DEPARTMENT OF THE INTERIOR
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The First 20 Years of CALNET, The Northern California Seismic Network

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INTRODUCTION

Since 1967 the U.S. Geological Survey has operated a telemetered seismic network in central and northern California that is widely known as the "CALNET". The network has provided data that are vital to a wide range of research topics and hazard-reduction activities, including regional earthquake monitoring and forecasting, fault mechanics, tectonics, volcano hazards, earth structure, and geothermal investigations. This report describes the network as it exists today, some highlights of its accomplishments, and provides a bibliography of research it has spawned.

At the time of its inception, the network's originators did not envisage all of the functions it would perform more than twenty years later. The earliest network consisted of seismic instruments deployed to record the aftershocks of the 1966 Parkfield earthquake and seismicity of the creeping sections of the San Andreas fault. Simple, inexpensive seismometers were installed and a telemetry system was developed to enable centralized recording of the seismic data in Menlo Park, California. The new network was capable of detecting earthquakes a full two magnitude units smaller than those detected by the existing University of California at Berkeley regional seismic network. This increased sensitivity provided a way to test whether observations of microseismic activity could be used to predict the occurrence of large and damaging earthquakes on the San Andreas fault. Twenty years later many advances have been made, but the earthquake prediction problem still remains largely a challenge. However, the legacy of the network - a wealth of high quality seismic data collected continuously over two decades - is a unique and invaluable resource for earthquake research today.

With an increased understanding of earthquakes has come a shifting of the network's focus. The CALNET now serves many different functions, but foremost is still the collection of reliable, continuous, high-quality seismic data for research on the San Andreas fault system. We study the San Andreas fault system because it poses a significant hazard to one of the most urbanized regions of the United States. The San Andreas system in northern California also is an ideal workshop for earth scientists because 1) much of it is onshore, 2) it is seismically active, 3) the seismogenic region is relatively shallow, 4) it includes a variety of stress regimes and faulting behavior, and 5) the strain rates are high enough to yield reliable observations over a period of years. Because the San Andreas system is such an optimal laboratory for earthquake research, we apply a large effort to studying this fault in the hope that the results will be applicable to understanding seismic hazards elsewhere in the world.

CALNET OPERATIONS

The CALNET is designed to detect all local earthquakes having signal strength above the background level of microseisms. The network configuration was motivated by the need to monitor active faults and volcanoes with a station density sufficient to determine the focal depth of shallow (0-15 km) crustal earthquakes and be recorded by at least 6 stations. The sparse network that was installed in the central California Coast Ranges between the San Francisco Bay and Parkfield beginning in 1967 increased in geographic extent and station density through time, so that by the early 1980's it reached its present configuration (Figure 1). The network currently consists of 345 stations with high-gain, vertical component seismometers. In addition, 38 stations distributed throughout the network have horizontal seismometers for measuring shear-wave arrival times and amplitude for determining local (M_L) magnitude. Horizontal seismometers also are used for seismological research into particle motion analysis, tomography, and teleseismic studies. The CALNET also records data from instruments deployed in the Parkfield Prediction Experiment and 33 stations from the Southern California Seismic Network (SCSN) along the southern border of the CALNET, bringing the total number of components recorded in Menlo Park to approximately 500. Depending on the concentration of stations in a region, the magnitude level at which earthquake detection is complete varies from approximately 1.4 in parts of the central Coast Ranges to 3.3 in the Klamath Mountain Range. However, earthquakes with $M<1.0$ are routinely detected throughout the network.

The amplified output of each seismometer is frequency modulated, multiplexed, and transmitted to Menlo Park, California via a combination of radio, telephone, and microwave communications, so that all stations are recorded in common with the same time base. Most of the network is designed to record ground motion between 0.2 and 20 Hz with 40-50 db of dynamic range (see the series of Open-File Reports by *Eaton*), but the passband and dynamic range is greater for special instrument clusters along the Hayward fault and at Parkfield. Because the primary goal of the network is earthquake detection, the combined effect of high signal amplification and limited dynamic range results in "clipped" signals for stations in the near field of $M>1.5$ earthquakes and for large portions of the network for $M>3.0$ earthquakes. Clipping limits the utility of the signal for many purposes, but still permits accurate determination of the P-arrival time, first-motion, and coda duration. To provide on-scale recordings for larger earthquakes, the CALNET records 34 stations located throughout the network that have low-gain vertical seismometers.

Earthquake Detection Systems

Earthquake detection and location occurs on two independent data acquisition systems, the Real-Time-Picker (RTP) and CalTech-USGS-Seismic-Processing (CUSP) system. The RTP is a parallel microprocessor system developed by the CALNET (*Allen*, 1978, 1982) which provides earthquake locations and magnitude estimates within minutes of the earthquake occurrence. The RTP only generates earthquake origin times and locations, station arrival times and coda-durations; no seismograms are retained.

The same data is analyzed with the CUSP system, a complete earthquake detection, location, and data management system developed by Carl Johnson of the California Institute of Technology. This system operates on a cluster of computers that perform specialized functions. The "on-line" computers digitize 512 channels of input at 100 samples/sec with 12 bit A/D resolution, detect any earthquakes, demultiplex the digital data stream, and tag each "trigger" with a unique identification number for data management. Software then automatically computes the P-arrival times, coda durations, locates the earthquake, and "posts" the earthquake for review by seismic analysts. The analysts examine the digital seismograms on computer screens and revise the parameters as necessary to properly locate the earthquake. Subsequently the digital seismograms and earthquake locations are stored on magnetic tape for later research. In the event of catastrophic computer failure all data can be recovered from continuous data recordings on FM tape. The combined power of the CUSP, RTP, and FM tape systems ensures complete recording of ongoing earthquake sequences.

Real-time Earthquake Monitoring and Response

The CALNET acts a source of real-time earthquake information to earth scientists, the news media, and disaster officials. This information content can take various forms, such as informing the public of the anticipated number of aftershocks following a main shock, issuing warnings of the likelihood of subsequent larger shocks immediately after the occurrence of felt earthquakes (*Agnew and Jones*, 1991), and advising scientists and governmental bodies when seismicity in certain regions is anomalous. Because of these monitoring responsibilities, the CALNET has taken considerable efforts to operate their earthquake detection system with a high degree of reliability. Electricity for the computers and portions of the microwave telemetry system is supplied through an uninterruptable power supply with standby emergency power backup. Critical hardware is seismically braced. A skeleton seismic network is directly telemetered to Menlo Park to maintain minimal operating capacity in the event of catastrophic failure of the main telemetry system. Battery-operated, satellite telephone communications are available if the local telephone system should fail during a seismic crisis. In addition, earthquake acquisition and monitoring functions occur simultaneously on backup computers.

The CALNET has also developed computer software that continuously monitors the RTP output and notifies by radio pager the seismologist on duty if pre-established alert criteria are exceeded (*e.g.*, magnitude, number of earthquakes per hour). This software finds application in three areas. First, when an earthquake occurs that is large enough to be felt, the seismologist on duty can quickly assess the situation and apprise public officials and the news media of the earthquake location and likelihood for further earthquakes.

