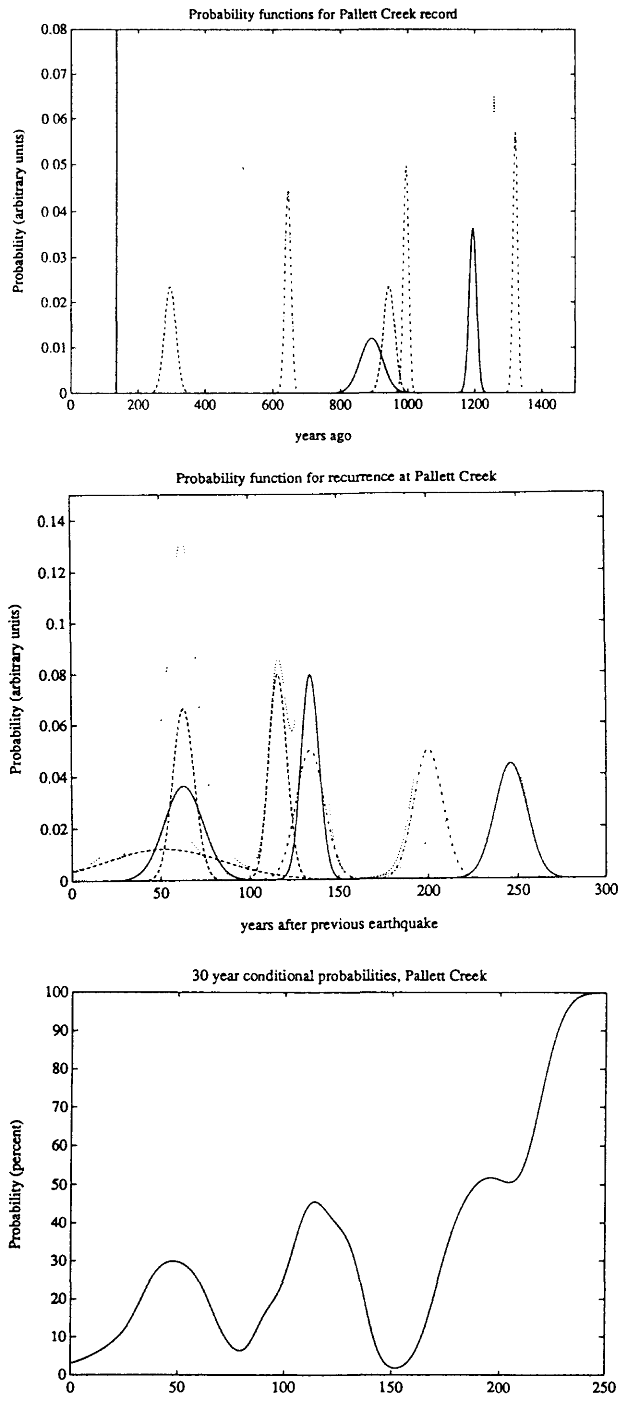


Figure 47. The Pallett Creek record. a) the sequence of events from Sieh and others (1989), represented with gaussian uncertainties; we do not include 1812 in Pallett Creek record, and have modified the uncertainties slightly. b) probability function for Pallett Creek, derived by simply adding up the intervals with uncertainties determined from uncertainties of the limiting events. Notice the trimodal shape, like that at Wrightwood (Figure 46). c) 30-yr conditional probability derived from b. Due to the multimodal shape of the probability function, the conditional probability goes up and down; this may simply be an artifact of too few data to define the function.

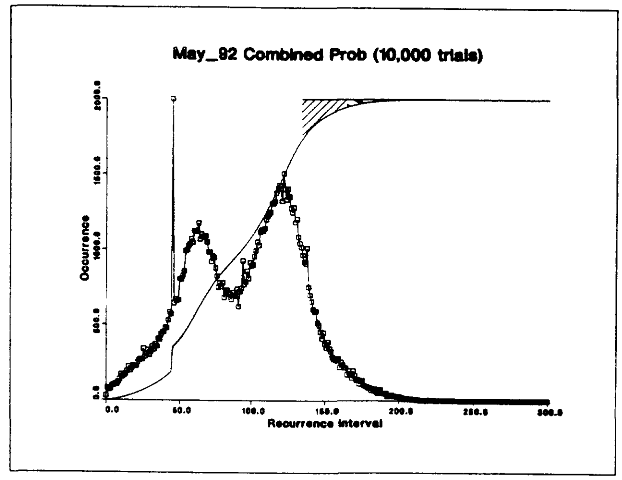


Figure 48. Probability function for recurrence of ground-rupturing earthquakes on the Southern San Andreas fault. The curve with points is generated by picking many times from the distribution functions for the age range of individual earthquakes, dated at paleoseismic sites. The spike is the exact interval between the historic 1812 and 1857 events. The ascending curve is the cumulative probability. The hatchered regions are the areas under the curve within and beyond the next 30 years. The conditional probability of an earthquake during the next 30 years, from this empirical probability function is 80%.

Several interesting statements were made during the ensuing discussion of stratigraphic details, assumptions, and statistical methods. **R.WELDON** noted that since we cannot expect every event to rupture both of the two sites, the 80 to 90 percent probability isa minimum hazard estimate. This would indicate a probability greater than 1 percent, which would put us at a Level C alert as defined in the illustration presented by T.Heaton (Table 2).

May 8, 1992
Morning Session

J.HEALY, of the USGS in Menlo Park, described the activities involved to test the earthquake prediction algorithm, M8, which are described in an advance draft of an open-file report (See Appendix G). Many of these activities involved obtaining a consensus about what constitutes a "valid" test. A global test was developed in the Circum-Pacific region with 147 circles 700 to 800 km in diameter (Appendix G, Fig. 1). The circles are declared either "in TIP" (time of increased probability) or "not in TIP."

When we ran the test in our final chosen configuration, of 10 $M \geq 7.5$ in the circles, we predicted 8; two were missed. This would give us a confidence level of 97 percent, if other problems didn't exist, but they do.

A number of data fixing methods exist that would allow us to obtain such results. In the first run, the investigators made the assumption that when a large earthquake occurred, the warning would terminate. Under that assumption, only six earthquakes were predicted. After looking at the data set, of the more than 200 M7.5 earthquakes in those circles since 1900, about 20 percent occurred in pairs. This shows that a strong tendency exists for earthquakes to occur together at distances beyond the range we would normally consider to be a mainshock-aftershock relationship. If we ignore the assumption for the period under investigation, we predicted 8 of 10 events.

J.HEALY indicated that he and his colleagues would like to publish this work and were seeking NEPEC's guidance about what sort of statement they might use in the article to point out that the article is a scientific test, not a public policy document.

J.DEWEY of the USGS in Denver, Colorado, presented NEPEC with some additional written documentation (Appendix H) and explained the TIP concept in more detail. The M8 algorithm uses a circle drawn in the region of investigation and counts various measures of seismicity. When 6 of 7 functions reach an anomalous alpha level, the program declares a TIP, which indicates that, somewhere in this vast circular region, a higher probability exists for a large earthquake within the next five years.

A number of successes have been claimed for M8, and the question remains as to whether they are statistically significant, given the size of the areas and the 5-year period for which the TIPs are declared. **J.DEWEY** and colleagues think that the best method to test the algorithm is with a forward test with predefined parameters and null hypotheses to see if the statistics turn out to be significant. We have set up the null hypotheses and performed a retrospective test (called Test A) for the period 1985 to 1991 to test the procedure. In the course of this test, we modified the procedure for the forward test which we call Test B. We will run both Test A and Test B to see how these modifications impacted the algorithm.

The test is focused on the prediction of M7.5 and greater earthquakes occurring on the margins of the Pacific Ocean. We will use hypocenters and magnitudes computed by the National Earthquake Information Center (NEIC) in Golden which computes three catalogues of earthquakes with different levels of completeness and time delays. One comes out after only 7 days after the occurrence of earthquakes; this is very incomplete. The PDE Weekly comes out with a four week delay; we will use this for provisional prediction in M8. In the final analysis for counting successes and failures, we will use the monthly PDE which has a delay of 7 months.

We use the Global Hypocenter CD/ROM Version 1 produced by NEIC in 1989 for determining the background level of seismicity, for determining anomalies, and for analysis of seismicity occurring in 1988 and earlier. This CD/ROM has a number of catalogs with some duplication, so we have defined conventions for identifying and removing duplicates.

M8 requires that a single magnitude be associated with every earthquake. This requires a convention when several magnitudes might be associated with a given event. The data base used has fields for four magnitudes; two correspond to the NEIC M_B and M_S magnitudes and the other fields correspond to contributed magnitudes, which are usually from Berkeley and Pasadena. The convention is that the magnitude for M8 purposes will be the maximum magnitude of the four or fewer that are listed for each earthquake in the data base. Thus for small and moderate events, which M8 counts in order to issue the TIPs, most of the magnitudes will be M_B magnitudes, but, on the other hand, for the largest events, magnitudes will be M_S magnitudes.

Using a M_M convention, one would have a somewhat different set of objects of prediction. For instance for the period 1985 to 1991 during which M8 predicted 10 earthquakes, using a M_M convention, one would predict 11 events, four of which were not predicted using the convention outlined above.

We propose issuing semi-annual updates during the course of this test. This seems appropriate as long as we make it clear that we are conducting a test, not attempting to issue predictions for use by civil authorities.

K.SHEDLOCK asked how the radius and locations for the circles were chosen, since the distribution of circles seemed somewhat unequal.

J.DEWEY noted that the 427 km radius was determined by the threshold magnitude of 7.5. The centers were arbitrarily assigned around the margin of the Circum-Pacific seismic belt and the regions overlap by 30 to 40 percent. If no more than about 20 small events per year occurred within a circle, the background level was too low to be able to confidently detect an anomaly against that background level and those circles are not considered. The remaining 147 circles have an average level of seismicity of 20 events or more per year over a period of about 30 years. This batch of circles is different from those addressed by our Russian colleagues.

J.DEWEY concluded by addressing a null hypotheses proposed by J.Dieterich that TIPs randomly distributed among the 147 regions of investigation, but assigned according in proportion to the level of historical activity, would do as well as TIPs generated by M8. A factor of 40 difference exists between the most active region and the least active region. This hypothesis produced interesting results: where M8 Test A estimated with a level of significance of 76 percent, his Test A estimated a 68 percent level and where M8 Test B estimated a 97 percent level, his estimated a 94 percent level.

J.DIETERICH described his null hypothesis (Appendix I) as a method of looking at the Poisson model, or long-term rate, of activity in the circle. This might produce a useful result against which to judge the efficacy of the performance of M8. Successes per TIP interval for the weighted random assignment of TIP is about 1.3 percent and for M8 is 1.5 percent. So, while some differences exist and the numbers are small, M8 may provide as much as a 50 percent probability gain over the background rate. This doesn't provide enough information on which to base public policy or action. Nevertheless, for the first time we have a procedure with which we can evaluate M8 and the claims that have been made for it. For these reasons, **J.DIETERICH** supports this test of M8.

W.BAKUN asked what would happen in the Los Angeles area if a TIP is declared for that area. What would NEPEC's response be? **T.McEVILLY** reiterated, what would Healy ask of NEPEC? **J.DIETERICH** discussed wording of his memo (Appendix I) concerning the algorithm's principal use being for scientific purposes, not public policy. **J.DEVINE** opined that some commotion might result if the existence of a TIP were announced without an explanation of the probabilities, but that a minor news report would likely result if the probabilities were explained.

J.DAVIS pointed out that a statement from NEPEC at this stage could lay the foundation for whatever might come about as a result of the M8 experiment. He noted that since this was an experiment with low probability gain and high false alarm rate, it was not an appropriate source of information for public policy decisions. In fact, **J.DIETERICH** stated, statements to the contrary in the press, M8 has not predicted any specific events. **K.SHEDLOCK** noted that a consensus had been reached by pointing out that numerous suggestions concerning a NEPEC statement on M8 have been made. The Council agreed to make a recommendation during the afternoon session.

J.LANGBEIN of the USGS in Menlo Park presented materials (Appendix J) concerning the Parkfield Prediction Experiment that were prepared for a workshop to be held in June, 1992. The workshop participants will review and discuss accomplishments and priorities. **J.LANGBEIN** also mentioned a review of the Parkfield experiment by a panel of scientists who have no direct ties to work there. A draft charter had been prepared by W.Ellsworth in anticipation that NEPEC would consider chartering an ad hoc working group.

J.DIETERICH suggested that the draft charter outlined the problem well, but that an ad hoc panel should also be charged with determining the efficacy of the methodology used to make the long-term forecast, which had a high level of confidence. **J.DAVIS, W.BAKUN, J.DIETERICH,** and **R.WESSON** discussed the importance of separating an evaluation of the prediction made for the next event at Parkfield from an evaluation of the Parkfield experiment itself. Although the Council rapidly reached the consensus that such a panel was warranted, it decided to make final decisions on the topic at the outset of the afternoon session.

J.LANGBEIN also presented some thoughts about matched filters and how to evaluate creep events that occur at Parkfield during periods of rainfall. To reiterate a statement made at the last NEPEC meeting (Frizzell, 1992, p. 26-27, appendix F), rainfall was not mentioned in the description of alert levels determined on the basis of creep events. He proposed footnotes to the creep rules (Bakun and others, 1987) that would down-rate, by one level, creep events that are preceded by significant rain (Appendix K):

> **Levels D-A**: If >2 cm of rain falls in a 24 hour period in the week preceding a creep event, then decrease by one unit the status level as defined in the Table (page 28 of Parkfield Scenarios....).

> **Levels B-A**: Should a strain change be detected at the 95% confidence level or better on a nearby dilatometer or tensor strainmeter, then the status level for creep will remain as defined in the Table (page 28 of Parkfield Scenarios....)

This proposal prompted some discussion concerning the rationale and efficacy of using a "hard wired" decision-making process rather than individual judgment. The present system of decision making allows scientists to determine levels of alert and communicate those levels without involving the Director. This is particularly important at Parkfield, because one of the goals is to make a near real-time short-term prediction. After some additional discussion, NEPEC endorsed Langbeins's proposed change.

J.LANGBEIN concluded by stating that the matched filter analysis is a good method of assessing the sensitivity of an instrument. In designing experiments this technique should be used, because they provide a good way to characterize statistics of creep events, which have a high signal to noise. **W.BAKUN** supported the concept and procedure and urged Langbein to also consider data from the borehole strain meters.

May 8, 1992
Afternoon Session

T.McEVILLY presented W.Prescott's suggested modifications concerning questions that would be presented to the ad hoc working group on Parkfield in the draft charge provided by W.Ellsworth. After some discussion and modification of the draft and consideration of possible working group members, the Council agreed on particulars and asked the Chair to complete the charge (Appendix L).

The Council asked the Executive Secretary to draw upon written documents submitted to NEPEC by J.Dewey and J.Dieterich and discussions undertaken at the meeting to draft the NEPEC statement on M8 for the Chair to finalize (Appendix M).

The Council readdressed the proposed NEPEC statement presented yesterday by K.Shedlock on the Cascadia subduction zone and the charge to, and membership of, the proposed ad hoc working group on the CSZ. Although numerous modifications to the draft statement were suggested, the group decided to await the report of the working group before completing the NEPEC statement and requested that the Chair circulate a draft charge (Appendix F) to Council members before asking Craig Weaver to chair the working group.

J.DIETERICH presented a short report on the possibility of convening a workshop to evaluate various prediction methodologies, especially to address the long-term forecasts, which have become a prominent aspect of earthquake hazard assessment. These forecasts derive from several hypotheses that have not had systematic review. A letter of invitation and attendees has been drafted, but no other action has been taken. Four tentative goals include: identify the major issues, summarize the range of views on these issues, present statements of consensus where possible, and outline work needed to resolve issues. Tentative topics include: fault segmentation, characteristic earthquakes, recurrence models, uncertainty of probabilities. Incorporation of model uncertainty, which might be the dominating uncertainty, in the computations would be addressed during discussion of the last topic.

While asserting that NEPEC should address these issues before taking on another major forecasting/prediction effort, **J.DIETERICH** pointed out that this would be a major undertaking and everyone seems over committed. **K.AKI** and **R.WESSON** briefly discussed the possibility of a joint NEPEC/Southern California Earthquake Center (SCEC) workshop to address the topic.

Three issues seem to be of importance here, according to **R.WESSON:** the original methodology workshop that J.Dieterich discussed would address the 1988- 1990-type probability reports, how to address southern California (which SCEC had indicated it would address), and the relationship of probabilities and ground motion.

R.WESSON continued by stating that the last issue almost seems counterintuitive, because if one looks at the current Algermissen ground motion map of the US, two things seem evident. With a 300- or 500-year recurrence, for instance in the PNW, the probabilities hardly show up at all, in terms of the ground motion maps that looks at 30 or 50 years. The difference in distribution of ground motion between tight sources and distributed sources can appear erratic. For instance, higher probabilities of exceedence exist for parts of New England than for large parts of Idaho, because the Borah Peak source is fixed, but the Charleston earthquake is invoked up and down the east coast. **R.WESSON** acknowledged that his comment was an excursion from the concepts that **K.AKI** was presenting, but asserted that the USGS and NEPEC must eventually rationalize such different approaches to producing probabilistic risk analyses. Anything that NEPEC might do to force or stimulate progress in the methodology would be important. **J.DIETERICH** suggested that an alternate approach would be for the USGS to fund some focused research in this area. **T.McEVILLY** agreed, suggesting that the topic was larger than might be accommodated by a workshop or on a pro bono basis and that it would seem to require concerted, full-time effort on the part of several workers for 6 months to a year.

In light of the NEPEC activities related to the CSZ and Parkfield working groups, and especially in light of the fact that SCEC might have addressed at least part of the issue in a year's time, the Council decided to delay further consideration of the topic.

The Chair pointed out that, in light of the Council's report from the meeting in Utah, the Director has agreed to communicate with the State of Utah concerning earthquakes. The Vice Chair and Executive Secretary agreed to follow up on the issue.

J.DAVIS addressed the San Francisco Bay Area ground motion maps. He would like to have some sort of popular document to accompany the J.Evernden intensity maps (Evernden, 1991), which have been open-filed. **J.DAVIS** is attempting to use his staff to prepare such a document, which might be presented in an issue of California Geology. He noted that M.Reichle is working through W.Bakun with J.Boatwright on a set of probabilistic ground shaking maps for the individual events addressed in the probability assessments from the 1990 working group (Working Group on California Probabilities, 1990). **R.WESSON** pointed out that a couple approaches are possible: J.Evernden's approach seems somewhat standardized and appears to derive ground motion from intensity and J.Boatwright's approach may have a higher degree of detail and resolution with regards to substratum conditions. J.Boatwright and others are attempting to better understand and document J.Evernden's approach and to bring together a couple additional methodologies for predicting ground motion and/or intensity together on a regional scale. **A.LINDH** pointed out that K.Coppersmith has addressed the

San Francisco Bay area with a state-of-the-art model using characteristic earthquakes with conditional probabilities plus regional b-slope with a strain budget constraint and is asking hundreds of thousands to millions of dollars per site. **A.LINDH** proposed San Mateo County as the trial region because of the availability of a digitized Quaternary materials map. **T.HEATON** agreed that this would be a good idea, but that most scientists don't want to address intensity (which is convenient for interpretation and planning) because it is subjective. The Council discussed the topic and several alternative activities and concluded that at a future meeting NEPEC would review the map results of various methods of predicting ground motions and/or intensities from a specific earthquake scenario using different methodologies presented at a meeting to be organized by USGS personnel in Menlo Park.

