U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Southern California Seismographic Network[1]: Report to the U.S. Geological Survey, August 21, 1990

By

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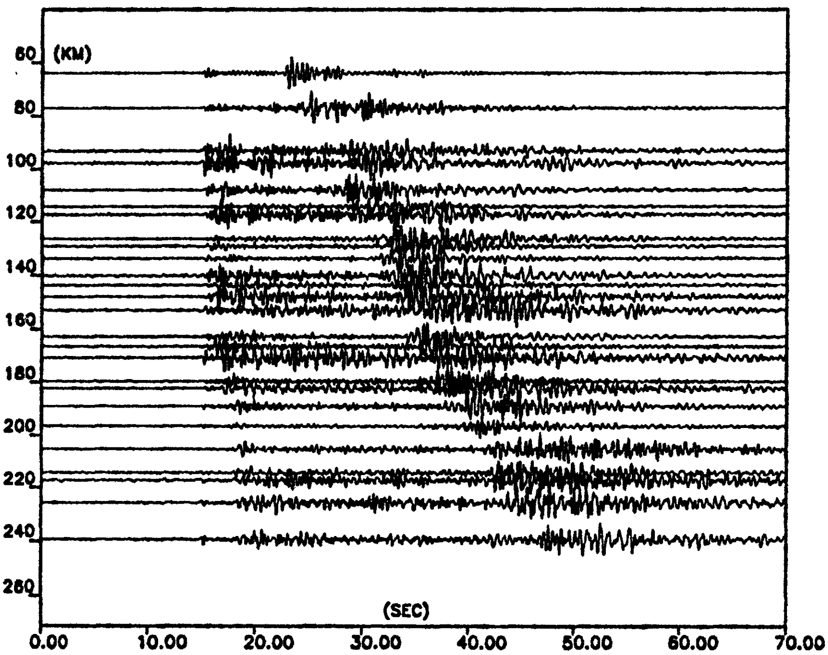

Open File Report 91-38

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[1] A cooperative project of the Seismological Laboratory, California Institute of Technology and the U. S. Geological Survey, Pasadena, California

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Introduction

On August 21, 1990, the U. S. Geological Survey held a meeting to review the status of regional seismic networks in the United States. The purpose of the meeting was to provide information to the U.S.G.S. to assist them in setting priorities for future funding of seismic networks in a time of increasingly tight budgets. Each of the networks was therefore asked to prepare a report describing their goals and accomplishments. Three specific questions were raised: how the objectives of the network have been met, the potential for future productivity and opportunities for additional funding.

This document is the report prepared by the Southern California Seismic Network, a cooperative project of the California Institute of Technology and the Pasadena office of the U. S. Geological Survey. The division of responsibilities between these two institutions is flexible and changes from time to time. In general, Caltech has had responsibility for producing the earthquake catalog and archiving phase data and seismograms. The USGS has maintained the bulk of the remote stations and provided hardware and software support for real-time digital recording of data. Both institutions are actively doing research with the data and share the responsibility for information transfer to the general public, media and government. In this report we give an overview of the network operations. We have intentionally not attempted to separate what is done by each institution because the combined contribution from both institutions is what makes this network a successful operation.

The objectives of the network are continuously being met. The network was installed to gather data from local, regional and teleseismic earthquakes and to use these data for earthquake hazards reduction as well as for basic scientific research. The earthquake hazards reduction effort has become more important as moderate-sized earthquakes continue to occur within densely populated areas in southern California. For instance, rapid determination of epicenter and magnitude is provided to emergency response agencies and to the media to aid in recovery efforts. The average rate of 10 publications per year over the last 20 years based on the network data illustrates the strength of the ongoing research activities that use the network data.

Continued efforts to improve data quality and accessibility have created the arguably best regional earthquake data base in the world. The new TERRAscope stations and ongoing upgrading of the quality of the waveforms recorded by the short-period network and the addition of low-gain seismometers and accelerometers provide numerous new avenues of research. Most important of these is analysis of on-scale waveforms to determine source, path and site effects. The proposed Southern California Earthquake Center will greatly increase the use of the data for scientific research. The availability of 60 years of catalog and 30 years of phase data on both UNIX and VMS computers and on-line over INTERNET/NSFNET greatly improves the access to the data.

The TERRAscope project is a new Caltech initiative aimed at raising funds from private sources to upgrade the seismograph instrumentation in southern California. The Whittier Foundation of South Pasadena has already donated funds to pay for 4 permanent broad-band, high dynamic range stations and 2 portable broad-band PASSCAL type stations. The data from the TERRAscope stations are available: 1) through direct dial-up to the stations; 2) from an on-line data archive at Caltech; 3) from the IRIS data center in Texas. In addition, the US Army Corps of Engineers has funded the USGS to install a new broad band station in San Bernardino, near the San Andreas fault.