Since seismicity is often an intermediate (months-to-days) precursor to volcanic eruptions, the real-time earthquake monitoring system is also used alert the seismologist on duty of unusual seismicity in volcanic regions. The CALNET monitors volcanoes located near The Geysers-Clear Lake, Coso Range, Lassen Volcanic National Park, Mammoth Lakes-Long Valley, Medicine Lake, Mono Lake, and Mt. Shasta. In addition, the capabilities of the CALNET permit detection of unusual seismicity at other volcanoes within the network, such as those at Sutter Buttes, Truckee, or Death Valley. Continuous, long-term monitoring is required to establish "normal" background seismic behavior, and during the past 20 years seismicity has been detected at most of these volcanic regions. The high level of seismicity in the Mammoth Lakes-Long Valley region since 1978 is thought to be directly attributed to active magmatic intrusion, and low-frequency earthquakes have been observed at Medicine Lake, Lassen, and the Clear Lake region that are also believed to be related to magmatic processes. When prescribed alert criteria are exceeded in the Mammoth Lakes-Long Valley region (*Hill et al.*, 1991), the CALNET seismologist on duty notifies the Chief Scientist of the Long Valley project who has responsibility for notifying California and Nevada state geologists, emergency services officials, seismologists at the University of Nevada at Reno and California Division of Mines and Geology, scientists throughout the USGS, local U.S. Forest Service personnel, Federal Emergency Management Agency, and Mammoth local governmental officials.

The third application of real-time monitoring occurs near the town of Parkfield, California. Six *M*6 earthquakes have occurred there since 1857 that are believed to have repeatedly ruptured the same 25-km-long segment of the San Andreas. Based on analyses of seismic and geodetic data, the USGS has formally issued a long-term prediction for another *M*6 earthquake at Parkfield (*Bakun et al.*, 1987). Consequently, the USGS in cooperation with the California Division of Mines and Geology has installed an extensive network of geophysical instrumentation in the region for the purposes of identifying anomalous signals techniques that might provide a short-term (minutes-to-days) warning of the next Parkfield earthquake. The CALNET actively participates in the Parkfield Prediction Experiment through operation of the earthquake network. When earthquake activity exceeds prescribed alert criteria, the CALNET seismologist on duty notifies the Chief Scientist of the Parkfield Prediction Experiment, who has responsibility for notifying the California Office of Emergency Services.

Earthquake Catalog

The CALNET maintains a catalog of earthquake locations for the area spanned by the seismograph net (Figure 1). All earthquakes have a minimum of 4 P and S arrival time readings from at least 3 independent stations. Because the geographic coverage and analysis methods improved with time, the magnitude detection threshold generally decreased with time. Figure 2 demonstrates this property of the catalog and also indicates the times of major earthquake sequences. There are about 280,000 events in the 1968-1990 catalog with about 25,000 added each year (Figure 3).

The catalog is comprised of earthquake locations based on P and S arrival time data from analog microfilm records (pre-1984), the RTP (1981 and after), the CUSP system (1984 and after), as well as arrival time data from deployments of portable seismographs. In addition, arrival time data for events recorded by the University of Nevada, the California Institute of Technology, Tera Corporation (Humbolt Bay), Pacific Gas & Electric Corporation, and Woodward-Clyde Consultants have been merged into the CALNET database. Both individual Wood-Anderson amplitude measurements and the UCB catalog magnitudes were merged into the CALNET database to provide an independent estimate of magnitude. Because the CUSP and RTP systems detect and locate earthquakes independently, their data are merged together to generate a comprehensive catalog. CUSP data takes precedence over RTP data for events which have data from both sources.

The merged arrival time data is relocated using the program HYPOINVERSE (*Klein*, 1989). The location program uses one of 34 crustal models appropriate for the trial earthquake location (Figure 4). The model velocities vary with depth, and each model has an accompanying set of station corrections. Multiple crustal models are a simple way of modeling the lateral velocity variations within the crust and locally improving the accuracy of earthquake locations. Duration and amplitude magnitudes are also recalculated using the equations of *Eaton* (1991) which produce magnitudes that are in close agreement with the M_L scale applied by U.C. Berkeley. The method uses station corrections, a distance and depth term and the time dependent gain history of the seismic station.

Data access and archival

With the advent of large capacity storage devices and computer networks, data access and exchange is improving. Because the number of earthquakes in the CALNET catalog exceeds 280,000, it is neither practical nor desirable to distribute the catalog through printed media. Instead, most users prefer to have the data in a computer-readable format. Therefore, we provide 24-hour access to the earthquake database for scientists anywhere in the world who are connected to the Internet computer network. Data requests by individuals without Internet access are routinely obliged through the distribution of computer tapes, floppy disks, customized maps, and paper records.

The finite capacity of on-line storage devices still limits the amount of digital data that is easily accessible. For example, the size of the earthquake catalog for 1967-1991 is approximately 40 Mbytes and is always stored on-line, but the arrival time and other associated parametric data is nearly 1.2 Gbytes and is stored on magnetic tape. The amount of storage required to archive all of the digital seismograms acquired by the CUSP system since 1984 now exceeds 150 Gbytes and resides on more than 1400 9-track tapes. To preserve this is unique and invaluable set of data and facilitate Internet data access, the CALNET also stores its data on a 330 Gbyte optical data storage system jointly purchased by the USGS and U.C. Berkeley. This storage device provides random access to all files within seconds, and the optical storage media are purported to have a life on the order of 100 years.

Public outreach

The ultimate goal of the CALNET is to meet the needs of the public, whether it be long-term hazard assessment, hazard reduction, public education, or real-time earthquake warning. We meet these needs via several products. On a daily basis we update a telephone message and provide access to a computer file that describes the previous day's seismic activity. We generate approximately 140 weekly FAX reports for public officials, university colleagues, and the news media that describe the previous week's seismicity. These reports are reproduced in several newspapers and are an accurate source of information for the public and news reporters. In addition, the staff of the CALNET regularly speaks to the public and the news media throughout the San Francisco Bay region on all aspects of earthquakes.

Future Directions

The operation of a large seismic network presents unusual technological challenges. It takes considerable resources and expertise to maintain the seismometers, telemetry, and computers of the network. Advancements in electronics and seismic instrumentation provide the opportunity for improving the quality of the data we collect as well as making the acquisition of data more efficient. In the coming decade we anticipate enhancing the network configuration by installing seismic stations in regions of sparse station coverage and augmenting existing stations with horizontal seismometers. On-site digital recording in combination with digital telemetry will greatly increase the dynamic range of the recorded seismic signal. Coordinated development of dense, high-gain, short-period stations of the CALNET and sparse arrays of broad-band sensors operated by U.C. Berkeley, U.C. Santa Cruz, and Stanford will provide seismologists a far better data base for studying earthquakes than any institution could accomplish alone.

Likewise, improvements in computer technology will allow us to provide new services to the research community and the public. Real-time systems currently under development by the CALNET will be able to generate real-time warnings of strong ground motion within seconds of earthquake initiation that will initiate automated shut-down of hazardous facilities. Similarly, routine earthquake locations will be transmitted instantaneously to the public via radio pager systems, as is being done by the USGS and Caltech in southern California. The CALNET data for the period 1974 - 1983 that is now stored on hundreds of analog tapes will be automatically digitized, processed, and stored on the optical device at U.C. Berkeley. All of these network enhancements will require substantial commitment of human and capital resources, but, in return, will quickly supply earthquake information where needed and greatly advance our understanding of earthquakes.