The Chair asked the members to address the next meeting both in terms of topics and venue. **J.DIETERICH** mentioned that for some time the Council had been talking about addressing earthquake hazards and outstanding predictions in Hawaii. **T.HEATON** noted that the Hawaii Volcano Observatory is very interested in addressing the issue in a more robust manner. **R.WESSON** pointed out that is organizing a workshop on Hawaiian earthquakes and several mainlanders will be attending that event. As an alternative to a meeting on Hawaiian earthquakes in Hawaii, the Council determined to evaluate the Hawaiian predictions at a mainland meeting and to invite the four or five most active workers to attend.

J.DAVIS noted that the Council had been considering addressing the work that R.Weldon presented in the evening session, and **R.WESSON** suggested that, if the Council were to address that work, K.Sieh should be invited to present his analysis. **J.DIETERICH** thought out loud that if we address the results of these two workers, shouldn't the whole issue of southern California probabilities be readdressed. While **R.WESSON** said that it might not be warranted to readdress the probabilities for a region each time a new article is published, he agreed that Weldon's and other recent work emphasized the need for a reevaluation of southern California, especially noncharacteristic models. He suggested that a long-range plan for evaluating the situation in the region seems warranted, starting with the predictive ground motion analysis that SCEC was addressing. The next step might be the methodology for predicting ground motions and/or intensities addressed previously. By 1994, 6 years after the first report, NEPEC might produce a definitive update of the consensus view for southern California.

A meeting in the East was mentioned. **R.WESSON** summarized the issue concerning how to do probabilities in the East and pointed out that A.Johnston and others have produced some estimates for the New Madrid zone and elsewhere in the East. NEPEC could address methodology in order to determine the best ways to estimate recurrence probabilities for the East.

The Council proposed two future meetings. A meeting held in the Menlo Park in October or November, 1992, would address the strong ground motion issues and the Hawaiian predictions, as well as receive the reports of the two working groups (Parkfield and CSZ). Next winter, a meeting in the East would address probabilities there and any remaining business from earlier meetings.

R.WESSON reported that NEPEC Member J.Davies, in addition to his seismological and NEPEC interests, is a member of the Borough Assembly, which demands a considerable amount of time, and also serves the seismology community as a member of the NEHRP Advisory Board. J.Davies reports being over committed and has indicated that he will soon be sending a letter of resignation from NEPEC. The decision concerning a replacement is the Director's, but it would not be unreasonable for the Council to make a recommendation to him. A tradition of having a person knowledgeable about Alaska is of long standing, and J.Davies has suggested M.Wyss as his replacement. The Council agreed that it would include him on a list that will be presented to the Director upon J.Davis' resignation.

Meeting was adjourned at 4:40 pm.

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APPENDICES

Appendix A Agenda for the May 7 and 8, 1992, NEPEC meeting at Portland, Oregon.

Appendix B Document provided NEPEC by Malone, presenting earthquake hazards in the Pacific Northwest based upon historic seismicity.

Appendix C Document provided NEPEC by Somerville, concerning the prediction of strong ground motion.

Appendix D Document presented to NEPEC by Beaulieu, outlining the Oregon Earthquake Hazard Plan for the period 1990 to 1995.

Appendix E Document presented to NEPEC by Walsh, outlining the Washington Framework for Seismic Risk Reduction.

Appendix F Earthquake Hazards in the Pacific Northwest: Information and charge to the NEPEC working group on the Cascadia subduction zone.

Appendix G Document provided NEPEC by Healy: An advance draft of an open-file report on M8, an earthquake prediction algorithm.

Appendix H Document provided NEPEC by Dewey, detailing several aspects of the M8 algorithm and of M8 Tests A and B.

Appendix I Document provided NEPEC by Dieterich, presenting a comparison of the M8 algorithm with a Poisson model.

Appendix J Letter dated June 4, 1992, presented to NEPEC by Langbein outlining a workshop/review of the Parkfield prediction experiment.

Appendix K Letter dated November 15, 1991, presented to NEPEC by Langbein outlining a revision to the Parkfield earthquake prediction scenario based upon rainfall.

Appendix L Earthquake Research at Parkfield - 1993 and Beyond: Information and charge to the NEPEC working group for the Parkfield Prediction Experiment.

Appendix M M8 Prediction Algorithm Study: NEPEC Review of Results, May, 1992.

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Appendix A

Agenda for the May 7 and 8, 1992, meeting of NEPEC at Portland, Oregon.

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National Earthquake Prediction Evaluation Council
May 7-8, 1992

Portland, Oregon

Thursday, May 7 --

8:30	Introductory remarks, comments on agenda	Tom McEvilly, Chairman Rob Wesson, Vice Chairman
8:45	Overview of the Pacific Northwest (PNW)	Craig Weaver, USGS
9:00	Paleoseismology of the PNW	Alan Nelson, USGS
9:20	Paleoseismology of Puget Sound	Bob Bucknam, USGS
9:40	PNW crustal architecture	Ray Wells, USGS
10:00	Break	
10:15	Monitoring seismicity	Steve Malone, University of Washington (UW)
10:25	Monitoring strain accumulation	Mike Lisowski, USGS
10:45	Predicting strong ground motion	Paul Somerville, Woodward-Clyde
11:05	Oregon ground acceleration maps	Ray Weldon
11:10	Portland hazards map	Ian Madin, Department of Geology and Mineral Industries
11:30	Oregon: activities and goals	John Beaulieu, DOGAMI
11:45	Washington: activities and goals	Tim Walsh, Division of Geology and Earth Resources
12:00	Lunch and Posters	
1:30	Posters:	
	Paleoseismology --	Brian Atwater, USGS Bob Bucknam, USGS Gary Carver, Humboldt State University (HSU) Wendy Grant, USGS Alan Nelson, USGS Curt Peterson, Portland State University (PSU) Tom Yelin, USGS
	Oregon hazards --	Marv Beeson, PSU La Verne Kulm/Chris Goldfinger, OSU Ian Madin, DOGAMI Roger McGarrigle,Van Domelen/Looijenga/McGarrigle/Knauf Engineers Ray Weldon Bob Yeats, OSU
	New refraction lines --	Anne Trehu, Oregon State University (OSU)
	New geodetic data --	Mike Lisowski, USGS

2:00	Gorda plate update	Gary Carver, HSU
2:30	Cape Mendocino earthquakes & predictions	David Oppenheimer, USGS
3:00	Regional setting and offshore faults	Sam Clarke, USGS
3:30	West coast tsunamis	Eddie Bernard, NOAA
4:00	Break	
4:15	Open discussion -- possible topics include the program proposed by 1067, cooperative studies, subduction zone events, monitoring needs, possible NEPEC activities, needs of OR & WA, Cape Mendocino events	
5:00	Focussed discussion -- consideration of consensus statement by Weaver, Shedlock and Kanamori	
6:00	Dinner	
8:00	Joshua Tree earthquakes & predictions	Tom Heaton
8:30	Review: Southern California working group	Tom Heaton, Rob Wesson, & Tom McEvilly
9:00	Southern California probabilities: density functions from "real" recurrence interval data	Ray Weldon
9:30	Discussion	
10:00	Adjourn	
Friday,	**May 8**	
8:30	M8, an earthquake prediction algorithm	Jack Healy & Jim Dewey, USGS
9:30	Discussion of M8	
10:30	Break	
10:45	Parkfield Experiment:	
	Matched filters	John Langbein, USGS
11:15	Proposal for review	John Langbein & Members
12:00	Lunch	
1:30	Review: Prediction methodologies workshops	Jim Dieterich
2:00	Review: Wasatch front: what next?	Members
2:30	Review: S.F. Bay ground motion maps	Bill Bakun & Jim Davis
3:00	Open	
3:30	New business	
4:00	Executive session	
4:30	Adjourn	

(1 May 1992, Draft)

Appendix B

Document provided NEPEC by Malone, presenting earthquake hazards in the Pacific Northwest based upon historic seismicity.

Pacific Northwest Earthquake Hazards based on Historical Seismicity

Steve Malone
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University of Washington
Seattle, WA 98195

About 190 seismograph stations are currently operated in the Pacific Northwest (between 41°-51°N and 111°-126°W) by eleven different organizations. The largest individual network is the Washington Regional Seismograph Network (WRSN) which operates 124 stations in Washington and Oregon. Earthquake phase and location information is routinely distributed to other network operators by the WRSN and data from these other networks are often made available to the WRSN for the purposes of refining location in areas not well covered by seismograph stations.

A review of historic seismicity in the region reveals major concentrations of seismicity with characteristics particular to different areas. These areas include the Rocky Mountains of Montana and central Idaho, the Cape Mendocino area of California, the Columbia River Plateau of Eastern Washington, the flanks of the Cascade Range, and the greater Puget Sound and Willamette Valley areas of western Washington and northern Oregon. Current seismicity shows no low angle thrust mechanisms along the Oregon-Washington coast and thus does not indicate the presence of a potential mega-thrust zone. If even moderate sized earthquakes with such mechanisms were to occur it would be cause for re-evaluating the potential for a large subduction type of event in the near future. The major historic cause of earthquake damage in Washington and Oregon has been slab-bend type events at depths of 40-60km under the Puget Sound-Willamette lowlands. Major, historically active crustal faults have not been identified in Washington or Oregon; however the Mount St. Helens seismic zone may represent such a fault zone. The source structure for the 1872 north Cascades earthquake may, likewise, be on a hidden crustal fault. Minor crustal faults, show concentrated seismicity along the flanks of the Cascades in Washington and northern Oregon, in the eastern Olympics and coast ranges, and in parts of the Columbia River Plateau of eastern Washington. Basin and Range type normal faulting occurs in eastern Oregon, though the associated historical seismicity is much less here than it is farther south in Nevada. Several of the Cascade volcanos show moderate historic seismicity both in association with volcanic activity (Mount Lasen and Mount St. Helens) and without such activity (Mount Shasta, Mount Hood, and Mount Rainier).

The general concentration of historic seismicity in the greater Puget Sound and Cape Mendocino areas rather than all along the Cascadia subduction zone is not well understood. The complexity of the Cape Mendocino triple junction helps explain the seismicity here. A warp or bulging up of the subducting slab in the Washington area caused by a change in strike of the subduction zone from north-south along the Oregon coast to northwest-southeast along the British Columbia coast is often used to explain the general seismicity pattern of western Washington, though the details of these patterns are not well understood in terms of this model.

Pacific Northwest Regional Network Cooperation

Steve Malone

Spring, 1992

The table below lists the regional network operators in the Pacific Northwest that have been contacted and have expressed, at least some interest, in the cooperative sharing of data. A map of the region showing the seismic stations for each recording center is shown on the reverse side. In some cases fairly formal data exchange procedures have been set up; in others it is very informal on an event by event basis. Some networks are undergoing significant development work either in station distribution or analysis procedures and thus routine data exchange has not yet been easy to establish. Information files for many of these networks are available through anonymous ftp (InterNet File Transfer Protocol) on host, *geophys.washington.edu* in directory, *seis-net*. Files with names, *net.info.???* contain a description of each network including name, contact people, area covered, recording type, etc. Files with names, *???.sta* are station location lists in the same format as used by that network.

PNW Regional Networks

RECORDING CENTER	CONTACT	# STA	TYPE & DATA EXCHANGE*
UW **Wash. Reg. S.N.**	Steve Malone steve@geophys.washington.edu quake@geophys.washington.edu	124	A- to USGS, OSU, UO, UM, HAN, NEIC R- to PGC, from PGC, OSU S- to BSU, from BSU, UO
PGC **Pacific Geo. Centre**	Gary Rogers rogers@pgc.emr.ca	~30	R- to UW, from UW S- to UW
OSU **Oregon State U.**	John Nabelek nabelek@jacobs.cs.orst.edu	1	A- from UW S- to UO, UW
UO **Univ. Oregon**	Gene Humphreys cpat@newberry.uoregon.edu	3	A- from UW S- to UW, OSU, from OSU, USGS
INEL **Id. Nat. Eng. Lab**	Suzette Jackson msj@inel.gov	24	R- to UM, U. of Utah, from U of Utah S- to BSU
UM **U. of Montana**	Mike Stickney mcstickney%mtvms1.dnet @terra.oscs.montana	12	A- from UW R- to INEL, from INEL S- to BSU, UW, from BSU
BSU **Boise State U.**	Jim Zollweg zollweg@hookipa.idbsu.edu	12	S- to UW, INEL, UM S- from UW, INEL, UM
USGS **Cal Net**	Al Lindh oppen@alum.wr.usgs.gov	300+	A- from UW S- to UW, UO
HAN **Hanford Net**	Norm Rasmussen dixie@geophys.washington.edu	16†	A- from UW S- to UW
CVO **Cascade Vol. Obs.**	Ed Wolf ?	8†	S- to UW, from UW
UI **Univ. Idaho**	Ken Spreenke ?	?	S- to BSU, UM, INEL (?)

*- Type 'A' means automatic data exchange by either the recording and/or the analysis computer, 'R' mean routinely exchanged in the course of producing catalogs, and 'S' mean data exchanged only on special request.

†- These network stations are recorded locally as well as part of the UW net.

Public information about recent or current earthquakes in the Pacific Northwest is available over the InterNet using *finger quake@geophys.washington.edu* or logging into the open account called, *quake* with password, *quake* at the dial-in phone number of (206) 685-0889.

Pacific Northwest Earthquake Hazards

-> Mega-thrust in coastal areas, M > 8

300 bp? - Wash-Oreg. coast

1992 - Cape Mendocino ?

No thrust mechanisms have been found for events along the Wash-Oreg coast. Should even modest sized events occur with thrust mechanisms it would be cause for concern.

-> Slab bend in Puget Sound / Willamette Valley, M ~ 7+

Seattle 1939 M = 6.2

Olympia, 1949 M = 7.2

Seattle, 1965 M = 6.5

These events have been the most historically damaging in the Pacific Northwest, have down-dip tension mechanisms and have very few aftershocks

-> Major crustal fault zones, M 6-7+

North Cascade, 1872 M = 7.3

Borah Peak, ID 1983 M = 7.3

Cape Mendocino, CA 1980 & 1992

Major fault zones have not been identified near large urban centers in the Pacific Northwest. In western Washington/ Oregon the St. Helens Seismic zone and the north Cascades may represent such zones. Large aftershocks are typical.

-> Minor crustal fault zones, M < 6

Milton Freewater, 1936 M = 5.5

Chelan, 1926, 1958, 1959 M= 5.0

Portland, 1962 M= 5.3

Goat Rocks, 1981 M = 5.1

Minor seismicity is common along the flanks of the Cascades, in the fold belts of eastern Washington, basin and range of eastern Oregon, and in the Olympics and coast range. Events may occur in main shock-after shock or swarm sequences.

-> Volcanos, M ~ 5

Mount Rainier, 1974 M = 4.9

Stevens Pass, CA 1978 M = 5.1

Mount St. Helens, 1980 M= 5.2

Usually occurs in swams, may or may not be associated with volcanic activity, and hazards from direct ground shaking are minimal.

Appendix C

Document provided NEPEC by Somerville,
concerning the prediction of strong ground motion.

NATIONAL EARTHQUAKE PREDICTION EVALUATION COUNCIL
MAY 7-8, 1992, PORTLAND, OREGON

PREDICTING STRONG GROUND MOTION

Paul Somerville
Woodward-Clyde Consultants, 566 El Dorado Street, Pasadena, CA 91101

Subduction Earthquakes. The occurrence of the magnitude 8 Michoacan, Mexico and Valparaiso, Chile earthquakes in 1985 provided strong motion recordings close to large subduction earthquakes that are very relevant to the prediction of strong ground motion in the Cascadia subduction zone. These recordings have been used by several authors to refine empirical strong motion attenuation relations, and to test seismologically-based ground motion models that were subsequently applied to the Cascadia subduction zone. The various ground motion prediction models are in general agreement, suggesting that there is a fairly good basis for predicting strong ground motions from large subduction earthquakes, at least on rock and for frequencies above about 1 Hz. The motions are expected to be somewhat larger than those for crustal earthquakes of the same magnitude and distance. The main uncertainties in the prediction of strong ground motions on rock sites in the Puget Sound and Portland regions are due to uncertainties in the downdip extend of the seismogenic part of the plate interface, and in the distribution of slip as a function of depth on the plate interface.

Wadati-Benioff Earthquakes. The largest strong motion recordings in the Puget Sound region are from the magnitude 6 3/4 1949 and 1965 Olympia and Seattle earthquakes which both occurred in the Wadati-Benioff zone. These recordings have been used to check empirical strong motion attenuation relations and to test seismologically-based ground motion models. The recordings appear to have been strongly influenced by site response, and have larger motions at periods longer than 1 second than predicted by most models. The motions are expected to be significantly stronger than those for crustal earthquakes of the same magnitude and closest distance. The ground motions from magnitude 8 subduction earthquakes are expected to be about twice as large as those recorded during these two events at periods shorter than 1 second, and more than twice as larger at longer periods.

Site Response. In recent years, information on the shallow velocity structure in the Portland and Puget Sound regions has been gathered for use in estimating site response, and recordings from explosions and earthquakes have been used to empirically estimate site amplification factors. These shallow velocity models and recorded data are probably relevant for estimating site response at high frequencies. Modeling studies have been done that take into account the focussing effects of topography on the contact between bedrock and sediments in the Puget Trough from motions arriving almost vertically from below. However, these studies have not considered the possible effects of trapping of waves in basin structures.

Basin Response. Both the Puget Sound and Portland regions are potentially subject to the effects of trapping of waves in basin structures. The Puget Trough has unconsolidated sediments as thick as 1,000 meters, and the Tualatin and Portland Basins have sedimentary rocks overlying the Columbia basalt at depths as much as 300 meters. The large velocity contrasts in these structures may be very effective in trapping seismic energy at periods of about one second and longer. These effects are expected to be important both for subduction earthquakes and for crustal earthquakes in which the motions enter the basins through their margins. For crustal earthquakes, there is evidence of basin response in the intensity pattern observed in the Puget Sound region from the 1981 Elk Lake earthquake. Subduction earthquakes have large spectral amplitudes at long periods, and the potential amplification of these large long period motions by basin response has important implications for the safety of structures such as bridges and highrise buildings. These effects are not included in conventional site response analyses using 1-D velocity models, because waves arriving from below cannot become trapped in such structures. Modeling of strong motion recordings from the 1971 San Fernando and 1989 Loma Prieta earthquakes using 2-D and 3-D velocity models indicates the importance of considering the role of laterally varying structure in amplifying strong ground motions.

Appendix D

Document presented to NEPEC by Beaulieu, outlining the Oregon Earthquake Hazard Plan for the period 1990 to 1995.