The Southern California Seismographic Network has received the same dollar amount in funding over the last 10 years. Even though the funding in real dollars has decreased when inflation is taken into account, the network has continued to operate. Significant financial savings have already been realized by an efficient new data processing system (CUSP) reducing the time consuming procedures of the 1970s analog data acquisition systems. However, because of the limited funding, significant data gaps exist in the data processing, real-time information about location and magnitude is limited, and computers and field instrumentation are aging and obsolete. Presently a capital equipment upgrade over two years and a funding increase of 20-30% is needed to significantly improve the infrastructure and to maintain high data quality.

Objectives of Network Operations

The Southern California Seismographic Network was first established in the 1920's by the Seismological Laboratory, then part of the Carnegie Institute. H. O. Wood argued for a network to locate small earthquakes in the hope that knowing the locations of the small earthquakes would allow scientists to predict the locations of the great earthquakes to come [*Goodstein*, 1984]. Of course, we have found that great earthquakes do not in general occur at the locations of the small earthquakes, but other uses were found for the data from the network, and the objectives of the network have evolved as the science of seismology has developed and the population in southern California has grown. The present objectives fall into three categories: earthquake monitoring, earthquake hazard assessment and seismological research.

Earthquake Monitoring. The area monitored by the southern California seismic network includes two of the ten largest cities in the United States (Los Angeles and San Diego) and almost 20 million inhabitants. More than one hundred earthquakes (not including aftershocks) are felt each year and an average of 1.5 events per year are potentially damaging (magnitude greater than 5.0). The need for information about these earthquakes is great. Immediately after a moderate or large earthquake, information about the size, location and damage from the event is needed to coordinate rescue operations, guide inspectors in the search for damage, and to satisfy public curiosity. The record of earthquake occurrence in California is important to insurers, geotechnical engineers, and city planners (see distribution list in Appendix C). The Southern California Seismographic Network has maintained and published a catalog of earthquakes above magnitude 3.0 since 1932 and above magnitude 2.0 since 1980 with consistent magnitudes over the whole time.

Hazard Assessment. Although reliable prediction of the time, place and magnitude of impending earthquakes is not yet possible, scientists can recognize times of increased hazard of damaging earthquakes, for instance after a potential foreshock or during an aftershock sequence. Recent advances have made it possible in some situations to estimate the probability that an event will be followed by a larger earthquake [e.g., *Jones*, 1985; *Agnew and Jones*, 1990] and the probabilities of damaging aftershocks [*Reasenberg and Jones*, 1989]. One of the objectives of the Southern California Seismographic Network is to provide the data necessary to make these evaluations. The earthquake data recorded in southern California are processed in near real time, and if appropriate, probabilities of future earthquakes are calculated. These probabilities and other requested advise are provided to the State of California and through the Governor's Office of Emergency Services (OES) to the public.

Seismological Research. The third objective of the Southern California Seismographic Network is to provide data for research in seismology, earthquake physics and prediction, and tectonics. Southern California is the seismically most active region in the contiguous United States and provides a unique seismotectonic environment of moderate convergence along a transform plate boundary. The large numbers of earthquakes and the long history of the catalog make this data set an important resource for studies in seismology and earthquake physics. The earthquake data also can provide important constraints in the analysis of the geology of southern California.

We have begun and expect to continue the process of upgrading the network to meet the demands of modern seismology. With the new techniques available for analyzing the waveforms of local earthquakes, the quality, bandwidth and dynamic range of the seismic signals have become much more important. By the end of the year we expect to have six digital, broadband, high dynamic range seismic stations with Streckeisen seismometers installed. We intend to install more such instruments and to improve the quality of the existing short-period network. The on-scale, calibrated waveforms needed for research also could form the basis of an early warning or SCAN (Seismic Computerized Alert Network) system. Such a system would automatically analyze incoming seismic signals to determine within a few seconds if a large earthquake was starting and if so, the epicenter and probable magnitude. We expect the network to evolve and in the future to provide an early warning of large earthquakes to the people of southern California.

Technical Configuration

The original seven station Caltech network was installed in the late 1920's. This network was expanded following the 1952 (M_S=7.7) Kern County and the 1971 M_W=6.6 San Fernando earthquakes. Since 1978 the number of stations has remained approximately the same, and the emphasis has been on producing a consistent catalog, high quality phase data, and calibrating the instrumentation to improve the quality of the waveforms.