ACCOMPLISHMENTS

There is no single standard by which to assess whether a seismic network is serving the needs of the research community or the public. Some might argue that if the ultimate goal of the network is to provide data that leads to earthquake prediction, then two decades of monitoring is too short a period of time to pass judgement, since the seismic cycle for significant earthquakes can be 5-10 times as long. For others the network has already proven its worth for the insights that it has provided on earth structure and tectonics. One measure of the network contribution can be found in the number and quality of its research publications. The individual scientist will be motivated to conduct research if the data are of sufficient quality and can advance our understanding of the earth, whereas the external scientific community regulates the publication process by reviewing the quality and relevance of all submitted research. This section describes these publications and provides an overview of the attached bibliography, which cites more than 350 publications based on CALNET data. Nearly 250 of the publications appear in refereed research journals and are written by CALNET as well as non-CALNET scientists. The remainder are internal Open File Reports[2] that document the network characteristics, computer programs, processing techniques, and earthquake catalogs.

Local Earthquake Network Operations

Since the CALNET was one of the first permanent seismic networks designed to continuously record and locate local earthquakes, it became, by necessity, a leader in the development of seismic instrumentation and methodology of earthquake analysis. Many of the early efforts were devoted to describing this instrumentation and establishing the fundamental principles governing analysis of local earthquakes (a comprehensive overview of these principles can be found in *Lee and Stewart* (1989)). Some of these achievements are the pioneering work on real-time earthquake location methods, computer programs for locating earthquakes and computing focal mechanisms, and advances in the CUSP data acquisition and processing software that is in use by the California Institute of Technology, University of Nevada at Reno, Hawaii Volcano Observatory, Parkfield Prediction experiment, and the Idaho National Engineering Laboratory.

- Network Instrumentation: *Eaton* (OFR-1975b, OFR-1976a, OFR-1976b, OFR-1976c), *Ellis and Lindh* (OFR-1976), *VanSchaack* (OFR-1975, OFR-1980).
- Network System Response: *Bakun and Dratler* (1976), *Dratler* (1980), *Eaton* (OFR-1975a, OFR-1975b, OFR-1977, OFR-1980, OFR-1984), *Eaton and VanSchaack* (OFR-1977), *Healy and O'Neill* (OFR-1977), *Stewart and O'Neill* (OFR-1980)
- Network Station History: *Houck et al.* (OFR-1975, OFR-1976), *Klein et al.* (OFR-1988).

[2] Designated as "OFR" in references. See latter part of Bibliography.

- Earthquake Magnitude Estimation: *Bakun* (1984a, 1984b), *Bakun and Joyner* (1984), *Bakun and Lindh* (1977), *Eaton* (1991), *Hirshorn et al.* (OFR-1987), *Lee et al.* (OFR-1972), *Michaelson* (1990).
- Earthquake Location Methods: *Eaton* (OFR-1969), *Engdahl and Lee* (1976), *Klein* (OFR-1978, OFR-1985, OFR-1989), *Lee and Lahr* (OFR-1975), *Pavlis and Booker* (1980, 1983).
- Focal Mechanism Determination: *Reasenberg and Oppenheimer* (OFR-1985).
- Real-Time Earthquake Location: *Allen* (1978, 1982), *Stewart* (1977).
- Real-Time Digital Seismogram Acquisition Systems: *Dollar* (1989), *Stewart* (1991).
- Earthquake Catalogs: *Bufe et al.* (OFR-1975), *Fluty and Marks* (OFR-1981), *Hall and Lester* (OFR-1979, OFR-1981), *Kirkman-Reynolds and Lester* (OFR-1986), *Lee et al.* (OFR-1972), *Lee et al.* (OFR-1972), *Lee et al.* (OFR-1972), *Lester and Meagher* (OFR-1978), *Lester et al.* (OFR-1976), *Lester et al.* (OFR-1976), *Mantis et al.* (OFR-1979), *Marks and Lester* (OFR-1980a, OFR-1980b), *Marks and Fluty* (OFR-1981), *McHugh and Lester* (OFR-1978, OFR-1979), *Murphy and Lester* (OFR-1981), *Nishioka* (OFR-1988), *Riley and Lester* (OFR-1981), *Walter and Weaver* (OFR-1985), *Wesson et al.* (OFR-1972), *Wesson et al.* (OFR-1972), *Wesson et al.* (OFR-1973), *Wesson et al.* (OFR-1974a, OFR-1974b), *Wesson et al.* (OFR-1972).

Seismotectonics and Properties Governing Faulting

The CALNET has been the source of numerous seismicity studies in central California since 1969 because of its catalog of earthquake locations and magnitudes. Its earthquake data provide high resolution images of geologic processes within the crust. These studies have contributed to our understanding of the current state of stress along the San Andreas fault system, the strength profile of the crust, variations in fault zone properties, aftershock mechanics, and the tectonics of this active plate margin. A complete review of the these findings is beyond the scope of this report (see, for example, *Hill et al.* (1990)). However, the following seismicity studies highlight both the regional scope and quality of science possible from data obtained by the CALNET.

- Seismicity: <u>Calaveras Fault</u> - *Bakun* (1980), *Bakun et al.* (1984), *Bakun et al.* (1986), *Beroza and Spudich* (1988), *Bouchon* (1982), *Bufe* (1976), *Cockerham and Eaton* (1984, 1987), *Eaton* (1987), *Eneva and Pavlis* (1988), *Michael* (1988), *Oppenheimer et al.* (1988), *Oppenheimer et al.* (1990), *Reasenberg and Ellsworth* (1982), *Thurber* (1983).

  <u>Coalinga</u> - *Eaton* (1990), *Eaton et al.* (1983), *Eberhart-Phillips* (1989a, 1989b), *Eberhart-Phillips and Reasenberg* (1990), *Fehler* (1989), *King and Stein* (1983), *Michelini and Bolt* (1986), *Reasenberg et al.* (1983), *Segall and Yerkes* (1990), *Stein* (1983), *Wentworth and Zoback* (1990), *Yerkes* (1990).

Coast Range - *Eaton and Rymer* (1990), *Dehlinger and Bolt* (1984), *LaForge and Lee* (1982), *Wong and Ely* (1983), *Wong et al.* (1988).

Coso Range - *Walter and Weaver* (1980), *Weaver and Hill* (1979).

The Geysers/Clear Lake - *Bufe et al.* (1981), *Denlinger and Bufe* (1982), *Eberhart-Phillips* (1988), *Eberhart-Phillips and Oppenheimer* (1984), *Oppenheimer* (1986).

Cascadia and subduction zone - *Cockerham* (1984), *Klein* (1979), *Smith* (1983), *Walter* (1986), *Walter et al.* (1984), *Weaver et al.* (1982), *Weaver et al.* (1990), *Wilson* (1989).

Long Valley-Mammoth Lakes-Chalfant Valley - *Cockerham and Corbett* (1987), *Hill et al.* (1985), *Hill et al.* (1990), *Savage and Cockerham* (1987), *Smith and Priestly* (1988).