Oregon

DEPARTMENT
OF GEOLOGY
AND MINERAL
INDUSTRIES

Administrative Office

OREGON EARTHQUAKE HAZARD PLAN FOR 1990-1995

During the 1980's, research carried out by earth scientists in Oregon and Washington has greatly improved our understanding of earthquake hazards in Oregon. Abundant evidence now exists in support of the theory that great subduction zone earthquakes have occurred repeatedly in Oregon. Quaternary faulting and active crustal seismic zones have also been identified in the Portland-Vancouver Metro area and the northern Willamette Valley. These results underscore the fact that significant earthquakes are possible in Oregon, earthquakes for which Oregon cities are not prepared. This Five Year Plan is intended to define the unique role of the Oregon Department of Geology and Mineral Industries (DOGAMI) in addressing this unmet need.

Leadership Role

The 1989 session of the Oregon Legislature passed a bill (SB 955), which designated DOGAMI as the lead agency for earthquake hazard research in Oregon. In keeping with those responsibilities, this plan seeks to meet the need for hazard information with a broadly based and funded program coordinated by DOGAMI. DOGAMI will make the most effective use possible of existing state and federal research, resource and funds.

Since 1987, DOGAMI has been involved in a cooperative research program with Oregon universities and the U.S. Geological Survey, through the National Earthquake Hazard Reduction Program (NEHRP) to assess earthquake hazards in Oregon. Public education through DOGAMI efforts and NEHRP-sponsored workshops has greatly increased public awareness of the hazard, and individuals, businesses and local governments are actively seeking to reduce their risk of earthquake damage. These and similar efforts will continue.

DOGAMI will seek to create new funding opportunities, to coordinate research activities of university and government scientists and to involve private industry. DOGAMI will emphasize applied research both with in-house and sub-contracted efforts, to bridge the gap between research and practice. DOGAMI will arrange to translate and transmit hazard information to the public through a wide range of outlets.

To achieve these ends DOGAMI will establish cooperative programs with other government and private agencies, and with universities in Oregon and adjacent states. DOGAMI will also consult with the Seismic Safety Policy Advisory Commission on a regular basis, to integrate DOGAMI activities with statewide hazard reduction policy goals.

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Prediction of Earthquake Effects

The goal of the plan is the prediction of earthquake effects. The aspects of local geology that influence earthquake effects will be measured and analyzed in order to predict relative earthquake effects. Concurrently, we will pursue a long-term goal of characterization of earthquake sources. The specific goal of the plan will be to provide 1:24,000 scale relative hazard maps and scenario earthquake maps for the Portland-Vancouver, Salem, Corvallis-Albany, Eugene and coastal urban areas by 1995.

Under this plan, DOGAMI will begin to produce earthquake hazard maps for the major urban areas of western Oregon. Using detailed geologic mapping and geotechnical data, DOGAMI will produce a series of digital relative hazard map layers at a scale of 1:24,000. These maps will show relative liquefaction potential, relative amplification potential and relative earthquake-induced landslide potential.

The individual hazard map layers will be stacked to produce a composite relative earthquake hazard map. These maps may also be published to provide detailed hazard information in a format that will be easily understood by non-specialists. In the Portland area, the maps will also be provided in digital form to Metro, the regional service agency. Metro can incorporate these data layers into their existing regional GIS system where the information can be used for sophisticated land-use, engineering and emergency management planning. For other urban areas, the data will be distributed in appropriate formats through the appropriate local and State agencies.

Some agencies for their specific interests will find that the digital relative hazard maps will lend themselves to production of a series of earthquake scenarios based on a selection of realistic earthquake sources for emergency response planning and loss estimation. As improved earthquake source information becomes available in the future, it can be combined with the existing relative hazard map layers to produce deterministic or probabilistic hazard maps. There, in turn will guide zoning, building practice and other related functions.

Hazard maps will also be prepared for coastal communities which face the additional threats of coastal subsidence and tsunami inundation in the event of a great subduction earthquake.

Characterization of Earthquake Sources

DOGAMI will expand the understanding of geologically young crustal faulting in western Oregon through mapping, trenching, drilling and seismic monitoring. Numerous faults have been identified in the Portland and Willamette Basins, but very little is known about the age and stratigraphy of the rocks cut by these faults. Fault trenching is needed to investigate the possibility that several faults may cut very young rocks.

DOGAMI will continue to encourage and assure a leadership role in facilitating research to understand the size and frequency of great subduction zone earthquakes in Oregon through offshore studies and coastal paleoseismological studies accompanied by detailed mapping of coastal geology. Improved seismic monitoring and imaging by University and USGS seismologists will be encouraged and integrated with geologic studies.

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Appendix E

Document presented to NEPEC by Walsh, outlining the Washington Framework for Seismic Risk Reduction.

— PAGE 95 FOLLOWS —

Washington Framework for Seismic Risk Reduction

by
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Washington Department of Natural Resources
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Olympia, WA 98504-7007

In 1990, the Washington State legislature enacted House Bill 2929, the Growth Management Act (GMA). The GMA required the largest and fastest growing counties and all of their included cities to adopt comprehensive plans and to make zoning consistent with the plan. Planning is required to consider geologic hazards (among other things). The 1991 legislature extended the requirement to identify and protect critical areas (including geologically hazardous areas) to all 39 counties and their included cities.

The basic approach of most jurisdictions for regulations that relate to seismic risk is the mapping of liquefaction susceptibility coupled with a requirement that applicants for building permits within potentially hazardous areas must demonstrate the safety of the proposed project.

Some other jurisdictions are also attempting to zone areas of amplification, but historic intensity and shear-wave velocity data are generally not available outside the Seattle-to-Olympia corridor.

The legislature also created a temporary Seismic Safety Advisory Committee to make recommendations for improving the state's earthquake preparedness. The implementing legislation narrowly failed in the 1992 legislature but will be reintroduced in the 1993 legislature. The committee recommended, among other things:

> that the state of Washington support a strong motion instrumentation program as outlined in U.S. Geological Survey Open-File Report 89-374. As an initial effort, the Washington Department of Natural Resources (DNR), Division of Geology and Earth Resources, is sharing with the U.S. Geological Survey the cost of instrumenting DNR's new headquarters building in Olympia.
>
> that the seismic zonation for western Washington be re-evaluated (in conjunction with the state of Oregon, which is attempting to upgrade western Oregon to seismic zone 3). The application to amend the Uniform Building Code is in preparation and will be sent to the International Conference of Building Officials in June, 1992. The seismic zone map is not yet complete but will put all of western Washington into zone 3.
>
> that DNR, in conjunction with the U.S. Geological Survey, support and coordinate the geologic mapping of sensitive areas, at least in part to achieve the goals of the GMA. The Division of Geology and Earth Resources is currently preparing a new state geologic map. The full color map is at a scale

of 1:250,000 and is supported by a more detailed set of open-file maps at a scale of 1:100,000. We are also investigating liquefaction, both in sets of liquefaction susceptibility quadrangle maps that aid land use planning and in geotechnical investigations of historic liquefaction events, such as the numerous sand blows induced by the 1949 Puget Sound earthquake. These studies have suggested that moderate-to-well-sorted, liquefiable sand can be deposited in valley bottoms as distal facies of volcanic eruptions or debris flows. These sands can be much thicker than sand deposited by normal fluvial processes. Studies are continuing to determine the sedimentary processes responsible for the deposition of these liquefiable sands and to map them in other drainages.

Appendix F

Earthquake Hazards in the Pacific Northwest:
Information and charge to the NEPEC working group
on the Cascadia subduction zone.

- PAGE 99 FOLLOWS -

EARTHQUAKE HAZARDS IN THE PACIFIC NORTHWEST:

Information and Charge to the NEPEC Working Group on the Cascadia Subduction Zone

Background

The tectonic and geologic setting of the Pacific Northwest (PNW) includes the active Cascadia Subduction Zone (CSZ), similar to those elsewhere in the world where great earthquakes occur. No known great earthquakes (M>8) from the CSZ have been recorded by seismographic networks, and none are known from the historical record. The late Holocene geologic record found in numerous coastal intertidal marshes however, contains evidence consistent with the occurrence of great earthquakes. This evidence includes multiple buried peat horizons, each of which may be interpreted to represent a previous soil surface that was suddenly submerged during a great earthquake. At some sites along the coast of the PNW, tsunami-like sands have been deposited directly on these submerged soils, supporting the interpretation that burial was the result of a great earthquake. Other data consistent with, but not nearly as unequivocal as the interpretation made from the marsh subsidence records, include landslides that occur with a frequency similar to the marsh subsidence events and geophysical interpretations of crustal strain data.

The repeat time for these great earthquakes and their probable magnitudes remain uncertain. Resolution of both issues requires demonstration of synchronicity among the specific marsh horizons at multiple sites along the coast, a difficult experimental task. Furthermore, little evidence exists to indicate that strong ground shaking accompanied the most recent event, estimated to have occurred about 300 years ago. Despite these uncertainties, the available data, within their tectonic and geologic setting, constitute ample evidence that the Pacific Northwest is subject to great subduction zone earthquakes, that these events occur on the average of a few times per thousand years, that they involve lengths of the coast sufficient to produce earthquakes of magnitude at least 8, and that the data permit events as large as magnitude 9.

Two other sources for major damaging earthquakes exist in the Pacific Northwest: those within the subducting Juan de Fuca and Gorda plates, and those within the crust of the North American plate. These events have provided the primary model for earthquake hazard assessments in the region. Recent studies have concluded that earthquakes should be expected anywhere within the subducting plates at depths comparable to those known this century (40-60 km), and that a realistic magnitude for planning purposes for these events is in the range of 7 to 7.5. Crustal earthquakes in the North American plate may be a major urban hazard in the Puget Sound basin because M=7 crustal events are known to occur in similar settings elsewhere. Considerable additional geologic and geophysical studies are needed on this issue, and current geological investigations in the Puget Sound region should improve our understanding of major crustal events there.

Further Studies

Recognition of the possibility of great CSZ earthquakes in the PNW calls for more emphasis on direct hazards implications, particularly in the urban areas of the Puget Sound basin and the Willamette Valley. Modeling of strong ground motion, on scales from whole sedimentary basins such as Puget Sound to representative local sites, is needed for the spectrum of sources expected in the region. Additional work is needed to understand potential long-period motions associated with the very long fault breaks expected during a great CSZ earthquake. Finally, because of the danger of locally-generated tsunamis, both along the coast and within Puget Sound, efforts need to be made to map the limits of paleo-tsunami runups and to model future wave heights. Public awareness of all these earthquake-related issues must be increased as an integral part of hazards reduction and mitigation.

Summary and NEPEC Response

The overview presented to the Council on research progress and current hypotheses on the earthquake potential of the CSZ calls for immediate action. Earthquakes of the size permissible under plausible models for the region represent a most serious threat to the U.S. Pacific Northwest from Cape Mendocino to the Canadian border. NEPEC therefore is chartering a CSZ Working Group on this issue to bring together and to summarize current evidence on possible modes of failure of the CSZ and to present the consequent implications for earthquake hazard assessment in the region.

CSZ Working Group Composition

The recommended CSZWG membership includes C. Weaver (Chair), Kanamori, Nelson, Carver, Caruer, Plafker, Malone, Atwater, Savage and Weldon. E. Bernard of NOAA is available for consultation on tsunami issues.

CSZ Working Group Charge

The charge to the CSZWG is to develop an objective assessment of all evidence and hypotheses for and counter to the proposed repeated great (M = 8.5-9) CSZ earthquakes, and to propose a best effort assessment of the possibility of future such earthquakes in the PNW and their potential effects on land. Specific questions surround issues of the frequency of the great earthquakes, the likely mode(s) of failure of the CSZ, and the implications of the plausible scenarios for earthquake preparedness. In addition, recommendations should be made for any specific investigative steps that hold promise for reducing uncertainties in the conclusions drawn from the available evidence.

Working Group Schedule

The CSZWG should strive for early completion of their review and assessment, given the potential impact of their conclusions. If at all possible, a draft consensus report should be developed by the end of 1992.

Appendix G

Document provided NEPEC by Healy,
An advance draft of an open-file report on M8,
an earthquake prediction algorithm.

— PAGE 103 FOLLOWS —

DRAFT 04/21/92 THE DESIGN OF A TEST TO EVALUATE THE EARTHQUAKE PREDICTION ALGORITHM, M8

J. H. Healy, V. G. Kossobokov, and J. W. Dewy

ABSTRACT

A test of the algorithm M8 is described. The test is constructed to meet four rules, which we propose to be applicable to the test of any method for earthquake prediction:

1. An earthquake prediction technique should be presented as a well documented, logical algorithm that can be used by investigators without restrictions.

2. The algorithm should be coded in a common programming language and implementable on widely available computer systems.

3. A test of the earthquake prediction technique should involve future predictions with a black box version of the algorithm in which potentially adjustable parameters are fixed in advance. The source of the input data must be defined and ambiguities in these data must be resolved automatically by the algorithm.

4. At least one reasonable null hypothesis should be stated in advance of testing the earthquake prediction method, and it should be stated how this null hypothesis will be used to estimate the statistical significance of the earthquake predictions.

We will be testing a specific implementation of the algorithm "M8." The M8 algorithm has successfully predicted several destructive earthquakes, in the sense that the earthquakes occurred inside regions with linear dimensions of about 850 km that the algorithm had identified as being in times of increased probability for strong earthquakes. In addition, M8 has successfully "post predicted" high percentages of strong earthquakes in regions to which it has been applied in retroactive studies. The statistical significance of previous predictions has not been established, however, and post-prediction studies in general are notoriously subject to success-enhancement through hindsight. Nor has it been determined how much more precise an M8 prediction might be than forecasts and probability-of-occurrence estimates made by other techniques. We view our test of M8 both as a means to better determine the effectiveness of M8 and as an experimental structure within which to make observations that might lead to improvements in the algorithm or conceivably lead to a radically different approach to earthquake prediction.
Our implementation of the M8 algorithm will be directed to the

prediction of earthquakes of magnitude 7.5 or greater. M8 will be applied to 147 circles of investigation located in the Circum Pacific seismic belt and Indonesia. Each circle has a radius of 427 km. The algorithm identifies Times of Increased Probability, TIP's, in which there is hypothesized to be an increased probability for the occurrence of M => 7.5 earthquakes. In the first forward prediction, covering the period 1 July 1991 - 1 January 1992, TIP's were identified for 38 of the 147 circles. The predictions will be updated every six months until there is a sufficient record to evaluate the algorithm. We will evaluate M8 against the null hypothesis that TIP's randomly distributed in the 147 circles of investigation are as effective as M8. We refer to this test as "M8 Test A".

Simulated forward predictions were made for the 13 six-month intervals between 1 January 1985 and 1 July 1991, using procedures and parameters as they will be used in M8 Test A. There were ten earthquakes of M => 7.5 in the circles of investigation. Six of the ten earthquakes occurred in circles with TIP's. On average, TIP's were declared in 22 percent of the circles in each six-month period. Evaluation of the success ratio, six earthquakes predicted out of ten, against the null hypothesis implies that successes of M8 in 1985 - 1 July 1991 yield only a 76 % level of confidence which neither proves or disproves the validity of the algorithm. The number of circle-years of TIP per predicted earthquake is 34.1.

The process of running simulated forward predictions for 1985 - 1 July 1991 suggested a modification of the M8 algorithm that may improve its effectiveness and that is necessary to account for space-time volumes corresponding to TIP-regions in which strong earthquakes have occurred. Two of the four earthquakes missed in Test A occurred in the same circle as a preceding and predicted strong earthquake. These earthquakes were not predicted by M8 because of the convention that a TIP is terminated by a strong earthquake. Accordingly we investigated how the algorithm performed if a TIP is not turned off when a strong earthquake occurs but is allowed to run its full term (commonly five years). With this modification, eight of the ten strong earthquakes in the period 1 Jan 1985 - 1 July 1991 are predicted. This result is significant at a 97% level of confidence. The number of circle-years of TIP per predicted earthquake is 25.6. We will conduct a parallel test of this modified form of M8, which we will denote M8 test B.

INTRODUCTION

After the Loma Prieta earthquake on October 17, 1989, a group of scientists from the International Institute for Earthquake Prediction Theory and Mathematical Geophysics in Moscow came to Menlo Park, California, to explain and demonstrate their earthquake prediction algorithms. One of the algorithms, M8, had successfully predicted the Loma Prieta earthquake, in that the earthquake occurred inside a circle of 280 kilometers radius that the M8 algorithm had identified as being in a five year Time of Increased Probability (TIP) for an M => 7 shock (Keilis-Borok and others, 1990). The successful TIP was presented in a figure without accompanying textual discussion in Appendix A (10th page) of the Proceedings of a National Earthquake Prediction Evaluation Council (NEPEC) meeting. An M8 TIP for an M => 7.5 shock in California was also presented at this meeting. Many seismologists in the U. S. Geological Survey have viewed the Loma Prieta prediction with skepticism: the M8 approach to earthquake prediction seems to these seismologists to be inconsistent with their understanding of earthquake genesis, and, in view of the large area and long time associated with the successful TIP, the successful prediction may have been fortuitous. In this paper we describe a test of the M8 algorithm. We have described what we believe to be the essential features of a test of an earthquake-prediction technique, and we have constructed a test that has these features. We refer to this test as M8 Test A.

OVERVIEW OF M8 AND M8 TEST A

The M8 algorithm was originally designed for diagnosis of Times of Increased Probability (TIP's) of the strongest, magnitude 8 and above, earthquakes (Keilis-Borok and Kossobokov, 1986). The formulation of the algorithm was normalized in such a way, that it can be applied without additional data_fitting to diagnose TIP's of strong earthquakes of magnitude less than 8 (Keilis-Borok and Kossobokov, 1990b).

TIP's are defined for regions within circles having pre-defined radii. The radii are five to ten times larger than the lengths of coseismic faulting typical of earthquakes of the magnitude being predicted: for the M => 7.5 earthquakes that are the objects of prediction in M8 Test A, the radii will be 427 km. The algorithm analyses seven functions of seismicity from within each circle. M8 announces a TIP when most of these functions are anomalously high with respect to the long-term record of seismicity in the circle.

M8-defined TIP's are generally defined to last for 5 years beyond the date at which the criteria for TIP-declaration are fulfilled, provided that the criteria for TIP-declaration continue to be fulfilled at that date in the course of further semiannual updates of the seismicity data-base. A TIP will be terminated at the time of a semiannual update, before 5 years have elapsed, if the criteria for TIP-declaration are no longer satisfied with the updated data-base. A TIP may be extended beyond 5 years if the levels of seismicity (as parameterized by M8) continue to increase after the TIP-declaration criteria are first fulfilled.

In tests with M8 run up to the present time, a TIP has been terminated on the occurrence of a strong earthquake, and this convention has been continued with M8 Test A. In a later section (M8 TEST B -- A TEST OF A MODIFIED FORM OF M8), we will propose a parallel test with a version of M8 in which a TIP is not terminated on the occurrence of a strong earthquake within its circle. The decision to cancel or retain a TIP after a strong earthquake is rather the option of the user since the rest of the analysis remains precisely the same. The choice depends on whether the user prefers to miss the second earthquake in a pair at the cost of increasing the total alarm time.

The algorithm might diagnose a TIP in response to a dramatic short-term increase of activity near the source region of the future strong earthquake, but most earthquakes are not preceded by such premonitory seismicity, and M8 is tuned more generally to detecting premonitory patterns over a broader space-time window than would be characteristic of a short-term, near-source, foreshock sequence.