San Andreas fault - Bear Valley/Hollister/San Juan Bautista - *Bakun and McLaren* (1984), *Bakun et al.* (1980), *Ellsworth* (1975), *Schulz et al.* (1983), *Simpson et al.* (1988), *Spieth* (1981), *Wesson* (1987).

- Parkfield: *Bakun and Lindh* (1985a, 1985b), *Lindh and Boore* (1981), *Michael and Eberhart-Phillips (1991)*, *Harris and Segall* (1987), *King and Nábelek* (1985), *Lienkaemper and Prescott* (1989), *Nishioka and Michael* (1990), *Poley et al.* (1987), *Segall and Harris* (1987), *Simpson et al.* (1988), *Stuart et al.* (1985).

- Loma Prieta: *Beroza* (1991), *Dietz and Ellsworth* (1990), *Eberhart-Phillips et al.* (1990), *King et al.* (1990), *Langbein* (1990), *Lees* (1990), *Marshall et al.* (1991), *Michael et al.* (1990), *Olson* (1986, 1990), *Oppenheimer* (1990), *Schwartz et al.* (1990), *Seeber and Armbruster* (1990), *Simila et al.* (1990).

- Fort Ross: *Stickney* (1979)

East/North San Francisco Bay Region - *Budding et al.* (1991), *Ellsworth et al.* (1982), *Followill and Mills* (1982), *Lee et al.* (1971), *Lienkaemper et al.* (1991), *Scheimer et al.* (1982), *Taylor and Scheimer* (1982), *Weaver and Hill* (1979), *Wong* (1990, 1991), *Wong and Biggar* (1989)

Sierra Nevada Foothills - *Lahr et al.* (1976), *Lester et al.* (1975), *Marks and Lindh* (1978), *Wong and Savage* (1983)

- State of Stress: *Michael* (1985, 1987), *Michael et al.* (1990), *Oppenheimer* (1986, 1990), *Oppenheimer et al.* (1988), *Zoback et al.* (1987)
- Seismogenic Region Properties: *Dieterich* (1981), *Hill* (1992), *Meissner and Strehlau* (1982), *Sibson* (1982, 1984), *Stierman et al.* (1979), *Tse et al.* (1985), *Tse and Rice* (1986)

- Earthquake Source Properties: *Bakun et al.* (1976), *Bakun et al.* (1978), *Geller and Mueller* (1980), *O'Neill* (1984), *O'Neill and Healy* (1973)

Earthquake Prediction Studies

The CALNET has generated a unique data set for the purpose of assessing whether microearthquakes exhibit temporally and spatially dependent behavior that could lead to the prediction of earthquakes. A necessary condition for investigating such behavior is the existence of a continuous record of seismicity spanning the time of main shock occurrence. Not only is this condition met by the twenty-year period of monitoring by the CALNET, but twelve M>5.5 earthquakes have occurred within the network during its existence. Data recorded by the CALNET has revealed aspects of earthquake behavior and crustal properties that may contribute to a better understanding of the seismic cycle and where future main shocks may occur. The following studies describe some of the innovative methods and results of earthquake prediction studies based on CALNET data.

- Spatial patterns of seismicity: *Bakun* (1980), *Bakun et al.* (1980), *Bakun et al.* (1986), *Bakun and Lindh* (1985a), *Budding et al.* (1991), *Eneva and Pavlis*, (1988), *Harris and Segall* (1987), *Hartzell and Heaton* (1986), *King et al.* (1990), *King and Nábelek* (1985), *Liu and Helmberger* (1983), *Mendoza and Hartzell* (1988), *Michael (1989), Oppenheimer* (1991), *Oppenheimer et al.* (1990), *Seeber and Armbruster* (1990), *Wesson and Nicholson* (1988).
- Spatial patterns in velocity: *Michael and Eberhart-Phillips* (1991).
- Temporal changes in seismicity: *Bufe et al.* (1974), *Bufe et al.* (1977), *Ellsworth et al.* (1981), *Mavko* (1982), *Mavko et al.* (1985), *Poley et al.* (1987), *Reasenberg and Matthews* (1988), *Seeber and Armbruster* (1990), *Wesson and Nicholson* (1988), *Wyss* (1990, 1991), *Wyss et al.* (1990), *Wyss and Burford* (1987), *Wyss and Habermann* (1988).
- Temporal changes in crustal properties: *Boore et al.* (1975), *Fréchet* (1985), *Frémont* (1984), *Frémont and Poupinet* (1987), *Got et al.* (1990), *Lee et al.* (1986), *Lindh et al.* (1978a, 1978b), *Michael* (1985, 1987), *Nevskiy et al.* (OFR-1981), *Peng et al.* (1987), *Poupinet et al.* (1984), *Robinson et al.* (1974), *Robinson and Iyer* (1976), *Steppe et al.* (1977).
- Earthquake probabilities: *Agnew and Jones* (1991), *Reasenberg and Jones* (1989), *Reasenberg and Matthews* (1990).
- Statistical Properties of Earthquakes: *Eneva and Pavlis*, (1988), *Habermann* (1986, 1987), *Habermann and Craig* (1988), *Kagan* (1981a, 1981b), *Kagan and Jackson* (1991), *Kagan and Knopoff* (1978, 1980, 1981, 1987), *Pfluke and Steppe* (1973), *Reasenberg* (1985).

Volcano Studies

Several volcanic regions that have erupted during the Quaternary or Pliocene are located within the CALNET. In addition to the real-time monitoring functions performed by the CALNET that were described in the previous section, the seismic data recorded by the network has been studied to advance our understanding of volcanic systems. Seismic data has been used to detect and delineate the boundaries of magmatic intrusions, estimate the physical properties of the magma bodies, and estimate the state of stress of the following regions:

- Coso Range: *Reasenberg et al.* (1980), *Walter and Weaver* (1980).
- Clear Lake: *Eberhart-Phillips* (1988), *Iyer et al.* (1978, 1979, 1981), *Oppenheimer* (1986), *Oppenheimer and Herkenhoff* (1981), *Shearer and Oppenheimer* (1982).
- Cascadia: *Klein* (1979), *Walter et al.* (1984), *Weaver et al.* (1982).
- Long Valley-Mammoth Lakes: *Cockerham and Pitt* (1984-O.F. Rept.), *Dawson et al.* (1990), *Hill et al.* (1985, 1990), *Kissling et al.* (1984-O.F. Rept.), *Rundle et al.* (1985), *Rundle and Hill* (1988), *Sanders* (1984), *Savage and Cockerham* (1984, 1987), *Savage et al.* (1987).

Lithospheric structure and Attenuation

While geologists generally restrict their studies to the surface of the Pacific-North American plate margin, seismologists can analyze earthquake data to understand the third dimension of this boundary. Earthquake data from the CALNET is particularly well-suited for revealing the structure of the lithosphere because of the abundance of earthquake travel-time data, the large number and close spacing of stations, and the broad regional coverage of the network. In addition, earthquake sources have advantages over active sources because they are distributed both throughout the crust and globally. Moreover, earthquakes are efficient generators of shear waves in contrast to explosive sources. The following studies span a range of topics on earth structure, including travel-time inversions for 1-D structure, refraction/reflection profiling using local earthquakes, tomography from teleseismic and local earthquake travel-times, time-term analyses, attenuation, and detection of mantle velocity discontinuities through slant-stacking seismograms of teleseismic waves.