A more detailed discussion of the M8 functions and a listing of the algorithm are given in Appendix IV.

Rationale for M8 Test A

We propose M8 Test A because M8 appears promising to us from several standpoints, and we think the time has come to subject the algorithm to a rigorous test.

A demonstration of the validity of the algorithm M8 would confirm the following general perceptions on which it is based.

- A strong earthquake is commonly preceded by specific intermediate-term change of seismic activity the small and moderate magnitude ranges. Among these changes is an increase of activity, clustering of earthquakes and several other phenomena.
- These chanes take place over large areas which may include many active faults.
- These changes are similar in a wide variety of seismic regions.

M8 is based on a general geophysical hypothesis that has been widely proposed independently of M8, and the specific values of parameters used in M8 were determined by data-fitting so as to retroactively maximize the numbers of successful predictions in a series of retrospective studies. The general hypothesis, that a strong earthquake will commonly be preceded by an intermediate-term increase in small and moderate earthquake activity in a broad region that includes the future source of the strong earthquake, has been put forth in a number of different versions (e.g., Kanamori, 1981; Mogi, 1981; Reyners, 1981; Scholz, 1990): many versions postulate that the time-period and region of increased seismicity encompasses a smaller space-time window of seismic quiescence. Ideally, the data-fitting of M8 parameters should have achieved a partial optimization of the general hypothesis and have implicitly accounted for near-source seismic quiescences. The proceedings of the 1988 NEPEC meeting (Updike, 1989) contain several different perspectives on the philosophy of M8 and the process of data-fitting the M8 parameters.

As elaborated in Appendix IV, results of previous studies with the M8 algorithm are generally encouraging. Most previous studies have involved post-predictions. Analyses of the post-predictions suggest that the level of success is statistically significant. Although there have been several strong earthquakes that have occurred in regions of TIP's following the diagnosis of the TIP's, statistical estimates of the effectiveness of the algorithm have so far been based on post predictions.

From a practical standpoint, confirmation of the effectiveness of M8 may justify using TIP's as bases for some kinds of earthquake-mitigation efforts. The practical value of M8 TIP's would be particularly enhanced by development of techniques to more precisely define the source region of a future strong earthquake within the broad circle of investigation for which the TIP is issued (e.g., Keilis-Borok and Kossobokov, 1990b; Kossobokov and others, 1990).

The possibility that M8 might not be effective is implicit in our proposal to test the algorithm. The hypothesis may be false that regional seismicity tends to increase prior to strong earthquakes in the fashion parameterized by M8. The NEIC data base to which M8 is applied in Test A (Appendix I) may be too heterogeneous to permit recognition of precursory seismicity patterns. It is possible that successful predictions of M8 Test A will be statistically significant but that the probability gain of M8 over well-established methods of calculating earthquake probabilities will be too small to justify additional earthquake mitigation efforts on the basis of M8 TIP's. Arguments that M8 might not be effective are presented in more detail in the proceedings of the 1988 NEPEC meeting (Updike, 1989).

The setting up and running of M8 Test A, besides accomplishing its primary purpose of testing the present formulation of M8, also provides a basis for collecting and organizing observations that may lead to improved formulations of M8 or possibly to substantially different approaches to earthquake prediction.

M8 TIP's - should they be called predictions?

Throughout this paper we refer to M8 TIP's as "predictions." We think our usage is consistent with the philosophy and characteristics of "earthquake prediction" suggested by the U.S. National Research Council, Panel on Earthquake Prediction of the Committee on Seismology (1976, p.7): "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. Only by careful recording and analysis of failures as well as successes can the eventual success of the total effort be evaluated and future directions charted. Moreover, scientists should also assign a confidence level to each prediction."

Our usage of "prediction" is intended to be synonymous with "research prediction". The Seismological Society of America (1983) has accepted a definition of earthquake prediction which requires that the prediction have sufficient precision that actions to minimize loss of life and reduce damage to property are possible; Wallace and others (1984) propose that earthquake predictions should refer to a specific future earthquake. Under these more stringent definitions of "earthquake prediction," the TIP's issued by M8 Test A might not be classified as predictions. A prediction that was to be acted on by society, or a prediction of a specific future earthquake, would involve integration of all available evidence, of which M8 TIP's would constitute only one part.

GENERAL RULES FOR TESTING EARTHQUAKE PREDICTION TECHNIQUES

Our goal is to conduct a test of M8 that will be acceptable to a broad spectrum of the scientific community. In particular, if the test convinces us that M8 is effective at identifying times of increased probability of earthquake occurrence, we would like the test also to convince colleagues that this is the case, even if these colleagues now find the assumptions of M8 to be counter-intuitive. Our goal is clearly similar to that of many who have developed earthquake prediction techniques and presented their predictions to the public.

We agreed that a convincing test would have to be based on the following rules, which can be applied to all earthquake prediction techniques:

1. An earthquake prediction technique should be presented as a well documented, logical algorithm that can be used by other investigators without restrictions.

2. The algorithm should be coded in a common programming language and implementable on widely available computer systems.

3. A test of the earthquake prediction technique should involve future predictions with a black box version of the algorithm in which potentially adjustable parameters are fixed in advance. The source of the input data must be defined and ambiguities in these data must be resolved automatically by the algorithm.

4. At least one reasonable null hypothesis should be stated in advance of testing the earthquake prediction method, and it should be stated how this null hypothesis will be used to estimate the statistical significance of the earthquake predictions.

The rules are intended to eliminate the possibility of cheating or self deception on the part of the predictor. Rules 1 and 2 seem to us necessary, in addition, if the predictor is to communicate with scientists who are working from different earthquake-prediction paradigms.

SPECIFICS OF RUNNING AND EVALUATING M8 TEST A

We will apply M8 systematically to the intermediate-term prediction of future M => 7.5 earthquakes for a period of five years from 1 July 1991. These research predictions will be updated semiannually in February and August.

Values of seismicity functions are computed at six-month intervals for a span of years that begins at 1975/01/01 and ends at "Te". At February semiannual updates, "Te" will be 1 January of the current year; at August semiannual updates "Te" will be 1 July of the current year. The Qth percentiles that are used to define anomalous values of seismicity functions are based on a span of years that begins at "Tb" and ends at "T*." For most regions, "T*" will be six months earlier than "Te", in order that the definition of Qth percentiles be based entirely on Monthly PDE data.

We define a <u>unit of TIP</u> as six-months of a TIP in a single circle. TIP units are defined to span 1 January - 30 June or 1 July - 31 December respectively. 1 January - 30 June TIP units will therefore span between 98% and 99% of the time spanned by 1 July - 31 December TIP units. TIP-lengths defined by the M8 program are measured in minutes, rather than calendar days or months, and TIP's issued by the program are of equal length (5 years). As a result, there may be a mismatch between the beginnings or endings of TIP's issued by the M8 program and the 1 January - 30 June, 1 July - 31 December TIP units defined for Test A. For purposes of Test A, if a program-issued TIP spans 98 percent or more of a six-month span, the TIP is considered "on" for the entire TIP-unit. If a program-issued TIP spans 2 percent or less of a six-month span, we consider that there is not a TIP for the entire potential TIP-unit.

We define future events to be those occurring after September 19, 1991, and past events to be those occurring before that date. The demarcation between future and past corresponds to the date on which we submitted this paper to colleagues for internal review, in accordance with the standard USGS review procedure. Although the text of the paper has been revised significantly as a consequence of the review procedure, potentially adjustable parameters have not been changed since September 19, 1991. Between 1 July and 19 September 1991, there were no earthquakes of M => 7.5. The first TIP units to be evaluated in M8 test A will be those corresponding to 1 July - 31 December 1991, which will include no past earthquakes of M => 7.5.

For the purposes of the test, the M8 algorithm will be considered as a "black box", with potentially adjustable parameters in the algorithm fixed in advance of the date of the strong earthquakes that will be used to test the algorithm. We cannot rule out that some kind of change will be found necessary in the course of running Test A. Any such change in M8 parameters would be announced in our reports of semiannual updates, prior to the beginnings of the TIP's that are diagnosed on the basis of the changed parameter. Every half year we will run the same computer program in Moscow, Menlo Park, and Golden on the then-current NEIC data-base. We claim that these procedures will enable us to satisfy the third of our General Rules for Testing Earthquake Prediction Techniques (previous section).

Data

Analyses will be based on the NEIC data-base existing at the times of each update. The data base, and the conventions used in M8 Test A to select earthquakes and earthquake-parameters from the data base, are described in Appendix I.

Programs

Hypocenters and magnitudes are extracted from the NEIC data-base using standard NEIC software (see Appendix I). Processing of the catalogs to obtain predictions is done by programs prepared at the International Institute of Earthquake Prediction Theory (Appendices II, III, and IV).

We judge the documentation and accessibility of the programs as only marginally satisfying the first and second of our general rules for testing of earthquake prediction techniques. The spirit of rules 1 and 2, for example, suggests that the programs be written in a single, well-known, portable programming language. The C language would fulfill this requirement. A good C program written for an IBM PC computer could be easily transported to many other systems. As it stands, however, we use programs written in C and Fortran. In addition, we use a program (the EDBS software used for extracting the most recent NEIC data) that is not maintained by any one of us and that could, in principle, be altered during the period of conducting M8 Test A without our knowing it.

Regions covered by M8 Test A

We will run the M8 algorithm for 147 circles with radii of 427 km that are located in the Circum-Pacific seismic belt and Indonesia and that have on average at least sixteen magnitude 4.0 shocks per year. Coordinates of the circles are given in Table 1.

Reporting the Results

Each half-year we will report the results of applying M8 to the updated NEIC data base. The format of the semiannual update report is given in Appendix V.

Classification of predictions

A prediction of a future large earthquake is called a future prediction. A "prediction" of a past large earthquake using only the data from smaller earthquakes that occurred before the large earthquake is a simulated forward prediction. An example of a simulated forward prediction would be the prediction of a 1988 earthquake on the basis of 1985 - 1987 regional seismicity that was anomalous with respect to the regional seismicity of the entire period 1975-1987. A post prediction is defined to be the "prediction" of a past event in which the anomalous pattern of precursory seismicity is detected against background levels of seismicity that are defined using all available data, including events occurring after the earthquake. An example of a post-prediction would be the "prediction" of a 1980 earthquake on the basis of seismicity in 1977-1979 that was anomalous with respect to the regional seismicity during 1975-1991/07/01. Previous evaluations of M8 have been based substantially on post predictions (e.g. Keilis-Borok and Kossobokov, 1990a).

Practical considerations require introduction of the concept of the lagged future prediction. This is the "prediction" of an M => 7.5

earthquake occurring after 19 September 1991, made using the predetermined parameters and procedures of M8 and using only the catalog of smaller earthquakes that occurred before the large earthquake, but made using some hypocentral parameters of prior earthquakes that were actually computed after the occurrence of the large earthquake. The concept of the lagged future prediction is necessitated by the approximately seven-month time-lag between the occurrence of any sized earthquake and its final USGS cataloging in the Monthly PDE (see Appendix I for description of Monthly PDE). Our final evaluation of M8 test A will be based on hypocentral parameters as they are published in the Monthly PDE, and we will count lagged future predictions as successful research predictions. In principle, with future improvements in seismographic data collection, transmission, and inversion, it would be possible to drastically reduce the time-lag between the occurrence of an earthquake and its final USGS cataloging.

Several examples will illustrate how we would judge different types of future predictions. The terms NEIC data-base and PDE-weekly are defined in Appendix I.

Scenario 1 - Successful future prediction with no complications. The M8 algorithm recognizes an episode of anomalous seismicity in a time period for which the NEIC data-base contains only Monthly PDE hypocentral parameters. A TIP is accordingly identified and a prediction issued. The prediction is issued prior to a strong earthquake that occurs within the TIP space-volume. The earthquake is assigned M => 7.5 at every stage of the NEIC cataloging process.

Scenario 2 - Successful lagged future prediction at every stage of the NEIC cataloging process. A strong earthquake of magnitude about 7.5 occurs in early January 1992, before we have had a chance to analyze regional seismicity data from July - December 1991. When we perform a semiannual update of TIP's in early February 1992, we see that the strong earthquake occurred in a TIP that was identifiable in a time period that includes July - December 1991, for which the NEIC data-base contains PDE-weekly hypocenters. And we see that the earthquake is assigned a magnitude of 7.5 in the PDE-weekly. The TIP is provisionally judged a successful lagged future prediction. When we next perform a semiannual update in early August 1992, the NEIC data-base contains entirely Monthly PDE hypocenters in the time-period in which the TIP was declared. Reanalysis of the data-base in August

1992 confirms the TIP. In addition, in August the Monthly PDE magnitude of the January earthquake is confirmed to be 7.5. The successful lagged future prediction is confirmed, and the episode is counted as a successful prediction in our final evaluation of M8.

Scenario 3 - Apparently successful lagged future prediction that is later disqualified on the basis of data in Monthly PDE. A strong earthquake occurs in early January 1992, before we have had a chance to analyze smaller earthquake data from July - December 1991. When we perform a semiannual update of TIP's in February 1992, the PDE-weekly data indicate that the earthquake had M= 7.5 and occurred in a TIP. But either the TIP does not emerge when M8 is applied to the data-base as it exists in August 1992, or the strong earthquake is seen to have M < 7.5 in the Monthly PDE. The provisionally successful lagged future prediction has not been confirmed, and the episode is not counted as a successful prediction in our final evaluation of M8.

Scenario 4 - A successful lagged future prediction that is identifiable only after issuance of Monthly PDE. A strong earthquake occurs in early January 1992. In our semiannual update of February 1992, either the earthquake is assigned M < 7.5 or a TIP is not recognized prior to the earthquake. But in August 1992, application of M8 to the augmented data base reveals that the January earthquake did occur in a TIP. Moreover, the Monthly PDE for January shows that the strong earthquake had M => 7.5. The episode is therefore a successful lagged future prediction and is counted as a successful prediction in our final evaluation of M8.

<u>Evaluation of results</u>

In evaluation of these results we will look at two statistics: the number of successful predictions and the number of units of TIP's. Our evaluation of test results will not consider failures-to-predict except indirectly, as these are reflected in the count of successful predictions. The circles of investigation overlap and earthquakes usually occur in more than one circle. When circles with TIP's intersect circles without TIP's, the region of intersection is counted as being in a TIP. If the same earthquake is predicted by more than one TIP, we give credit for only one successful prediction.

We define a null-hypothesis algorithm in which TIP's are randomly distributed in the 147 circles of investigation. The number of TIP's declared in the null-hypothesis algorithm shall be equal to the number of TIP's declared by M8 during the period of comparison. The level of confidence of M8 will be taken to be the percentage of runs with the null-hypothesis algorithm in which TIP units overlap fewer earthquakes than are successfully predicted by M8. We think this satisfies the fourth of our General Rules for Testing Earthquake Prediction Techniques.

The test can be described by analogy to a gambling game in which the player is charged one dollar for each TIP declared during each six-month interval and wins a fixed sum for each earthquake predicted. The goal is to determine the amount the house can afford to pay for each successful prediction. This test can apply to any algorithm that assigns TIP's to circles. The results from other algorithms can be compared with M8 and with our null-hypothesis algorithm.

M8 TEST A APPLIED TO THE INTERVAL 1985 - 1 JULY 1991

We have run the algorithm as formulated for Test A and made simulated forward predictions for six-month intervals between 1 January 1985 and 1 July 1991. These results are presented in Table 1,(at end of paper) together with the results of the first future prediction (column 91b).

The total number of TIP units for 1985 - 1 July 1991 (columns 85a through 91a, Table I) is 409. There are 1883 possibilities for TIP units. Approximately 22 percent of the possible TIP-units actually had TIP's. Six earthquakes were ''predicted'' out of ten (Table 2 at end of paper) that occurred in the circles of investigation during the simulated forward prediction.

During the test period, six TIP's were terminated by earthquakes of magnitude => 7.5, and 29 TIP's ended without an earthquake. About eighty percent of the TIP's therefore ended without the occurrence of a large earthquake.

Table 3 summarizes the number of TIP-units and the number of analyzed circles in each time interval.

Table 3.
The number of circles under alarm from 1.

Year	1985	1986	1987	1988	1989	1990	1991

	a	b	a	b	a	b	a	b	a	b	a	b	a	b
Alarms	31	31	24	27	27	28	31	31	35	39	35	32	38	38
Circles	139	141	143	144	144	146	146	146	146	147	147	147	147	147

To test the significance of the 1985 - 1 July 1991 results using our proposed null hypothesis, we randomly assigned TIP's, equal in number to the number of TIP's in Table 3, to circles equal in number to the number of circles in Table 3. We used a random number generator to assign TIP's, and we made one million realizations of the null hypothesis algorithm. The results of these calculations are given in Table 4. Column 1 gives N, the number of earthquakes predicted. Column 2 is the number of times N earthquakes were predicted in 1,000,000 tries. Column 3 is the cumulative distribution of column 2, the number of times that at least N earthquakes were predicted; the level of confidence is this value divided by 1,000,000.

In the set of 1,000,000 realizations, the null hypothesis algorithm performed worse than M8 (less than 6 earthquakes predicted) 76.4 percent of the time, implying that the M8 results are significant at a 76.4 percent level of confidence.

Table 4

Random Distribution of TIPs in the A-test

Number of quakes predicted	Distribution of predictions	Cumulative distribution of predictions	Level of confidence %
0	2078	1000000	0.00
1	18893	997922	0.21
2	76832	979029	2.10
3	174846	902647	9.74
4	251732	727801	27.22
5	239570	476069	52.39
6	152444	236499	76.35 **
7	64040	84055	91.59
8	17237	20015	98.00
9	2635	2778	99.72
10	143	143	99.99

M8 TEST B - A TEST OF A MODIFIED FORM OF M8

One rule of the M8 algorithm as hitherto formulated is that the algorithm terminates a TIP when a strong earthquake occurs in the TIP region. Examination of M8 Test A applied to 1985 - 1 July 1991 revealed that two of the earthquakes that were not predicted occurred in regions for which TIP's had been declared within the previous five years, but in which previous strong earthquakes had occurred following declarations of the TIP's. The two shocks were those of 1985/03/03 and 1987/10/16. Region 143 (South America - 16), in which 1985/03/03 occurred, had a TIP declared for it beginning 1980/12/31. The TIP was followed by a magnitude 7.5 earthquake that occurred on 1981/10/16, which turned off the TIP that would otherwise have extended at least to 1985/12/31. A TIP for region 15 (New Guinea -5), in which 1987/10/16 occurred, was followed by the shock of 1987/02/08 (Tables 1 and 2) which turned off the TIP which would otherwise have extended at least to 1989/12/31.

We propose a modification of M8 in which a TIP is not terminated at the occurrence of a large earthquake. The three authors of this report agreed that this modification is desirable for the purposes of testing M8. Otherwise, some space-time volumes (such as that in which 1987/10/16 occurred) are formally inaccessible to M8 TIP's, and other space-time volumes (such as that in which 1985/03/03 occurred) are strongly biased against M8 TIP's. With the unmodified Test A convention, the occurrence of a strong earthquake in effect resets the clock used to evaluate TIPS; a TIP cannot in principle be announced for a region until at least one year has elapsed following the strong earthquake, and any subsequent TIP's can be based only on anomalous seismicity occurring after the strong earthquake. With the proposed modification, the number of TIP-units in a five year run will inevitably increase, but we will not have situations of strong shocks occurring in unclassifiable space-time volumes that are neither ``TIP'' nor ``non-TIP''. We refer to the new test as Test B. Test B will be identical in every respect to the algorithm in Test A, except that a TIP is not terminated at the occurrence of a large earthquake.

Had Test B conventions been in force in our simulated forward prediction study of 1985 - June 1991, the number of TIP-units would have increased from 409 to 442, and M8 would have predicted 8 of the 10 strong earthquakes. Formal use of the same null hypothesis as used in Test A would suggest that Test B was statistically significant at a 97 percent level of confidence (Table 5). However, this estimate of confidence level cannot be considered statistically rigorous, because Test B was formulated after the data had been examined using the Test A conventions.

Table 5

Random Distribution of TIPs in the B-test

Number of quakes predicted	Distribution of predictions	Cumulative distribution of predictions	Level of confidence %
0	1239	1000000	0.00
1	12768	998761	0.12

2	58081	985993	1.40	
3	148613	927912	7.21	
4	238153	779299	22.07	
5	252113	541146	45.89	
6	177789	289033	71.10	
7	82531	111244	88.88	
8	24350	28713	97.13	**
9	4105	4363	99.56	
10	258	258	99.97	

M8 Test B shall be run parallel to M8 Test A in the upcoming five years. Like Test A, Test B will be considered to have started on July 1, 1991.

CONCLUSION

We have presented a description of a test of the earthquake prediction algorithm M8. Two specific tests are formulated, which we have denoted M8 Test A and M8 Test B. We have attempted to formulate the specific tests so that they are compatible with four general principles that we believe should be applied to any earthquake prediction test. We have documented the algorithms we will use and the conventions we will use. The algorithms are coded in common programming languages and run on commonly available computers. The tests will involve future predictions. We have described the null hypothesis with which we will evaluate the performance of M8.

The future predictions issued in the course of our test will be research predictions. They are ''predictions'' in the sense that they are forecasts of time/space windows that have anomalously high probabilities of strong earthquakes and in the sense that their success or failure can be evaluated. They are ''research'' because they are generated for the purpose of testing the M8 algorithm and determining the algorithm's effectiveness.

Most of the areas of investigation are known to include regions of high seismic hazard, irrespective of M8 results. It is important to periodically review seismic hazard in such regions. If a prediction resulting from this study is of concern, it would not be inappropriate to conduct a seismic hazard study tailored to the needs of the region.

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Table I

Times of increased probability for earthquakes => M = 7.5

- 1 (shaded) — Time of increased probability, TIP
- 0 (boxed) — Earthquake > 7.5 in this circle at this time
- 1 (black) — Predicted Earthquake
- 0 (black) — Earthquake would have been predicted if TIP not closed by proceeding earthquake. (TESTB)

Region		Num	Lon	Lon	85 a	85 b	86 a	86 b	87 a	87 b	88 a	88 b	89 a	89 b	90 a	90 b	91 a	91 b
Tonga Kermades	1	1	−15.00	−175.00	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Tonga Kermades	2	2	−17.50	−174.00	0	1	1	1	1	1	1	1	1	1	0	0	0	0
Tonga Kermades	3	3	−20.00	−175.00	1	1	1	1	0	0	0	1	1	1	1	1	1	1
Tonga Kermades	4	4	−22.50	−176.00	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Tonga Kermades	5	5	−25.00	−177.00	0	1	1	1	0	0	0	0	0	0	0	0	0	0
Tonga Kermades	6	6	−27.50	−177.50	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Tonga Kermades	7	7	−30.00	−178.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tonga Kermades	8	8	−32.50	−179.00	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Tonga Kermades	9	9	−35.00	180.00	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Tonga Kermades	10	10	−37.00	178.00										1	1	1	1	1
New Guinea	1	11	−2.00	136.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	2	12	−2.25	138.50	0	0	0	1	1	1	1	1	1	1	1	1	1	1
New Guinea	3	13	−2.50	141.00	1	0	0	0	0	0	0	1	1	1	1	1	1	1
New Guinea	4	14	−3.75	143.50	1	1	1	1	0	0	1	1	1	1	0	0	0	0
New Guinea	5	15	−5.00	146.00	1	1	1	1	1	0	0	0	0	0	0	0	0	0
New Guinea	6	16	−5.00	149.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	7	17	−5.00	152.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	8	18	−6.25	154.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	9	19	−7.50	156.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	10	20	−8.75	158.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	11	21	−10.00	160.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	12	22	−10.50	162.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	13	23	−11.00	165.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Guinea	14	24	−13.00	166.25	0	0	0	0	0	0	0	0	1	1	1	1	1	1
New Guinea	15	25	−15.00	167.50	1	1	0	0	0	0	0	0	0	1	1	1	1	1
New Guinea	16	26	−17.50	168.25	1	1	1	1	0	0	0	0	0	0	0	0	0	0
New Guinea	17	27	−20.00	169.00	1	1	1	1	1	0	0	0	0	0	0	0	0	0
New Guinea	18	28	−21.25	170.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	1	29	9.5	93.75				0	0	0	0	0	0	0	0	0	0	0
Java	2	30	7.00	94.50			0	0	0	0	0	0	0	0	0	0	1	1
Java	3	31	5.00	95.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	4	32	3.00	97.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	5	33	2.00	98.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	6	34	−1.00	100.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	7	35	−3.00	101.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	8	36	−5.00	103.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	9	37	−6.50	105.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	10	38	−8.00	107.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	11	39	−8.50	109.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	12	40	−9.00	112.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	13	41	−9.25	114.50	0	0	0	1	1	1	1	0	1	1	0	0	1	1
Java	14	42	−9.50	117.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	15	43	−9.50	119.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	16	44	−9.50	122.00	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Java	17	45	−8.25	124.50	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	1	46	−7.00	127.00	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	2	47	−6.00	129.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	3	48	−5.00	131.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	4	49	−3.50	129.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	5	50	−2.00	127.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	6	51	−1.00	125.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	7	52	0.00	123.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	8	53	0.00	120.50	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Philipines	9	54	1.50	125.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	10	55	3.00	127.00	1	1	0	0	0	0	0	0	0	0	1	0	1	1
Philipines	11	56	5.25	126.50	1	1	1	1	0	0	0	0	0	1	1	1	1	1
Philipines	12	57	7.50	126.00	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Philipines	13	58	9.75	125.50	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	14	59	12.00	125.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	15	60	13.50	123.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Philipines	16	61	15.00	121.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 1 CONT.

Taiwan and S. Japan	1	62	35.00	136.00	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Taiwan and S. Japan	2	63	34.00	134.00	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Taiwan and S. Japan	3	64	33.00	132.00	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Taiwan and S. Japan	4	65	31.00	132.00	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Taiwan and S. Japan	5	66	29.00	131.00	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Taiwan and S. Japan	6	67	27.00	129.00	0	0	0	0	1	1	1	1	1	1	0	0	1	1
Taiwan and S. Japan	7	68	26.00	127.00	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Taiwan and S. Japan	8	69	25.00	124.50	0	0	0	0	0	1	1	1	0	1	1	1	0	1
Taiwan and S. Japan	9	70	25.00	122.00	0	0	0	0	1	1	1	1	1	1	1	1	1	1
Taiwan and S. Japan	10	71	22.50	121.50	0	0	0	0	0	1	1	1	1	1	1	1	1	1
Taiwan and S. Japan	11	72	20.00	121.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taiwan and S. Japan	12	73	17.50	121.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	1	74	45.50	150.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	2	75	44.00	148.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	3	76	43.50	145.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	4	77	43.00	143.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	5	78	41.00	141.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	6	79	39.00	142.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	7	80	36.50	141.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	8	81	35.00	139.00	0	0	0	0	1	1	1	1	1	0	0	0	0	0
Japan and Bonin	9	82	33.00	141.00	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Japan and Bonin	10	83	31.00	142.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	11	84	29.00	142.50	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	12	85	27.00	143.00	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	13	86	25.00	143.00	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	14	87	23.00	143.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	15	88	21.00	144.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan and Bonin	16	89	19.00	146.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bonin & Mariana Tr.	1	90	16.50	147.00	1	1	1	1	0	1	1	1	1	1	1	0	0	0
Bonin & Mariana Tr.	2	91	14.00	146.00	1	1	1	1	1	1	1	1	1	1	0	0	0	0
Bonin & Mariana Tr.	3	92	12.00	144.00	0	0	0	1	1	1	1	1	1	1	0	0	0	0
Bonin & Mariana Tr.	4	93	12.00	141.00			0	0	0	0	0	0	0	0	0	0	0	0
Kurils & Kamchatka	1	94	46.00	152.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kurils & Kamchatka	2	95	48.50	155.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kurils & Kamchatka	3	96	51.00	158.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kurils & Kamchatka	4	97	53.50	160.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kurils & Kamchatka	5	98	56.50	161.50	0	1	1	0	1	1	1	1	1	1	1	1	1	1
Aleutians & Alaska	1	99	55.00	166.50	1	0	0	0	0	0	1	1	1	1	1	1	1	1
Aleutians & Alaska	2	100	51.50	176.00	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Aleutians & Alaska	3	101	51.00	−178.50	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Aleutians & Alaska	4	102	51.50	−173.00	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Aleutians & Alaska	5	103	52.50	−167.50	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Aleutians & Alaska	6	104	54.00	−162.50	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Aleutians & Alaska	7	105	55.50	−157.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aleutians & Alaska	8	106	56.50	−152.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aleutians & Alaska	9	107	60.00	−153.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aleutians & Alaska	10	108	63.00	−151.00	0	0	0	0	1	1	1	1	1	1	1	1	1	1
Aleutians & Alaska	11	109	62.00	−145.00	0	0	0	1	1	1	0	0	0	0	0	0	0	0
North America	1	110	44.50	−130.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North America	2	111	43.00	−126.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North America	3	112	40.50	−128.00	1	1	1	0	0	0	0	0	0	0	0	0	0	0
North America	4	113	40.50	−123.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North America	5	114	38.00	−119.00	1	1	1	1	1	1	1	1	1	1	1	0	0	0
North America	6	115	37.50	−122.00	1	1	1	1	1	1	1	1	1	1	1	1	1	1
North America	7	116	35.00	−118.50	1	0	0	0	0	0	0	0	0	0	0	0	0	0
North America	8	117	37.00	−118.00	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Central America	1	118	16.00	−88.00	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Central America	2	119	16.00	−97.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Central America	3	120	15.00	−94.00	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Central America	4	121	14.00	−91.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Central America	5	122	12.00	−88.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Central America	6	123	10.00	−85.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Central America	7	124	8.00	−82.50						0	0	0	0	0	0	0	1	0
Central America	8	125	5.00	−82.50						0	0	0	0	0	0	0	0	0
Central America	9	126	6.00	−76.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Central America	10	127	8.00	−73.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 1 CONT.

South America	1	128	0.00	-80.00		0	0	0	0	0	1	1	1	1	1	1	0	0
South America	2	129	-5.00	-77.00	1	1	1	1	1	1	1	1	1	1	1	0	0	0
South America	3	130	-11.00	-74.00	0	0	0	0	0	0	0	0	0	0	1	1	1	1
South America	4	131	-12.00	-77.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	5	132	-15.00	-75.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	6	133	-17.50	-71.00	0	0	0	0	0	0	0	0	1	1	1	1	1	1
South America	7	134	-20.50	-69.00	0	0	0	0	0	0	0	0	0	1	1	1	1	1
South America	8	135	-22.00	-67.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	9	136	-23.50	-70.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	10	137	-25.00	-68.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	11	138	-27.00	-71.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	12	139	-28.00	-69.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	13	140	-30.00	-71.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	14	141	-31.00	-70.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
South America	15	142	-33.00	-72.50	0	0	0	0	0	0	0	0	0	0	0	0	0	1
South America	16	143	-34.00	-71.00	0	0	0	0	0	0	0	0	1	1	1	1	1	1
South America	17	144	-36.00	-73.00		0	0	0	1	1	1	1	1	1	0	0	0	0
Southern Sandwiches	1	145	-56.00	-27.00	0	0	0	0	0	0	0	0	1	1	1	0	1	1
Southern Sandwiches	2	146	-57.00	-25.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Southern Sandwiches	3	147	-58.50	-25.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total TIPs in each half-year					31	31	24	27	27	28	31	31	35	39	35	32	38	38

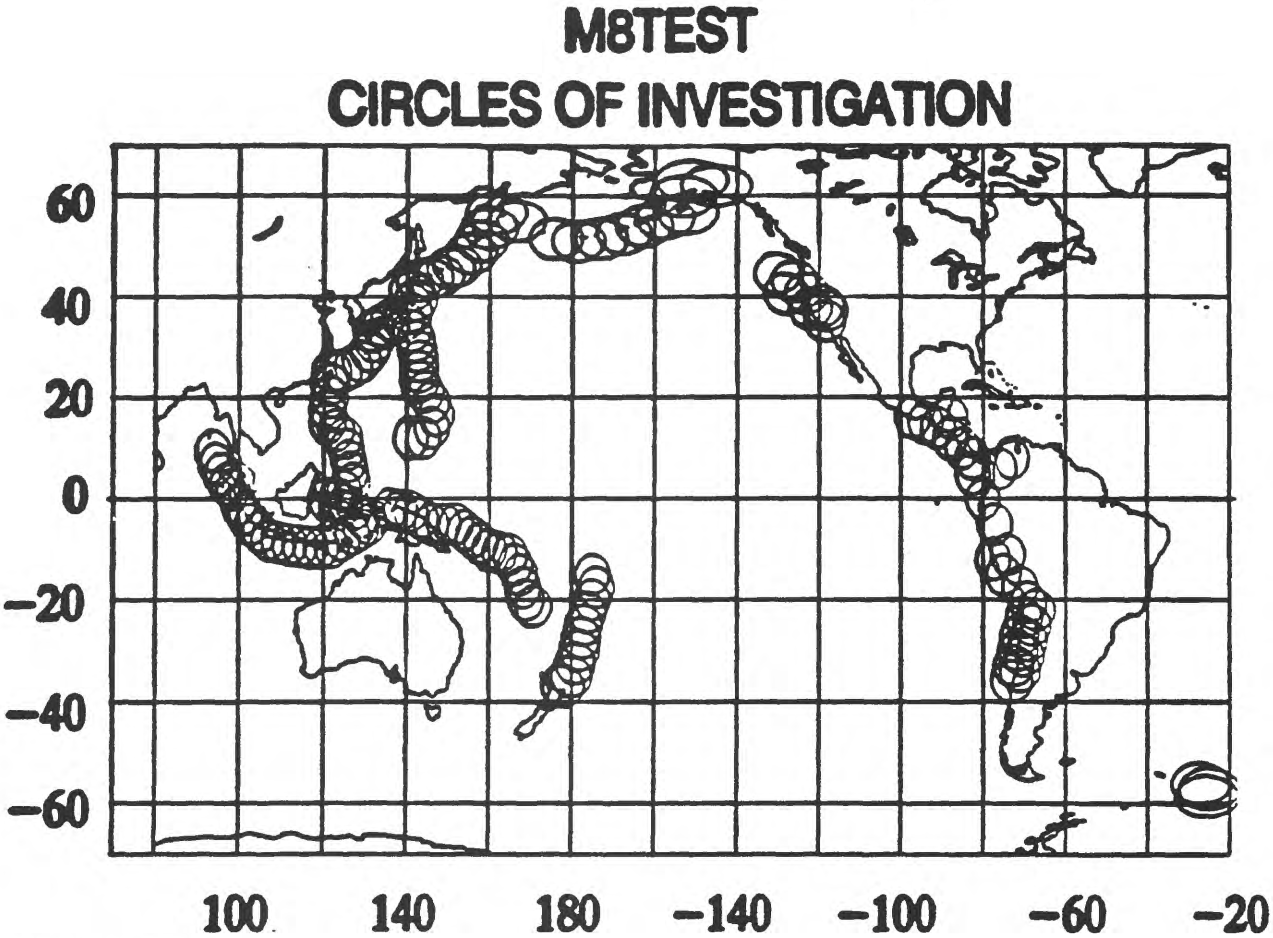
Total TIPs	409	Not including last period.
Possible TIPs	1883	147*28 – 28 no runs
Total TIPs / Possible TIPs	0.217	22%

TESTA

Earthquakes predicted	6
Earthquakes not predicted	4
Years of TIP per prediction	34.1

TESTB

Earthquakes predicted	8
Earthquakes not predicted	2
Years of TIP per prediction	25.6


M8TEST
CIRCLES OF INVESTIGATION
60
40
20
0
−20
−40
−60
100
140
180
−140
−100
−60
−20
Figure 1

Random Distribution of TIPs in the A-test

Number of quakes predicted	Distribution of predictions	Cumulative distribution of predictions	Level of confidence %	
0	2078	1000000	0.00	
1	18893	997922	0.21	
2	76832	979029	2.10	
3	174846	902647	9.74	
4	251732	727801	27.22	
5	239570	476069	52.39	
6	152444	236499	76.35	**
7	64040	84055	91.59	
8	17237	20015	98.00	
9	2635	2778	99.72	
10	143	143	99.99	