- Local Earthquake Tomography: *Aki and Lee* (1976), *Eberhart-Phillips* (1986, 1989a, 1989b, 1992), *Eberhart-Phillips et al.* (1990), *Kissling* (1987, 1988), *Lees* (1990), *Michael* (1988), *Michael and Eberhart-Phillips* (1991), *Taylor and Scheimer* (1982), *Thurber* (1981, 1983).
- Teleseismic Studies: *Benz and Zandt* (1992), *Benz et al.* (1991), *Dawson et al.* (1990), *Iyer et al.* (1978, 1979, 1981), *Mavko and Thompson* (1983), *Oppenheimer and Herkenhoff* (1981), *Powell* (1976), *Reasenberg et al.* (1980), *Vidale and Benz* (1992), *Weaver et al.* (1982), *Zandt* (1978, 1981).

- Misc. Crustal Structure: *Blümling et al.* (1985), *Blümling and Prodehl* (1983), *Cockerham and Eaton* (1984), *Crosson* (1976), *Eaton* (1990), *Eberhart-Phillips and Oppenheimer* (1984), *Ellsworth and Marks* (OFR-1980), *Healy and Peake* (1975), Iyer *et al.* (1978, 1979, *Kind* (1972), *Macgregor-Scott and Walter* (1988), *Mayer-Rosa* (1973), *Oppenheimer and Eaton* (1984), *Pavlis and Booker* (1983), *Peake and Healy* (1977), *Shearer and Oppenheimer* (1982), *Steppe and Crosson* (1978), *Wald and Heaton* (1991), *Walter* (1990), *Weaver et al.* (1982), *Wesson et al.* (1973).
- Attenuation: *Bakun and Bufe* (1975), *Lee et al.* (1986), *Reiter and Monfort* (1977).

Real-time earthquake warning

Telemetered seismic signals propagate at nearly the speed of light, whereas seismic waves propagate through the earth at much slower velocities. Therefore, it is possible for a computer monitoring a telemetered network of strong-motion sensors to issue a real-time warning that strong ground motion from an earthquake will be arriving at a particular site within a few seconds (*e.g., Heaton,* Science, v. 228, pp. 987-990, 1985). These warnings can be used to trigger automatic shut-down responses for critical public and commercial facilities such as nuclear power plants, freeway overpasses, computer systems, elevators, and numerous industrial processes. The CALNET was the first to successfully implement such a system, which warned California Department of Transportation employees who were working on the collapsed Cypress freeway structure of impending ground motion from Loma Prieta aftershocks.

Public outreach

In addition to the normal outreach functions described in the previous section, the staff of the CALNET has prepared videos that explain in simple terms about earthquakes and the public issues surrounding hazard mitigation (*Klein and Walter*, OFR-1989). Earthquake data recorded by the CALNET for the period 1972-1989 was combined with Landsat imagery to make the color poster "San Francisco Bay Area Earthquakes". The staff also assisted in the preparation of the Sunday newspaper insert "The Next Big Earthquake" that was distributed September 9, 1990 to 2.4 million people in the San Francisco Bay area.

SUMMARY

The Northern California Seismic Network has continually evolved over the last 20 years and today monitors the seismicity of three fourths of the state of California. It serves several functions, including providing data for the research community, real-time hazard assessment, real-time earthquake monitoring, volcano monitoring, and public education. The CALNET has produced an earthquake data set that has been used in nearly 350 publications to study a wide range of topics. These studies have significantly advanced our understanding of the tectonics of the San Andreas system, crust and upper mantle structure, volcanic processes, and the mechanics of faulting. The continuity and quality of this data set have permitted scientists to test theories on earthquake prediction through an examination of the statistics of the earthquake catalog and changes in crustal properties.

In the next decade we look forward to improvements in the accessibility of data, methods for earthquake analysis, computing environments, and quality and quantity of instrumentation. These advances will allow us to test new theories and expand into new research topics. Significant earthquakes like Loma Prieta will undoubtedly occur again within the network, yielding new information on earthquakes, and the data recorded by the CALNET from the preceding decades will be a critical component of the analyses. In this sense, the CALNET is just beginning to contribute to our understanding of the earth.

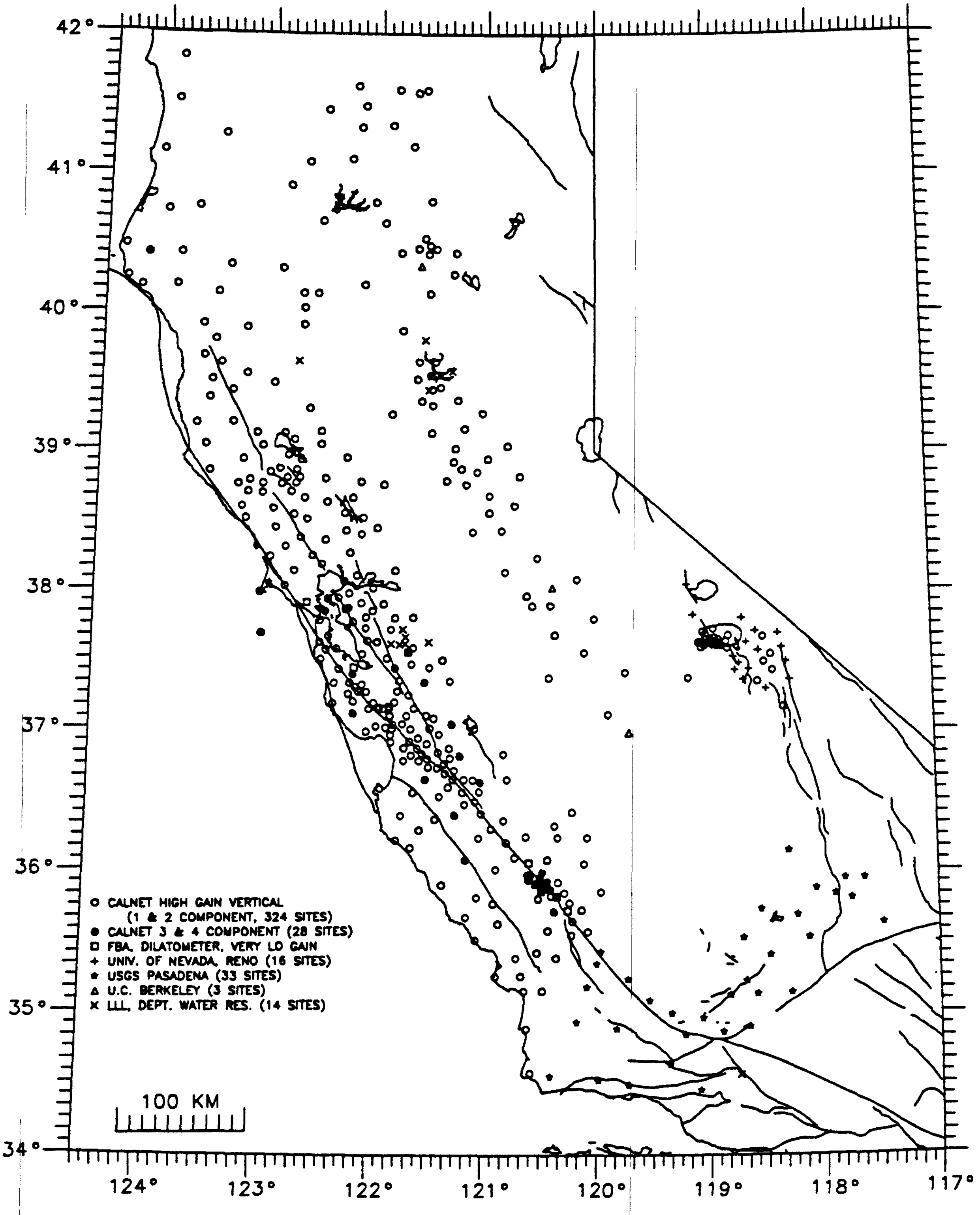


Figure 1. Location of seismic stations recorded by the Northern California Seismic Network as of May, 1991.