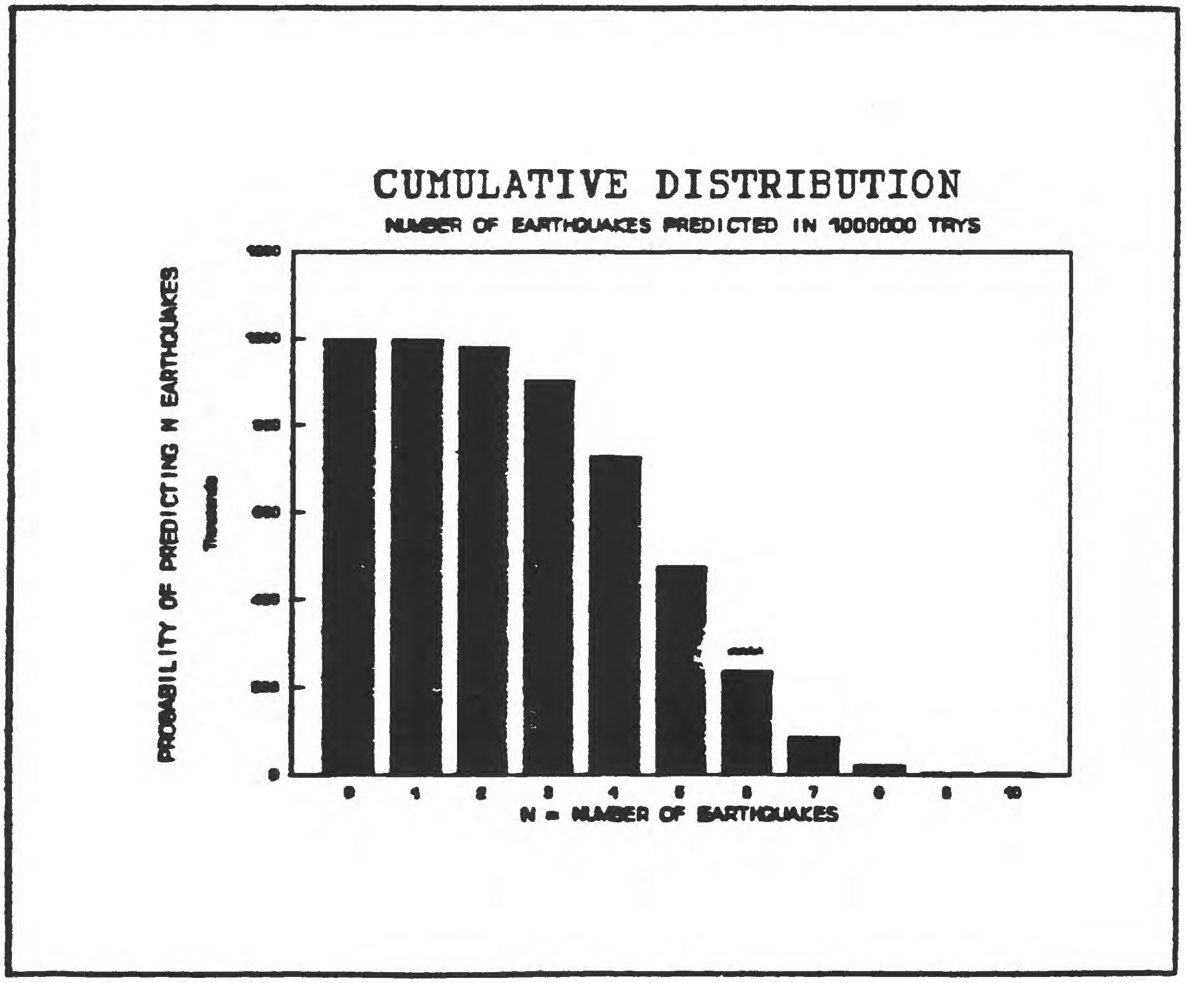


Fig 2

Random Distribution of TIPs in the B-test

Number of quakes predicted	Distribution of predictions	Cumulative distribution of predictions	Level of confidence %	
0	1239	1000000	0.00	
1	12768	998761	0.12	
2	58081	985993	1.40	
3	148613	927912	7.21	
4	238153	779299	22.07	
5	252113	541146	45.89	
6	177789	289033	71.10	
7	82531	111244	88.88	
8	24350	28713	97.13	**
9	4105	4363	99.56	
10	258	258	99.97	

CUMULATIVE DISTRIBUTION OF NUMBER OF
EARTHQUAKES PREDICTED IN 1000000 TRYS

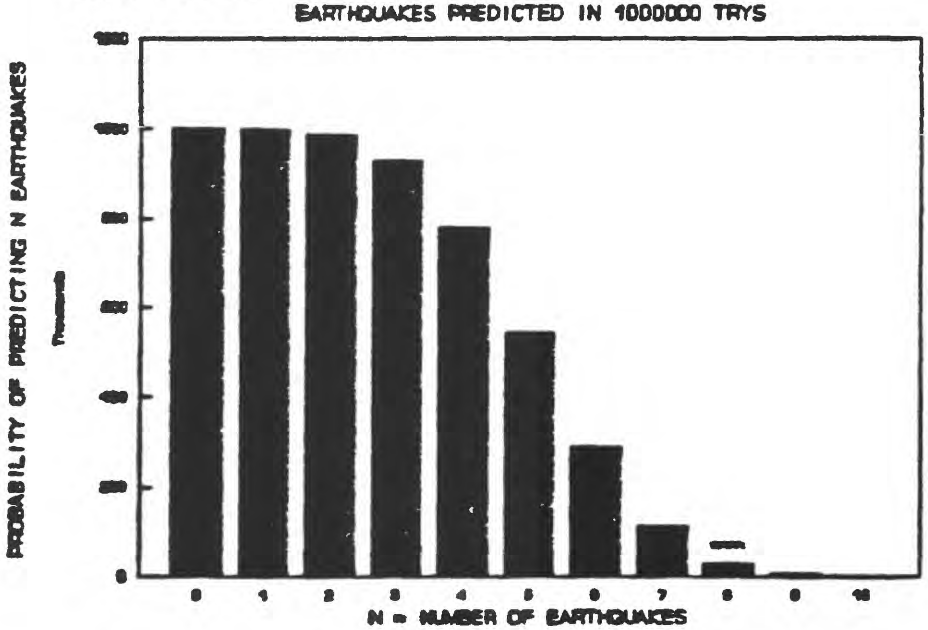


Fig 3

M8TEST
CIRCLES OF INVESTIGATION

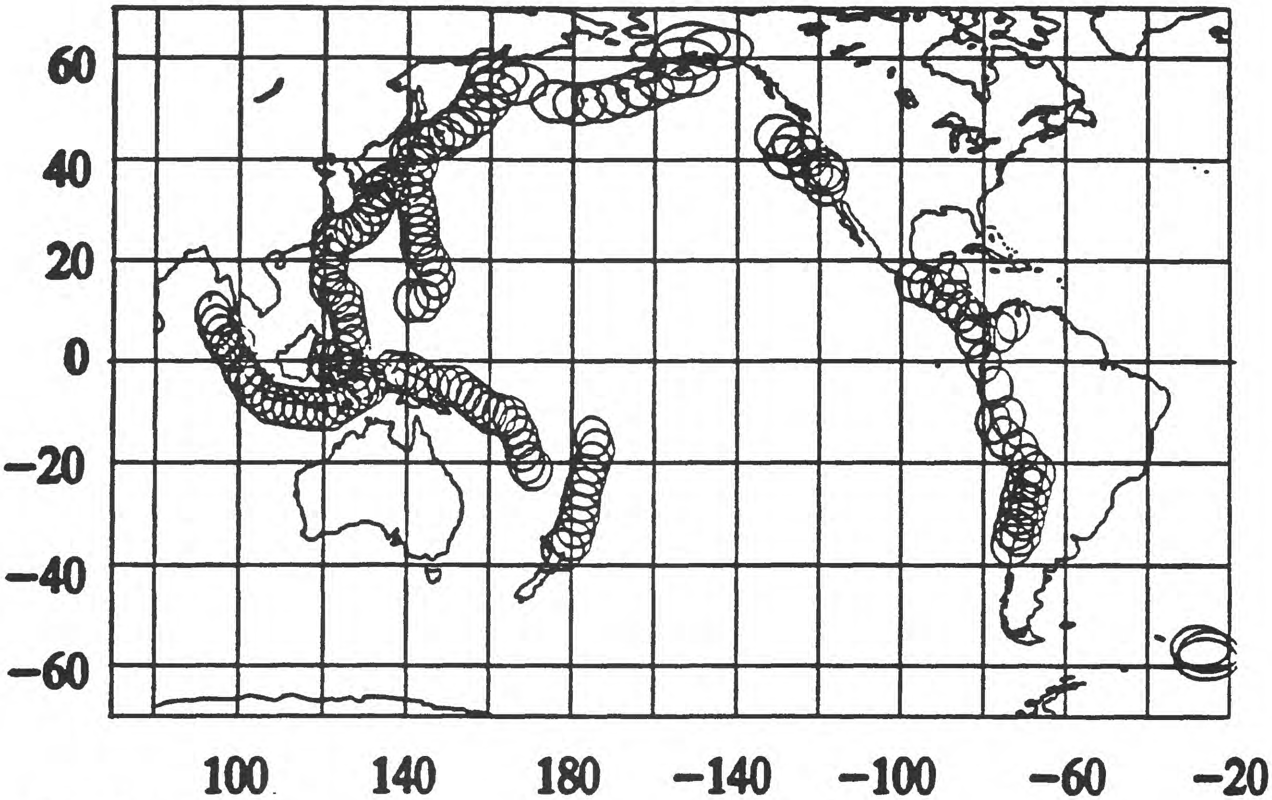


Figure 1

Random Distribution of TIPs in the A-test

Number of quakes predicted	Distribution of predictions	Cumulative distribution of predictions	Level of confidence %
0	2078	1000000	0.00
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10	143	143	99.99

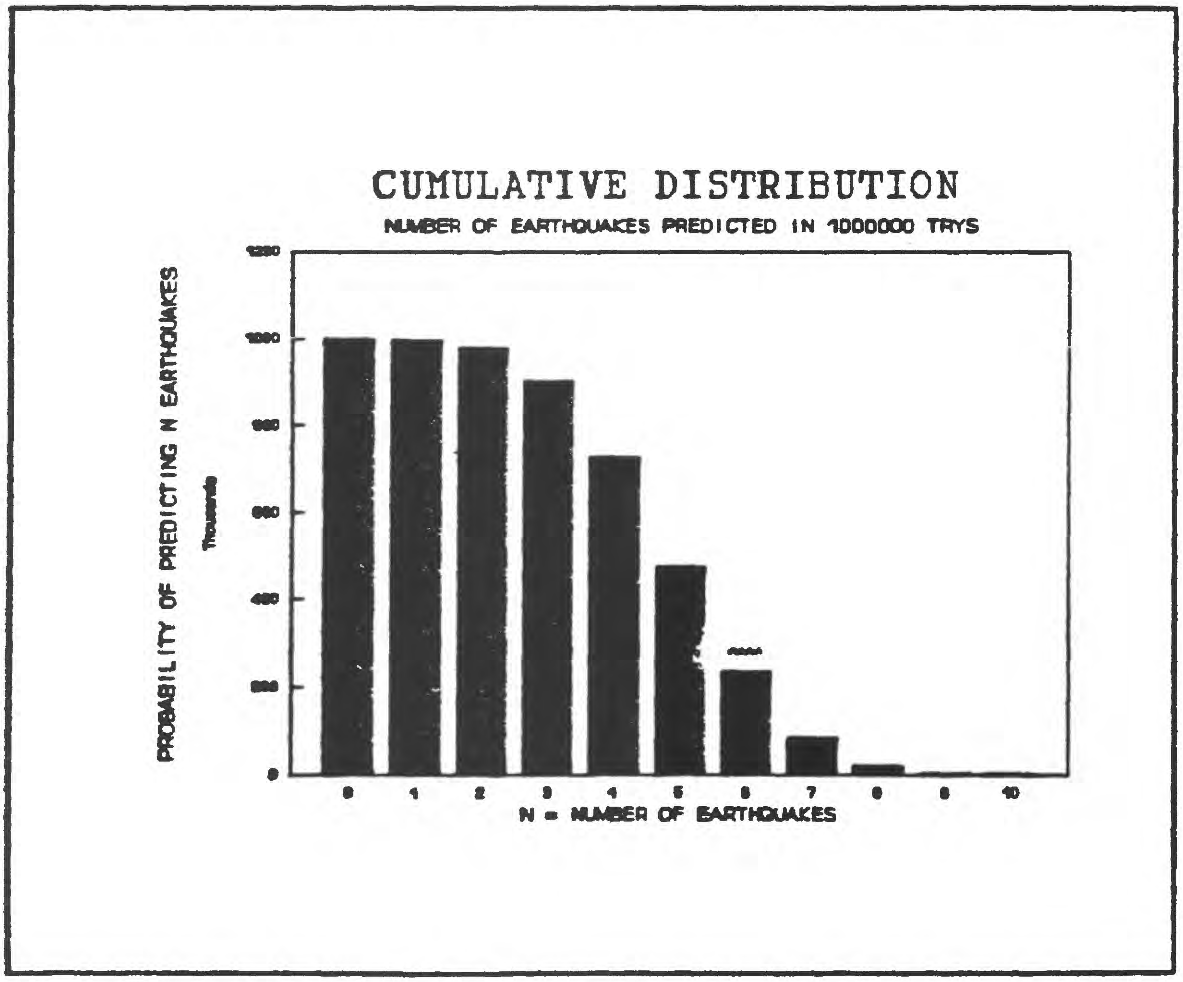

Fig 2

Random Distribution of TIPs in the B-test

Number of quakes predicted	Distribution of predictions	Cumulative distribution of predictions	Level of confidence %
0	1239	1000000	0.00
1	12768	998761	0.12
2	58081	985993	1.40
3	148613	927912	7.21
4	238153	779299	22.07
5	252113	541146	45.89
6	177789	289033	71.10
7	82531	111244	88.88
8	24350	28713	97.13 **
9	4105	4363	99.56
10	258	258	99.97

CUMULATIVE DISTRIBUTION OF NUMBER OF

EARTHQUAKES PREDICTED IN 1000000 TRYS

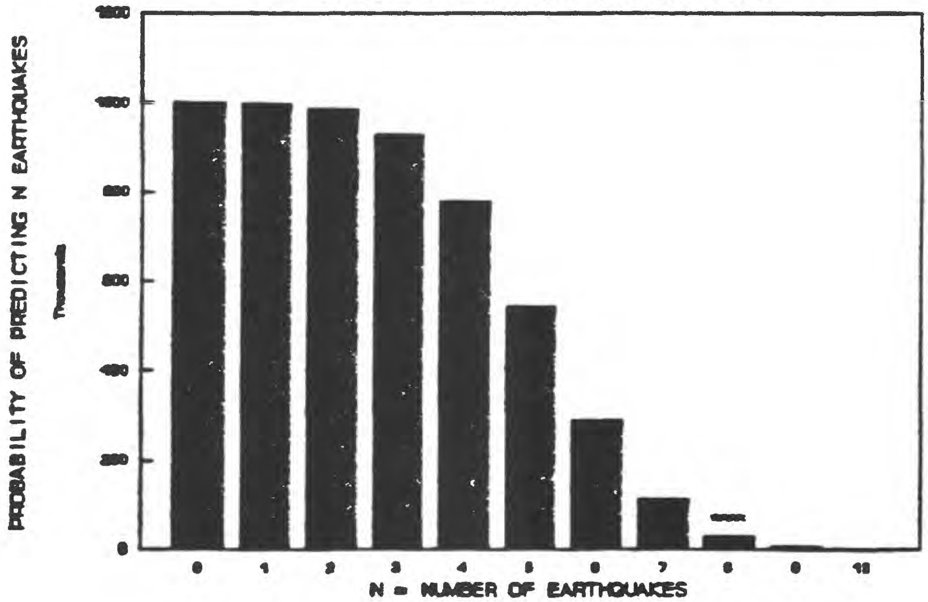

Fig 3

Appendix H

Document provided NEPEC by Dewey, detailing several aspects of the M8 algorithm and of M8 Tests A and B.

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TEST OF EARTHQUAKE PREDICTION ALGORITHM M8

James W. Dewey
U. S. Geological Survey, Denver, CO 80225

I would like to discuss several aspects of the mechanics of the M8 algorithm and of M8 Tests A and B.

The NEIC data-base: We will apply the M8 algorithm to various catalogs or sets of catalogs maintained in computerized data-bases by the National Earthquake Information Center (NEIC) (Figure 1). For analysis of seismicity occurring through 1988 we use the Global Hypocenter CD-ROM Data Base (Version 1.0). For analysis of seismicity occurring after 1988, we use the Monthly PDE and PDE-weekly. A detailed discussion of the NEIC data-base will appear as an appendix in the Open-File report of Healy, Kossobokov, and Dewey, a draft of which (without appendices) was distributed to NEPEC members in late April.

The magnitude convention used in our test (Figure 1) is a device to get around the different types and numbers of magnitudes reported for each event. For most small and moderate earthquakes, the magnitude used will be $m_b(GS)$. For most large earthquakes the magnitude used will be an M_S magnitude.

I tried a repeat of the retroactive simulated forward prediction study of 1985/1/1 – 1991/7/1, using the same TIP's but changing the criterion for judging the success of TIP's by using moment-magnitudes for the largest earthquakes. I converted HRV scalar moments to moment-magnitudes (M_W) for shocks of $M_S \geq 7.2$, using the relationship of Hanks and Kanamori (1979, Journal of Geophysical Research, v. 84, p.2348-2350). Within the circles of investigation, three of the shocks formerly assigned $M \geq 7.5$ had $M_W < 7.5$, whereas four shocks formerly assigned $M < 7.5$ had $M_W \geq 7.5$. The net effect was that seven of eleven shocks of $M_W \geq 7.5$ were successfully forecast, using both Test A and Test B procedures.

Sample semiannual update: I have distributed copies of a prototype update (Figures 2a and 2b). We would make similar updates available to parties interested in monitoring the progress of the test.

An alternate null hypothesis: Among the regions of investigation there is great variation in the historic level of seismicity at $M \geq 6.5$ (Figure 3). J. H. Dieterich has proposed a variation of our null hypothesis (p. 11 and 12 of our draft of 4/21/92) that would account for regional variations of activity. In his null hypothesis, TIP's would be randomly assigned to circles with a probability that is proportional to the number of $M \geq 6.5$ shocks since 1900. Applying his null hypothesis to the simulated forward prediction study for 1985/1/1 - 1991/7/1 yields a confidence level of 60 % for Test A (compared with our 76 %) and a formal confidence level of 94 % for Test B (compared with our 97 %). The confidence level for Test B would not account for the fact that Test B was constructed after inspection of the data. A memorandum from Dieterich explaining the development and application of his null hypothesis will appear as an appendix in our Open-File Report.

NEIC DATA-BASE

I. Current NEIC catalogs (used to predict future quakes)

   A. QED (Quick Epicenter Determination)

      1. *Publication time – Origin Time* is about 7 days.

      2. Not used in M8 Test.

   B. PDE - weekly

      1. *Publication time – Origin Time* is about 4 weeks.

      2. Used for provisional predictions in M8 Test.

   C. Monthly PDE

      1. *Publication time – Origin Time* is about seven months.

      2. About twice as many events listed as in PDE - weekly.

      3. Changes in magnitude and hypocenter from PDE - weekly.

      4. Used for final evaluation of M8 Test.

II. Global Hypocenter CD-ROM Data Base (Version 1.0)

   A. Used to define baseline rates of seismicity and anomalous seismicity since 1975.

   B. Contains multiple catalogs.

   C. Requires identification and removal of duplicate entries.

III. Magnitude convention used in M8 Test A and Test B

   A. M defined to be largest of up to four magnitudes in data-base.

   B. Magnitudes considered are $m_b(GS)$, $M_S(GS)$, and usually M_{PAS} and M_{BRK}.

Figure 1.

[SAMPLE SEMIANNUAL UPDATE]

The attached map [and tables] represent the results to date of an ongoing test of the earthquake-prediction algorithm M8. Algorithm M8 is described by Kossobokov and Keilis-Borok (1990). We refer to the test as M8 Test, and we refer interested parties to the paper by Healy and others (1992) for a more complete description of the test and its rationale.

The map [and Table 1] represent Times of Increased Probability (TIP's) that have been identified by algorithm M8 as configured for M8 Test. The purpose of the test is to estimate the statistical significance of M8 TIP's and to determine if an M8 TIP is in some sense an improvement on forecasts and probability estimates made by other widely used techniques. The TIP's should therefore be viewed as "research TIP's". Evaluation of the effectiveness of the M8 algorithm will consider the totality of TIP's and the number of earthquakes of magnitude 7.5 or larger that occur in TIP's.

The U. S.Geological Survey's National Earthquake Prediction Evaluation Council has not endorsed this algorithm as being capable of predicting earthquakes and does not recommend that any action be taken because of this information. The release of this information is being made to document M8 Test. In six months,the information will be updated.

Referencees

Keilis-Borok, V. I., and Kossobokov, V. G., 1990, Times of increased probability of strong earthquakes (M => 7.5) diagnosed by algorithm M8 in Japan and adjacent territories: Journal of Geophysical Research, v. 95, p. 12,413-12,422.

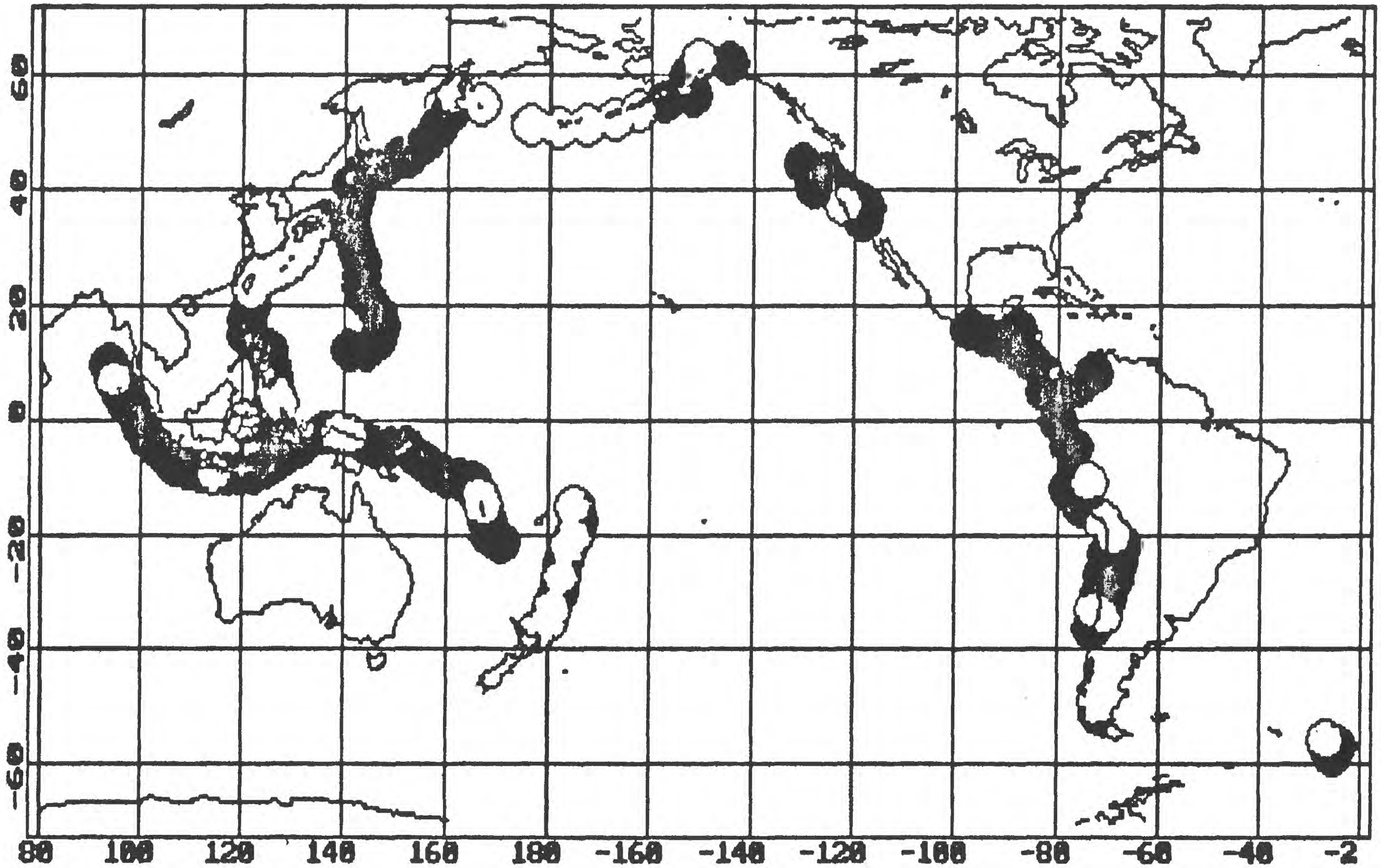
Healy, J. H., Kossobokov, V. G., and Dewey, J. W., 1992, The design of a test to evaluate the Soviet earthquake prediction algorithm, M8: U. S. Geological Survey Open File Report [**, ** p].

[Table 1 - TIP's by the M8 Algorithm after 7/1/91 and including current TIP's displayed in the accompanying map.]

[Table 2 - Strong earthquakes occurring since start of M8 Test A.]

Figure 2a

Regions of increased probability of magnitude 7.5+ earthquakes for the period from Jul 1, 1991 to Jan 1, 1992



Circles are regions of investigation

○ - According to criteria of M8 algorithm, region is in a Time of Increased Probability for M => 7.5 earthquake.

● - Region falls within one or more circles of investigation, but region is not covered by any circle for which a Time of Increased Probability of M => 7.5 earthquake has been declared.

Figure 2b

17) 165;	25) 159;	18) 155;	24) 153;	26) 145;
76) 138;	77) 127;	23) 126;	27) 125;	16) 120;
75) 119;	74) 117;	28) 110;	56) 109;	96) 104;
71) 104;	79) 99;	97) 98;	19) 98;	78) 96;
55) 96;	94) 94;	4) 93;	2) 93;	70) 91;
3) 91;	6) 89;	57) 88;	95) 86;	80) 86;
54) 86;	22) 85;	101) 84;	81) 83;	133) 82;
5) 82;	51) 81;	15) 81;	7) 81;	69) 79;
140) 78;	102) 78;	20) 77;	58) 75;	72) 72;
21) 71;	132) 68;	1) 68;	141) 66;	100) 66;
47) 66;	46) 66;	50) 64;	49) 64;	52) 63;
14) 63;	82) 62;	118) 61;	48) 59;	119) 56;
142) 55;	103) 55;	8) 55;	134) 54;	13) 54;
135) 53;	62) 52;	60) 52;	131) 51;	120) 50;
104) 50;	59) 50;	143) 48;	63) 48;	61) 48;
122) 47;	136) 45;	98) 45;	123) 44;	99) 44;
147) 42;	146) 42;	137) 42;	144) 41;	105) 41;
73) 41;	88) 39;	66) 39;	53) 39;	45) 39;
11) 39;	121) 38;	83) 37;	12) 37;	145) 35;
128) 35;	106) 35;	86) 35;	35) 35;	107) 34;
84) 34;	44) 34;	124) 33;	90) 33;	34) 33;
67) 31;	64) 31;	139) 30;	130) 30;	127) 30;
89) 30;	68) 30;	65) 30;	36) 30;	87) 29;
85) 29;	32) 29;	9) 27;	138) 26;	125) 26;
109) 26;	33) 26;	108) 25;	31) 24;	10) 24;
91) 23;	43) 23;	37) 22;	129) 21;	117) 21;
92) 20;	110) 18;	42) 18;	114) 17;	30) 17;
116) 16;	115) 16;	39) 16;	113) 15;	112) 15;
40) 15;	38) 15;	41) 14;	93) 13;	29) 10;
126) 5;	111) 4;			

Figure 3 – Regions of investigation ordered by the number of $M \geq 6.5$ earthquakes occurring within during 1900/1/1 - 1991/7/15. Regions in which earthquakes were "predicted" in simulated forward prediction study (1985/1/1 - 1991/7/1) are circled. Dashed lines enclose regions where earthquakes would have been predicted with Test B conventions that would not have been predicted with Test A conventions.

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Appendix I

Document provided NEPEC by Dieterich, presenting a comparison of the M8 algorithm with a Poisson model.

—PAGE 139 FOLLOWS—

OFFICE OF EARTHQUAKES, VOLCANOES, AND ENGINEERING
Branch of Tectonophysics
345 Middlefield Road, MS/977
Menlo Park, CA 94025

April 21, 1992

Memo
To: J. Healy, V. Kossobokov and J. Dewey
From: Jim Dieterich
Subject: Comparison of M8 test results with 'Poisson' model

Thank you for the opportunity to look at and comment upon the early version of your Open-File Report, and for supplying the data needed to undertake the comparison that I describe below. I fully endorse the goals of this study to develop an objective test of the M8 algorithm. This is an important topic and I believe what you have done is both reasonable and constructive.

As I discussed previously, I have been interested in the question: How does M8 compare with a simple scheme of assignment of TIPs based on a Poisson model for earthquake occurrence? The Poisson model is widely regarded as an acceptable zero-order model of earthquake occurrence. Hence, departures of the M8 test results from a Poisson-based method of TIP assignment, would be useful for evaluating the value and performance of M8.

I have written a computer program for a simple implementation of this comparison. The test assigns TIPs randomly to the circles, weighting the probability of a TIP by a measure of the long-term average rate of earthquake activity in the circle. I think this is an appropriate null hypothesis for the M8 test. It is a variant of your comparison of M8 that is based on unweighted assignment of TIPs. However, the unweighted assignment of TIPs has the problem that all circles will not have the same rate of seismic activity and consequently, may not have the same chance of randomly producing an earthquake in some interval of time.

The measure of average rate of activity for this test is taken to be the number of earthquakes $M \geq 6.5$ in each circle since 1900. For this I used the data you provided to me from the earlier draft version of the report.

The weighting parameter, F_i, for random assignment of a TIP for circle, i is

$$F_i = \frac{\text{number of earthquakes M}\geq 6.5 \text{ in circle } i \text{ (since 1900)}}{\text{total number of earthquakes M}\geq 6.5 \text{ in all circles (since 1900)}} .$$

The test is run in six month increments for the period covered by the M8 test. For direct comparison with the performance of M8, the total number of randomly assigned Poisson TIPs should be the same as produced by the M8 algorithm over the duration of the test. Hence, the average number of TIPs/6month, as declared by M8, over the entire 13 six-month intervals was used. For the weighted random TIP assignment, the probability, P_i, of a TIP being declared in circle, i for any six month interval is

$$P_i = F_i N \ ,$$

where N is the average number of TIPs per six month interval declared by M8 (*i.e.*, $N = 409/13$).

COMPUTATIONAL PROCEDURE

For each circle, i, find $P_i = F_i N$

Iterate though time the intervals and circles i

1) For each interval and circle, draw a random number R (range 0 to 1)
2) If, $P_i > R$, then, declare a TIP for circle i

At end of simulation, count number of earthquakes M≥7.5 that had at least one TIP declared for the circles and interval in which it occurred. Such earthquakes are defined by M8 as a successful prediction.

Repeat the simulation

(Note: in practice it is only necessary to iterate over the circles and interval in which each M≥7.5 earthquake occurred)

CIRCUM PACIFIC TEST: GENERAL CHARACTERISTICS

147 circles and 13 intervals of 6-month duration

10 M≥7.5 earthquakes occurred in the defined circles

Average number of earthquakes/circle for any half-year interval:

$$\frac{\text{26 circles affected by M}\geq 7.5 \text{ EQs}}{\text{(13 intervals)(147 circles)}} = 0.014$$

TEST A - THE BASIC MODEL

The first comparison is with the original test of the M8 algorithm. The M8 algorithm generated a total of 409 TIP intervals. Table 1 gives the results of the random assignment of TIPs to circles for 100,000 simulations. The columns labeled 'Weighted' are the results obtained for assignment of TIPs using the weighting procedure, described above, based on historical rate of seismicity in each circle. The columns labeled 'Unweighted' employ a simple unweighted random assignment of TIPs that should be equivalent to the random test given in the report. The results of 'Unweighted' agree quite well with the random test of the report.

Table 1: Random Model A
(100,000 simulations)

	Weighted		Unweighted	
Success	Number	Cumulative percent	Number	Cumulative percent
0	30	100.0	197	100
1	365	100.0	1920	99.8
2	2411	99.6	8406	97.9
3	8862	97.2	18566	89.5
4	20759	88.3	25344	70.9
5	27541	67.6	23217	45.6
6	23930	40.0	14796	22.4
7	11983	16.1	5643	7.6
8	3585	4.1	1622	1.9
9	519	0.5	274	0.3
10	15	0	15	0

Results of M8 algorithm (From Healy, *et al.*)

Successful TIPs = 6

(success is defined as earthquake, M≥7.5, occurring in a circle with active TIP)

Successes/TIP interval: 6/409 = 0.015

Results for weighted random assignment of TIPs:

Average successes/simulation = 5.13

Successes/TIP interval: 5.13/409 = 0.013

Weighted random assignment of TIPs does as well, or better, than M8, 40% of the time.

TEST B - THE MODIFIED M8 TEST

This comparison is with the test of the M8 algorithm, modified to not automatically turn off a TIP if an earthquake, M≥7.5, occurs. The modified M8 algorithm generated a 446 TIP intervals in the 13 six-month intervals. Table 1 gives the results of the random assignment of TIPs for 100,000 simulations. Again, the results of 'Unweighted' agree quite well with the random test of the report.

Table 2: Random Model B
(100,000 simulations)

	Weighted		Unweighted	
Success	Number	Cumulative percent	Number	Cumulative percent
0	0	100.0	75	100.0
1	72	100.0	1254	99.9
2	1401	99.9	5909	98.7
3	5812	98.5	15158	92.8
4	16776	92.7	23607	77.6
5	26833	75.9	24844	54.0
6	27469	49.1	17747	29.2
7	15472	21.6	8301	11.4
8	5082	6.2	2557	3.1
9	1010	1.1	518	0.5
10	73	0.1	30	0

Results of M8 algorithm (From Healy *et al.*)
Successful TIPs = 8
Successes/TIP interval: 8/446* = 0.018
(* 480 TIPS declared in 7 years, estimated as 446 TIPs in 13 intervals)

Results for weighted random assignment of TIPs:
Average successes/simulation = 5.45 (4.67 for unweighted random)
Successes/TIP interval: 5.45/446 = 0.012
Weighted random assignment of TIPs does as well, or better, than M8, 6% of the time.

DISCUSSION

From the results of Table 1, it appears that the original M8 algorithm was not significantly better at declaring successful TIPs than the simple method of random assignment based on the Poisson probability model.

The modified M8 algorithm (Test B) is more problematic. The results of Table 2 indicate that the weighted random model could do as well or better that the modified M8 only about 6 percent of the time. There is however, the much discussed and troublesome issue of altering the M8 algorithm after the results of the first test results were seen. While the arguments in support of the change seem very plausible, it also seems evident that the modified algorithm cannot receive an independent test from that data set. For the circum-Pacific, I feel the test begins now and will be decided by future earthquakes. I look forward with interest to see how it comes out.

Finally, I would like to take this opportunity to offer an opinion, based on these results, on the present status and appropriate uses of M8. I think it is at least plausible that future earthquakes could support the modified M8 algorithm and yield a success rate comparable to that indicated by the B test. If for the sake of argument we accept that speculation, the probability of an earthquake, $M \geq 7.5$, occurring in a circle during a 6 month TIP interval would be about 0.018. This remains is a rather low probability, not much greater than the observed average number of earthquakes/circle for any half-year interval of 0.014. Also, the method does not predict specific earthquakes because any earthquake, $M \geq 7.5$, located within the large area of a circle will satisfy a TIP. In view of these results, I believe at present, the method is principally of scientific interest to a) possibly improve our understanding of underlying physics of earthquake occurrence, and b) attempt to develop improved algorithms that could someday serve as a basis for recommendations of public response.

Copy to NEPEC

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Appendix J

Letter postdated June 4, 1992,
presented to NEPEC by Langbein,
outlining a workshop/review
of the Parkfield prediction experiment.

United States Department of the Interior

GEOLOGICAL SURVEY
OFFICE OF EARTHQUAKES, VOLCANOES, AND ENGINEERING
345 Middlefield Road - Mail Stop 977
Menlo Park, California 94025
415-329-4853

June 4, 1992

Dear Workshop participant;

Thank you for agreeing to participate in a review of the Parkfield Experiment. By now, you should be organizing your thoughts and ideas concerning both the past and the future of the Parkfield Experiment. For reference, I have included a list of current and past investigations at Parkfield. This is not a comprehensive list. In particular, please think about the following points as you organize your results. Since several of these issues are coupled, these points are listed without any priority.

What are the most important results from the Parkfield experiment and what areas require more attention in the future?

How can the experiment be reconfigured to accomplish the joint goals of basic science and short-term prediction research?

What do we think the long-term probability actually is for a moderate sized earthquake at Parkfield? How has the probability estimates been affected by recent work on the gap model and the characteristic earthquake hypothesis?

How would various levels of long-term probabilities affect how you would want to carry out your experiments over the next few years?

How should the Parkfield alert structure be modified both with respect to changing long-term probabilities and our experience with the existing structure.

How have results from Parkfield studies affected work in other areas?

How has the forecast of the Parkfield earthquake affected planning in society? Are there lessons that can be used for large metropolitan areas?

For your information, I have included a list of participants and the tentative title of the poster that they have given me. I have taken the liberty of grouping people into one of the four *sessions* mentioned in the first letter. If you do not fit into the assigned group or your poster applies to two or more groups, please feel free to contribute to the appropriate group(s).

In the next few paragraphs, I will discuss how you will get to Santa Cruz. The workshop begins on Sunday night, June 28 and ends at noon, July 1.

If you are **US Government** participant, please contact your Administrative Office and they will prepare your travel authorization. If you need airfare, please call Wanda Seiders at 415-329-5155 to obtain an account number.

If you are **NON-Government** participant, you will be sent a travel authorization number. Most likely, we will send these authorizations to you by FAX. Once you have this authorization number, you can make airline reservations if necessary. Please phone Corporate Travel services in San Francisco (415-433-4700 or 800-428-7736 from outside California) to make your reservations. Identify yourself as a participant in the

Parkfield Workshop, ask for **government rates** and give them your travel authorization number and the account number (9900-88807). Ask Corporate travel to send your tickets to you by Federal Express. If you are flying at government expense, please do not purchase your tickets by yourself because it will be extremely difficult for you to get reimbursed.

Please send a *copy of your itinerary* to:

Wanda Seiders
345 Middlefield Rd., MS 977
Menlo Park, CA 94025

Once you arrive either in San Jose or San Francisco Airport, call the Santa Cruz Airporter (408-423-1214 or 800-223-4142). I recommend that you reserve a place on the airporter.

The enclosed maps show the location of the Crown-Merrill College at UCSC. You will need to register for your room at the "Satellite Conference Center" in the center of Crown-Merrill apartments. Try to arrive between 3pm and 5pm on Sunday. In your itinerary, let Wanda know the time that you are scheduled to arrive.

We have been assigned a meeting room in Stevenson, Room 150.

Dinner is served between 5:30pm and 6:30pm at the Cowell dining hall.

If you are driving, you will not need to pay for parking, but you should obtain a parking permit when you check-in. This also applies to those of you who are commuting. We understand that the campus cops are vigilant giving parking tickets.

For those people who want gym facilities, passes can be purchased at the Office of Physical Education, Recreation and Sports located in the East Field House on Hagar Drive.

For the period from Sunday dinner through lunch on July 1, the eating and lodging expenses will be covered by USGS since we will be staying in the dormitory at UCSC. All rooms will be double occupancy. The phone number at the Conference Office is 408-459-2611. I have enclosed a map showing the UCSC campus and the location of the conference.