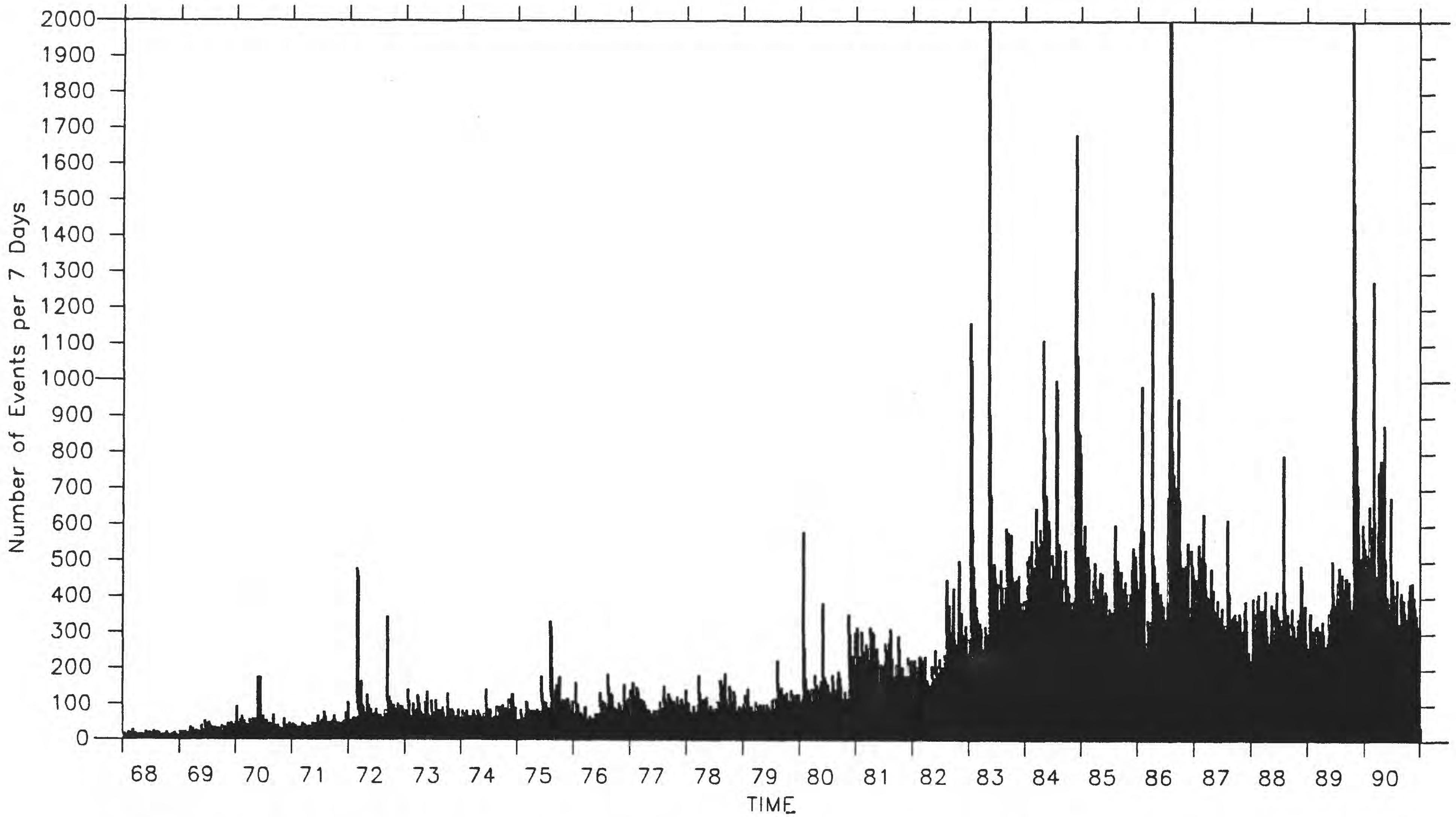


Figure 2. Histogram of the number of events per week recorded by the CALNET versus time. Large spikes indicate the times of major aftershock sequences. Approximately 280,000 events have been located by the CALNET during the time interval 1968-1990, and about 25,000 events are added each year.

a)