When you return home after the conference, you will need to submit your incidental travel expenses to Wanda Seiders.

Sincerely;
John Langbein for Andy Michael and Peter Malin

Enclosures

Current Participants 6/1

Name	Institution	Poster
Monitoring		
B. Baker	USGS	Alinement array measurements
K. Breckinridge	USGS	Creepmeter data
A. Michael	USGS	Eq. catalog from PKF
Leary	USC	Fault zone trapped waves
Malin	Duke	
McEvilly	UC Berkeley	Monitoring; Vibroseis and microearthquakes
Clymer		
P. Johnson		
Antoli		
Uhrhammer	UC Berkeley	Near-field moment tensor inversion
Wyss	U. Alaska	Rate and ave. depth of eq. at PKF
Hellweg	USGS	Coda Q; Spatial and Temporal relation
Fraser-Smith	Stanford	
R. Mueller	USGS	Magnetic field data
S. Park	UC-Riverside	Electrical Array data
Wescott	U. Alaska	VLF measurements at 82khz
M. Gladwin	Queensland	
M. Johnston	USGS	
Mortenson	USGS	
Quilty	USGS	Mid. Mtn water level and creep data
Riley	USGS-WRD	
Roeloffs	USGS	Eq. hydrology: past and future
N. King	USGS	Geodetic observations near PKF
Langbein	USGS	Two-color data and sensitivity analysis
Mark Matthews	MIT	Space-time inversion of geodetic data
C.Y. King	USGS	Radon
Sato	USGS	Rock-fluid interaction & eq. triggering mechanism
M. Thompson	USGS	Monitoring the PKF. BTA-1 well for major ions and water isotopes; 1988-1990
Armstrong	IBM	Acoustic emission monitoring
Lockner	USGS	
Modeling & Structure		
Ben-Zion	Harvard	Earthquake Failure sequences containing locked and creeping segments
J. Rice	Harvard	Interaction of SAF creeping zone with adjacent rupture zones and eq. recurrence at PKF

B. Stuart	USGS	PKF. instability model
Tullis	Brown	
J. Brune	UNR	Predictability and mechanism of stick-slip events in foam rubber; an analog of Parkfield?
Eberhart-Phillips	USGS	3D velocity, seismicity and structure
J. Sims	USGS	Geologic/Tectonic framework
Wentworth	USGS	Geologic framework
Forecast		
Bakun	USGS	
Lindh	USGS	
Dieterich	USGS	
D. Jackson	UCLA	Conditional Probability of PKF eq.
Toppazada	CDMG	
Reasenberg	USGS	
R. Harris	USGS	Parkfield geodetic modeling & potential for M7
Segall	USGS/Stfd.	PKF. eq. cycles from inversion of geo. data
R Simpson	USGS	Could Coalinga eq. delay the PKF event?
Bortugno	OES	
J. Goltz	OES	PKF public information
Jim Davis	CDMG	
Fitzpatrick	Hazards Assessment Lab	Societal sucess of the PKF eq. prediction
Post-earthquake & engineering		
Isenberg	Weidlinger	
Schneider	EPRI	Ground motion study from EPRI array
Shakal	CDMG	
J. Fletcher	USGS	
Spudich	USGS	PKF dense array UPSAR
Steck	USGS	
Others		
Eaton	USGS	
Ellsworth	USGS	
Filson	USGS	
A. Johnston	Memphis	
Klick	USGS	external program
K. McNally	UCSC	
Prescott	USGS	
K. Shedlock	USGS	
J. Stock	Caltech	
Rob Wesson	USGS	

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Appendix K

Letter dated November 15, 1991,
presented to NEPEC by Langbein outlining
a revision to the Parkfield earthquake prediction
scenario based upon rainfall.

United States Department of the Interior

GEOLOGICAL SURVEY
OFFICE OF EARTHQUAKES, VOLCANOES, AND ENGINEERING
345 Middlefield Road - Mail Stop 977
Menlo Park, California 94025
415-329-4853

November 15, 1991

Dr. Tom McEvilly, NEPEC chair
Department of Geology and Geophysics
University of California
Berkeley, CA. 94720

Dear Tom

I have examined both the creepmeter and rainfall data from Parkfield and I have estimated the amount of rain necessary (but not sufficient) to trigger fault creep. Three observations are important; 1) Heavy rainfall does not always trigger creep. 2) Some creepmeters are more sensitive than others to the effects of rain. 3) The amount or intensity of rain is not linearly related to the ensuing creep. I can only give a lower bound on the amount of rain that is necessary to trigger a creep event. If significant creep of more than 1 mm over 7 days has been detected and if more than 20 mm of rain has occurred on any single day during the 7 day window, then the creep can be considered to be triggered by rainfall. I propose that in the future when creep occurring under these circumstances that formally meets a status level, then we discount the level by one letter grade. For instance, last March's B-level alert from creep should be discounted to a C-level status because of the heavy rainfall.

The data that I used to establish the relation between rainfall amounts and creep are from two sources. The rainfall data are daily amounts of precipitation observed since 1961 at the Thomason Ranch located 2 km north of Parkfield. Because the data are recorded manually, there may be errors in recording the observations. Nonetheless, this set is the most complete record that we have for Parkfield. Our digitally recorded rain gauges were installed in 1985. Since most of the creepmeters were installed well before 1985, using the Thomason rainfall record maximizes the number of observed creep events. Although creep is recorded at 10 minute intervals, only the most recent two years of 10-minute data are accessible from the computer. However, we have data available from each instrument's installation date up to the present which have been decimated to a daily value to conserve disk space. Because the records of creep and rain were compared using daily values, the actual timing between the creep event and its possibly correlated rainfall is uncertain by plus or minus one day. So with this as a caveat, I used two schemes to relate creep and rain.

In the first scheme, I found all creep "events" which exceeded 1 mm in one day for all 11 creepmeters in the Parkfield region. I found 52 "events" excluding the effects of the 1966 earthquake recorded on the creepmeter CRR1. Of these events, 8 events coincide with either Coalinga or the Loma Prieta earthquakes, or in one case, excavation near the instrument XMM1 in 1986. Of significance are 9 "events" and possibly 3 others which had rain either in the week preceding the event or rain on the day of the event. For these 9 rainfall "induced" events, approximately 20 mm or more of rain fell during one day in the preceding week.

The second method found all creep events that exceeded 1 mm over a seven day period which qualifies the events at the D-level. This method found all the events from the first scheme plus many more. Of the 106 identified creep events, 9 were triggered by either the Loma Prieta or the Coalinga earthquakes, 1 was triggered by excavation near the creepmeter, and 33 followed rain falling within the previous 7-days. Shown on the enclosed plot are the values of the observed creep and the maximum amount of daily rainfall during the week previous to the creep events. Of the 33 rain related events, 11 of the events occurred on XPK1 and 6 occurred at XMM1. Although the amount of rainfall and triggered creep are not correlated, it appears that 2-cm of rain is necessary to trigger the larger creep events.

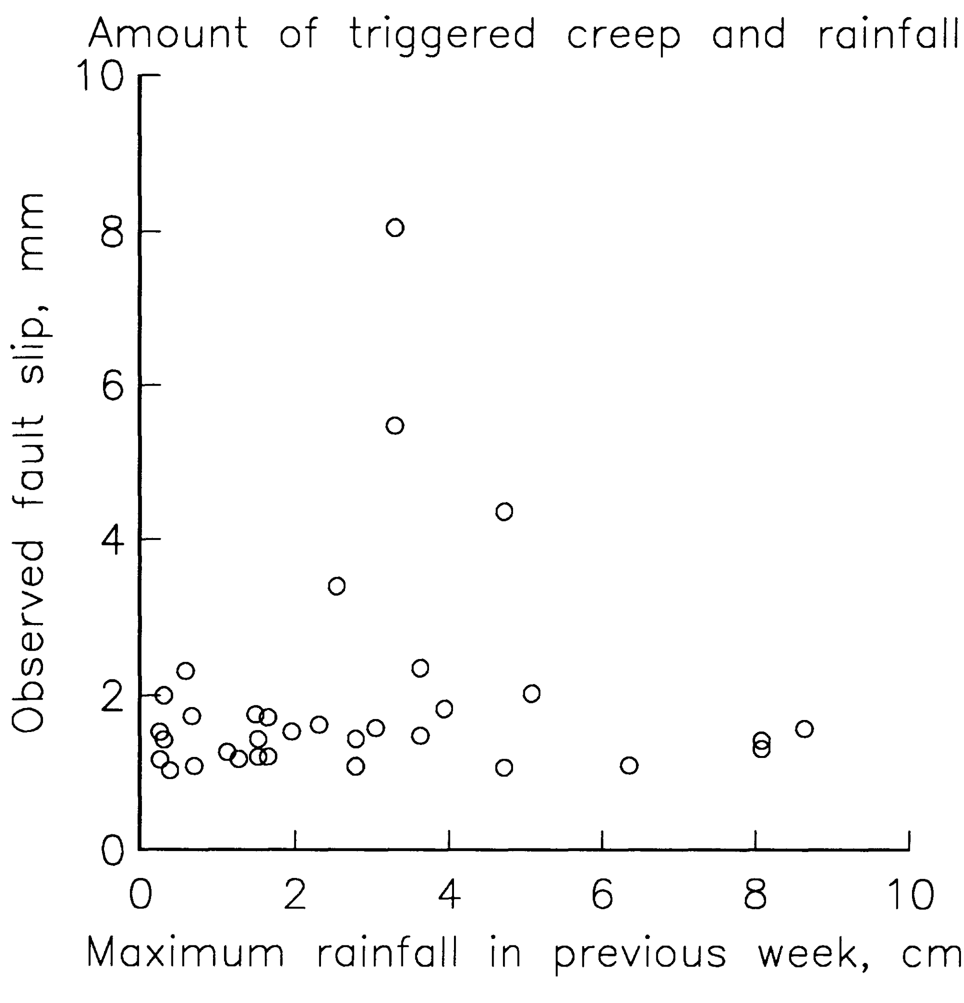
Finally, I'm currently gathering the equipment to measure the response to rainfall of the end piers of two creepmeters, XPK1 and XVA1. It happens that one of my employees, Mike Sanders, has an interest in soil mechanics and he will be working on this experiment. With the soil property data, and time-series data of soil moisture and pier tilts, he can gain some insight into our problem and also finish his master degree at Humbolt State University.

Sincerely yours,

John Langbein
Parkfield Chief Scientist

enclosures

cc: Rob Wesson
Virgil Frizzell


Amount of triggered creep and rainfall
Observed fault slip, mm
0
2
4
6
8
10
0
2
4
6
8
10
Maximum rainfall in previous week, cm

Appendix L

Earthquake Research at Parkfield - 1993 and Beyond:
Information and charge to the NEPEC working group
for the Parkfield Prediction Experiment.

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EARTHQUAKE RESEARCH AT PARKFIELD - 1993 AND BEYOND

Information and Charge to the NEPEC Working Group for the Parkfield Prediction Experiment

Introduction

On April 4, 1985, the State of California was advised by the U. S. Geological Survey (USGS) of the expectation that an earthquake of about magnitude 6 is likely to occur in the next several years on the San Andreas fault near the small community of Parkfield, California. The purpose of this notification was not to issue a hazard warning but to provide State and local officials with information that would be of use in hazard mitigation and emergency response planning. As a consequence of this announcement, the first coordinated, public attempt in the United States was begun to organize an operational system to issue a short-term warning of a potentially damaging earthquake. This short-term prediction experiment also served as a catalyst for a larger, more comprehensive experiment designed to capitalize on the anticipated occurrence of the earthquake by providing a natural laboratory to study the entire earthquake process.

According to statistical calculations made at that time, the earthquake should occur, with 95 percent probability, in the 1985-1993 time interval. Now that the end of this interval is approaching, the Director of the USGS has requested guidance from the scientific community regarding options for the future course of earthquake hazards reduction research at Parkfield.

Background

The Parkfield segment of the San Andreas fault is widely recognized as a world-class locality for the study of strike-slip faulting and crustal earthquakes. Several factors contribute to the importance of Parkfield, including its relatively simple tectonic setting, high rate of strain accumulation, and long history of repetitive failure in moderate-magnitude earthquakes. The 1966 Parkfield earthquake, M 6, marked a watershed in our understanding of the earthquake source and led to the initiation of long-term observational studies of this part of the San Andreas fault, beginning less than 6 months after the occurrence of the event.

Formal studies directed toward the prediction of the next Parkfield earthquake began in 1978 with the creation of a small project headed by Allan Lindh of the USGS. This work was carried out under the National Earthquake Hazards Reduction Act of 1977, which called for "the implementation in all areas of high or moderate seismic risk, a system (including personnel and procedures) for predicting damaging earthquakes and for identifying, evaluating, and accurately characterizing seismic hazards." By 1979, William Bakun of the USGS and Thomas McEvilly of the University of California, Berkeley, proposed that earlier M 6 earthquakes at Parkfield in 1901, 1922, and 1934 were remarkably similar to the 1966 earthquake. In 1984 they published a recurrence model for Parkfield earthquakes and suggested an average interval of 22 years between M 6 earthquakes along this segment of the San Andreas fault.

In 1985, Bakun and Lindh published a paper forecasting that the next Parkfield earthquake should occur before 1993, based upon their analysis of intervals between earlier Parkfield earthquakes. In the parlance of earthquake prediction, their prediction can be classified as a long-term forecast, and it depended solely upon the statistics of the intervals between large earthquakes in the sequence. This hypothesis was presented to the National Earthquake Prediction Evaluation Council (NEPEC), an advisory body to the Director of the USGS, in November 1984, and NEPEC endorsed the general aspects of the prediction. In April 1985, the Director of the USGS formally advised the State of California of the prediction and obligated the USGS to attempt to provide a short-term warning of the anticipated earthquake.

Real-time monitoring of the Parkfield region, made possible with funding from a joint State-Federal funding agreement, provides automatic analysis of seismicity, strain in boreholes, movements of the ground water table, creep along the fault, and other geophysical parameters. A formal set of rules governs the interpretation of specific observational conditions as probabilistic estimates that the next M 6 earthquake will occur within 3 days. There rules were reviewed and endorsed by the California Earthquake Prediction Evaluation Council and by NEPEC. The State of California has the responsibility for issuing a public warning, based on the advice and recommendation of the USGS. The State and all of the counties in the affected region also have formal response plans tied to the USGS rules.

The earthquake prediction experiment at Parkfield also serves a larger and potentially more significant purpose. The perceived high likelihood of an M 6 earthquake at Parkfield makes it one of the best sites in the world to study the earthquake process. A major investment has been made at Parkfield to study the earthquake preparation process, to measure the dynamics of rupture in the next event, and to quantify the response of varying surficial geologic materials and engineered structures to the anticipated strong ground motion. New experiments continue to be installed as opportunity permits, including the recent deployment of ultra-low frequency radio receivers following the 1989 Loma Prieta, California, earthquake. Other opportunities for capitalizing on the Parkfield experiment, such as those outlined in a 1986 National Research Council report, have yet to be undertaken.

Current Effort at Parkfield

Work now in progress at Parkfield can be classified approximately into three different types of activities: monitoring in support of the effort to issue a short-term prediction of the next M 6 event; basic research directed toward understanding the physics of earthquakes; and applied engineering experiments sited a Parkfield and designed to capitalize on the event when it occurs.

Monitoring of the Parkfield region is supported by a network of autonomous instruments equipped with real-time telemetry to the USGS offices in Menlo Park, California. Data are automatically analyzed, as they are received, by computers in Menlo Park that issue alert messages to project scientists. These same computers and personnel also perform many of the same functions for northern and central California using other instrumentation networks.

Basic and applied research at Parkfield spans a wide range of disciplines and involves researchers from government, universities, and the private sector, both in the United

States and from around the world. Parkfield research is supported by funds and grants from the USGS, the State of California, the National Science Foundation, the Electric Power Research Institute, and from several other private, government, and international sources.

The Parkfield Working Group Composition:

NEPEC has been asked by the USGS Director to create a Working Group (WG) to advise him on the future course of the Parkfield experiment, beginning with WG participation in the program review Workshop to be held June 28 - July 01, 1992 in Santa Cruz, CA. Recommended membership in the WG includes B. Hager (Chair), R.B. Smith (or Gilbert), Mogi, R. McGuire (or Cornell), Medigovich (or Grew), plus NEPEC members J. Stock and R. Weldon. Members are selected in part on the basis of their having had no substantial prior connection with the Parkfield experiment.

Questions for the Working Group:

Three classes of questions can be posed and answered in the Group's analysis of the program at Parkfield:

1. What is the current assessment of the Parkfield earthquake prediction? In 1985 NEPEC endorsed a prediction that an earthquake of about magnitude 6 had a 95% probability of occurring by 1993. In light of current knowledge, is it still considered highly likely that an earthquake will occur in the short term? If the earthquake has not occurred by the end of 1992, what does that tell us about the original prediction? Was the basis for the prediction in error?

2. What have we learned during the experiment? The experiment has had both scientific and response community aspects. What have been the principal benefits that have come from both of these aspects of the experiment?

3. Where should the experiment go in the future? In light of the reassessment of the likelihood of a Parkfield earthquake, how should we modify the scientific experiments taking place in Parkfield? Should the real-time surveillance and monitoring be continued, and if so, what changes should be made in the monitoring program? What modifications should be made to research priorities at Parkfield? What research efforts should receive the highest priority? Should there be any modification in the agreements that govern the interaction between the USGS and the State of California with regard to hazard warnings for an earthquake at Parkfield?

Working Group Schedule:

It is hoped that the Working Group can conduct the bulk of its business in conjunction with the Workshop, with possibly one further meeting to formulate its report to NEPEC for the Director by late summer. Recommendations on this schedule will allow timely restructuring the research program at Parkfield.

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Appendix M

M8 Prediction Algorithm Study:
NEPEC Review of Results, May, 1992.

M8 PREDICTION ALGORITHM STUDY:

NEPEC Review of Results, May, 1992

At its May, 1992 meeting in Portland, the National Earthquake Prediction Evaluation Council (NEPEC), a scientific advisory group to the Director of the U.S. Geological Survey, was presented the status of an ongoing evaluation of the M8 algorithm for defining times of increased probability (TIPs) of earthquake occurrence in seismically active regions. Using pattern recognition in a mix of activity indicators based on the ongoing record of seismicity in the region examined, the investigators have conducted a careful study of the technique, and they have established a monitoring experiment to assess the performance of the method in six-month increments in the future. Results to date indicate a small (~1.5, maximum) probability gain over random occurrence for a study of the circumpacific region. This low probability gain is accompanied by fairly high false alarm rates. NEPEC encourages the continued evaluation of the M8 method through the planned monitoring exercise, using fixed parameters in the algorithm.

NEPEC does not endorse the M8 algorithm as capable of reliably predicting earthquakes, nor does NEPEC recommend that any action be taken based on the information produced by the algorithm. While use of the algorithm may improve our understanding of possible coupling among earthquakes separated by large distances, and, perhaps someday provide information that may serve as a basis for recommendations for public response, NEPEC at present considers the method to be principally of scientific interest.