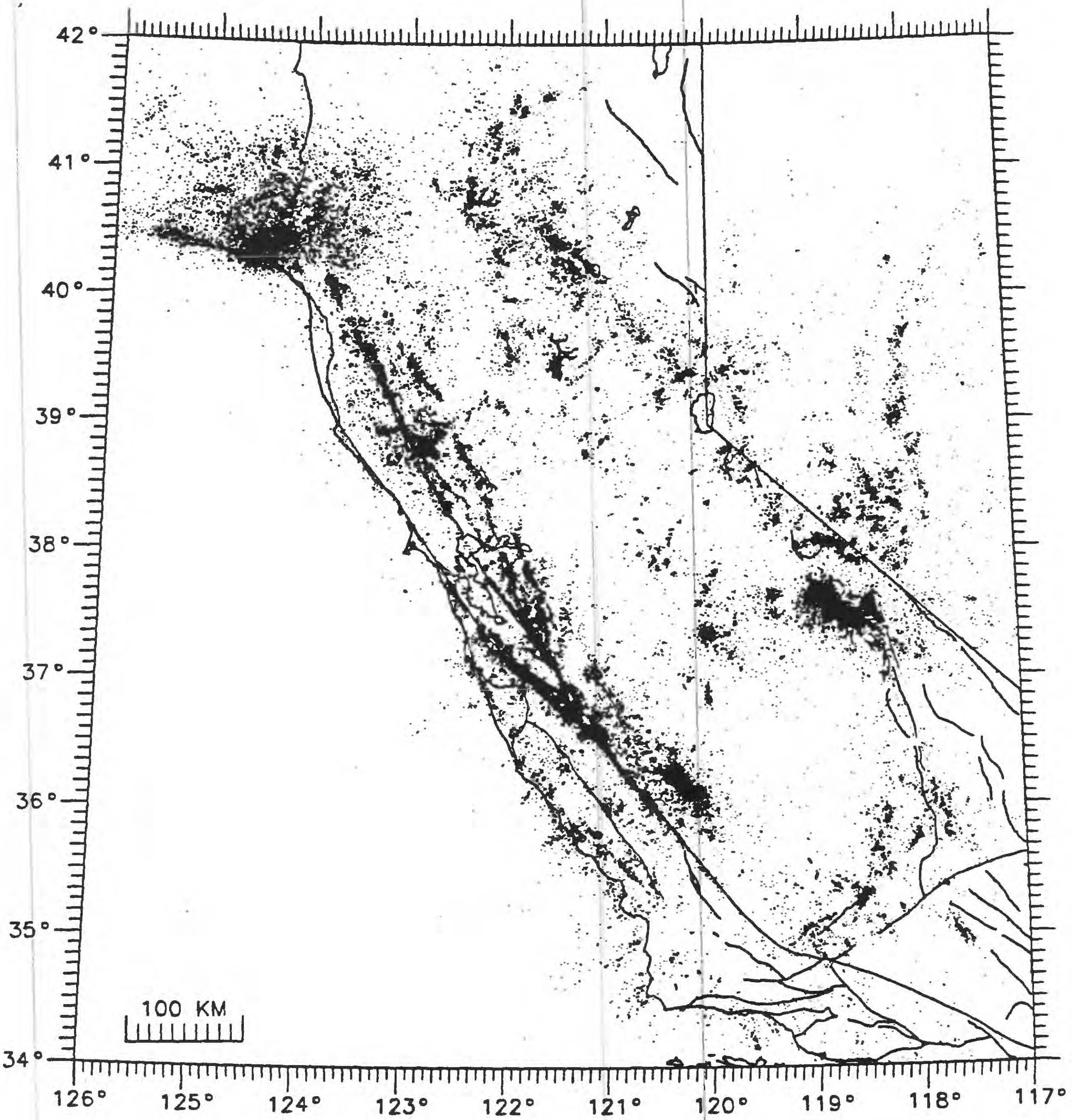
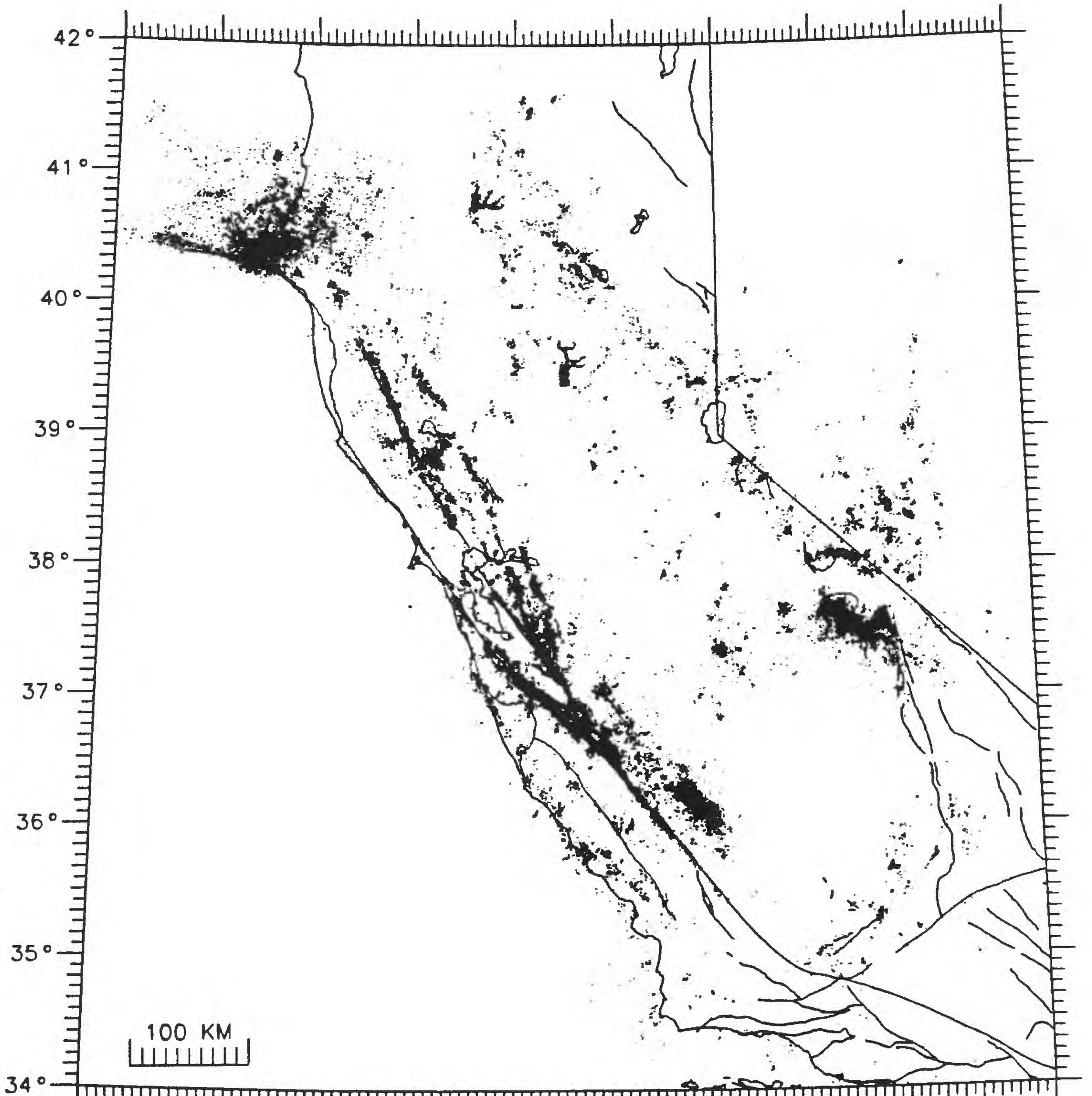


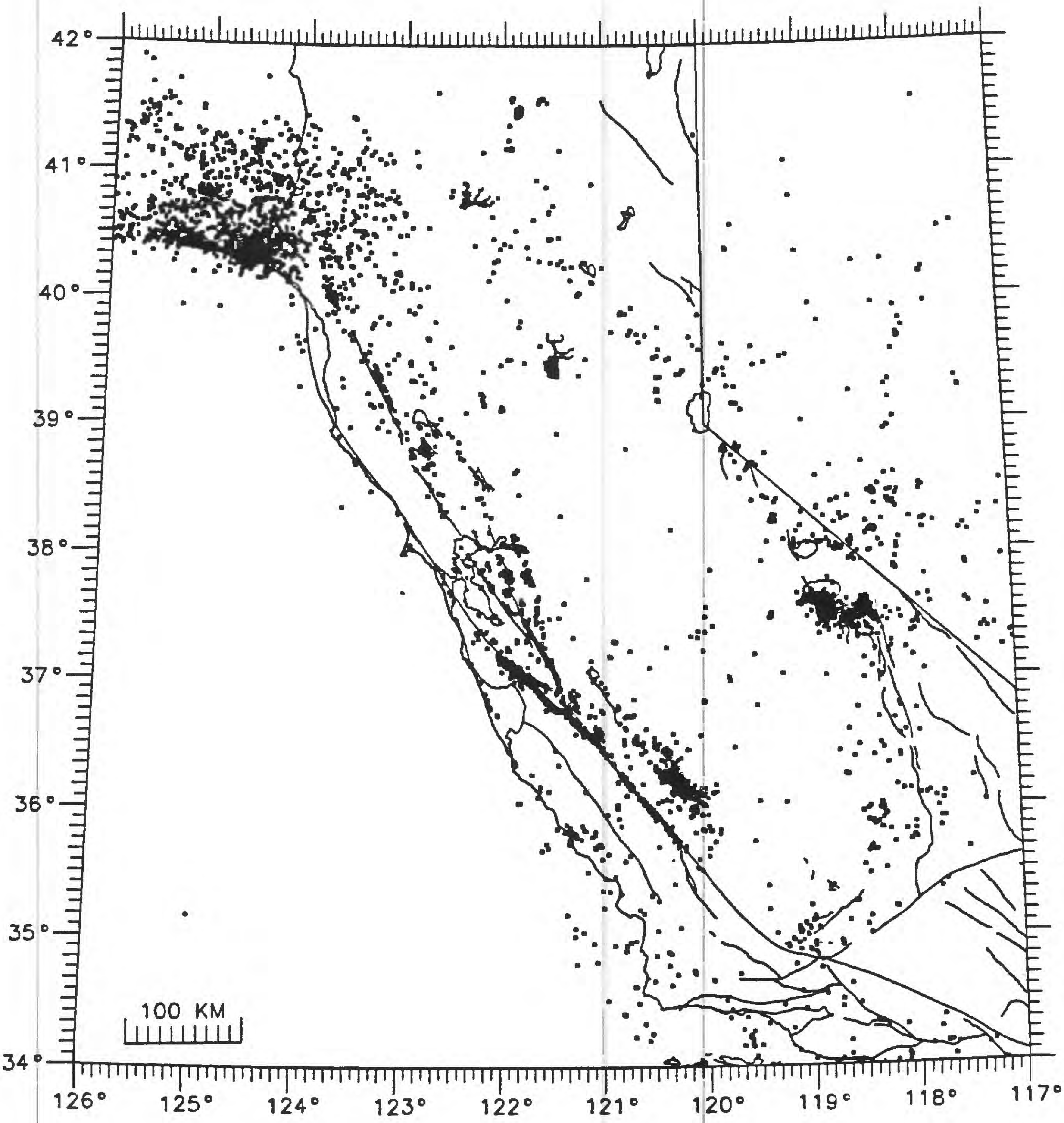
Figure 3. Locations of earthquakes from data recorded by the CALNET with supplementation from the UNR, Tera Corporation, Pacific Gas and Electric, and Woodward-Clyde Consultants networks. Events with the poorest locations (*RMS* residual > 0.30 sec) are excluded. Events known to be as quarry blasts are excluded, but not all quarry blasts have been identified. a) all magnitudes, b) all magnitudes, but the number of stations used to locate earthquake is greater than 6, and c) $M \geq 3$. Magnitudes of many earthquakes in the Cape Mendocino area in this plot are overestimated by about 0.5 unit due to differences in coda duration estimation by operators of the Tera Corporation network and the number of these events plotted in c) is too high.

b)



42°
41°
40°
39°
38°
37°
36°
35°
34°
100 KM
126°
125°
124°
123°
122°
121°
120°
119°
118°
117°

c)


42°
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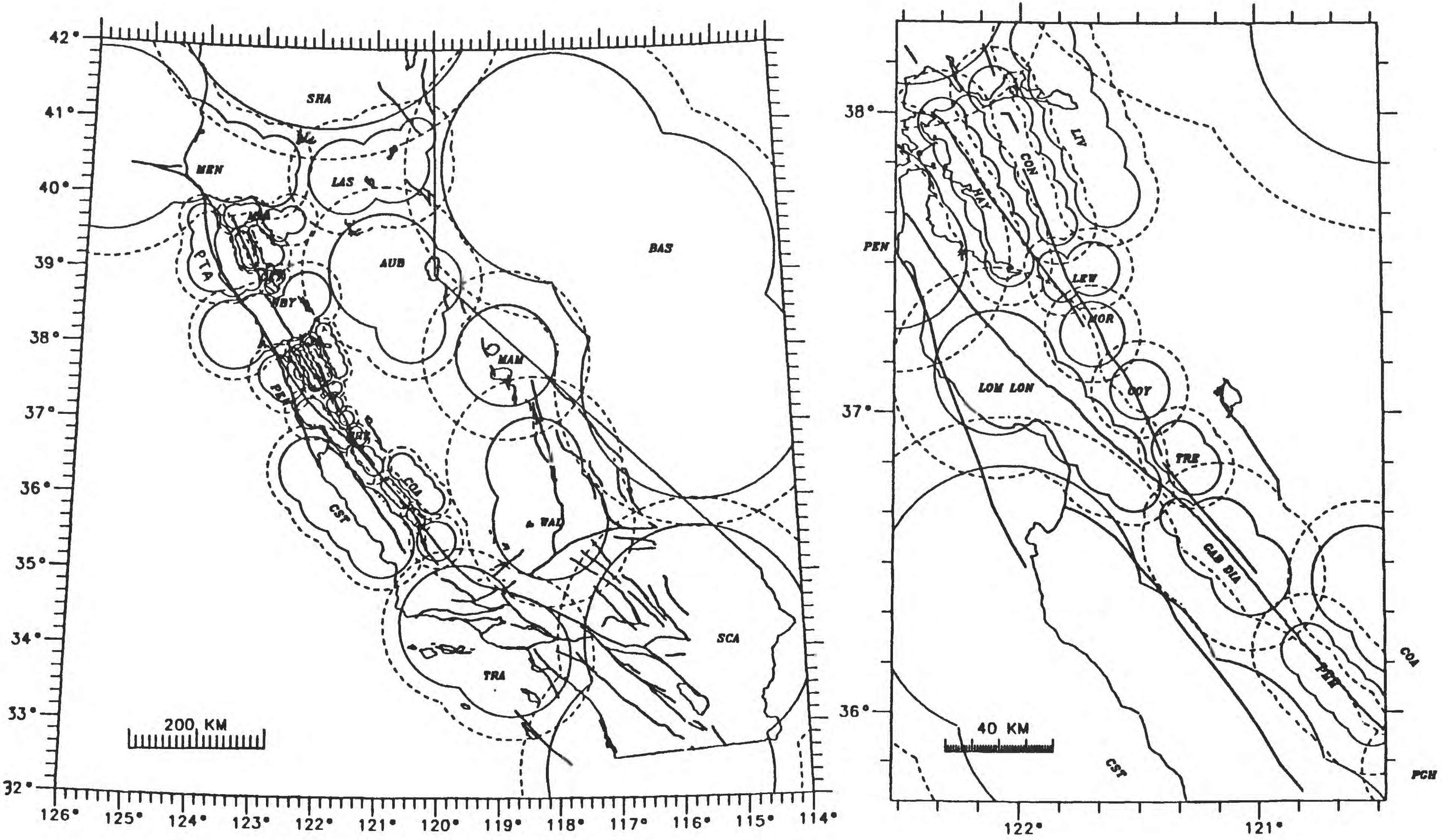

Figure 4. Boundaries of local velocity regions used by HYPOINVERSE to locate CALNET earthquakes. Earthquakes occurring between solid and dashed lines have locations based on a combination of up to 3 models. A default Coast Range model is used in areas without a local model, such as the Great Valley and the Pacific Ocean.

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