Remote Sites

At present the Southern California Seismographic Network records 289 channels of data from 220 sites (see Table 1). Most of the sites consist of a short-period (1 sec) vertical seismometer running at the highest gain permitted by the local noise levels. The station spacing is about 15 to 30 km (Figure 1) over an area of roughly 150,000 km^2. The data from some of the stations is augmented by other sensors. Ten three-component sites include an additional two horizontal seismometers. Ten sites have an additional vertical seismometer running at a lower magnification (typically 1/16 the magnification of the high-gain component). Eight sites have three-component Force Balance Accelerometers (FBA). Figure 2 shows the distribution of the sites that have these additional data channels. The analog data signals are amplified and modulated by Voltage Controlled Oscillators (VCO) at the station and then sent by various combinations of

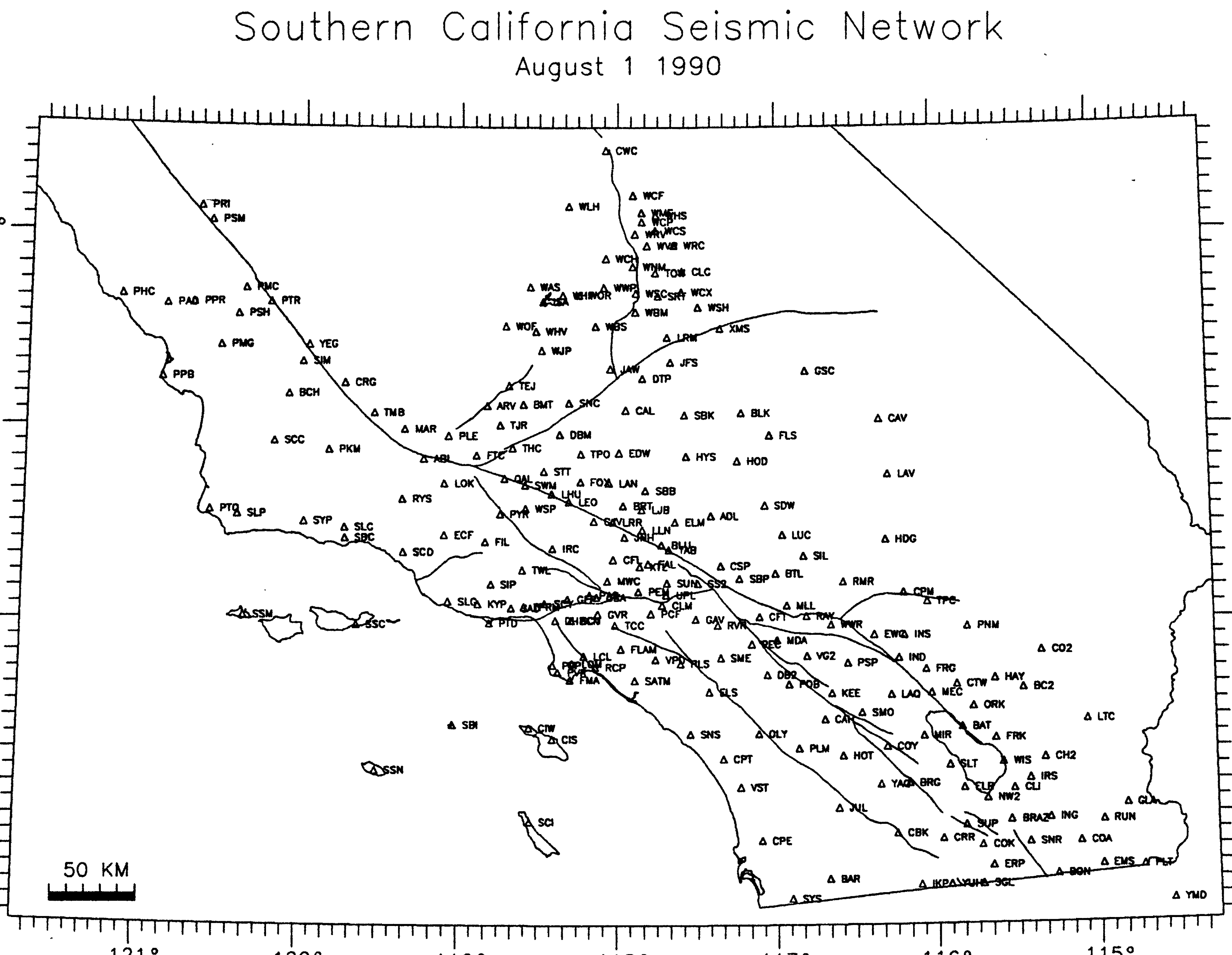

Figure 1. Southern California Seismographic Network - telemetered stations.

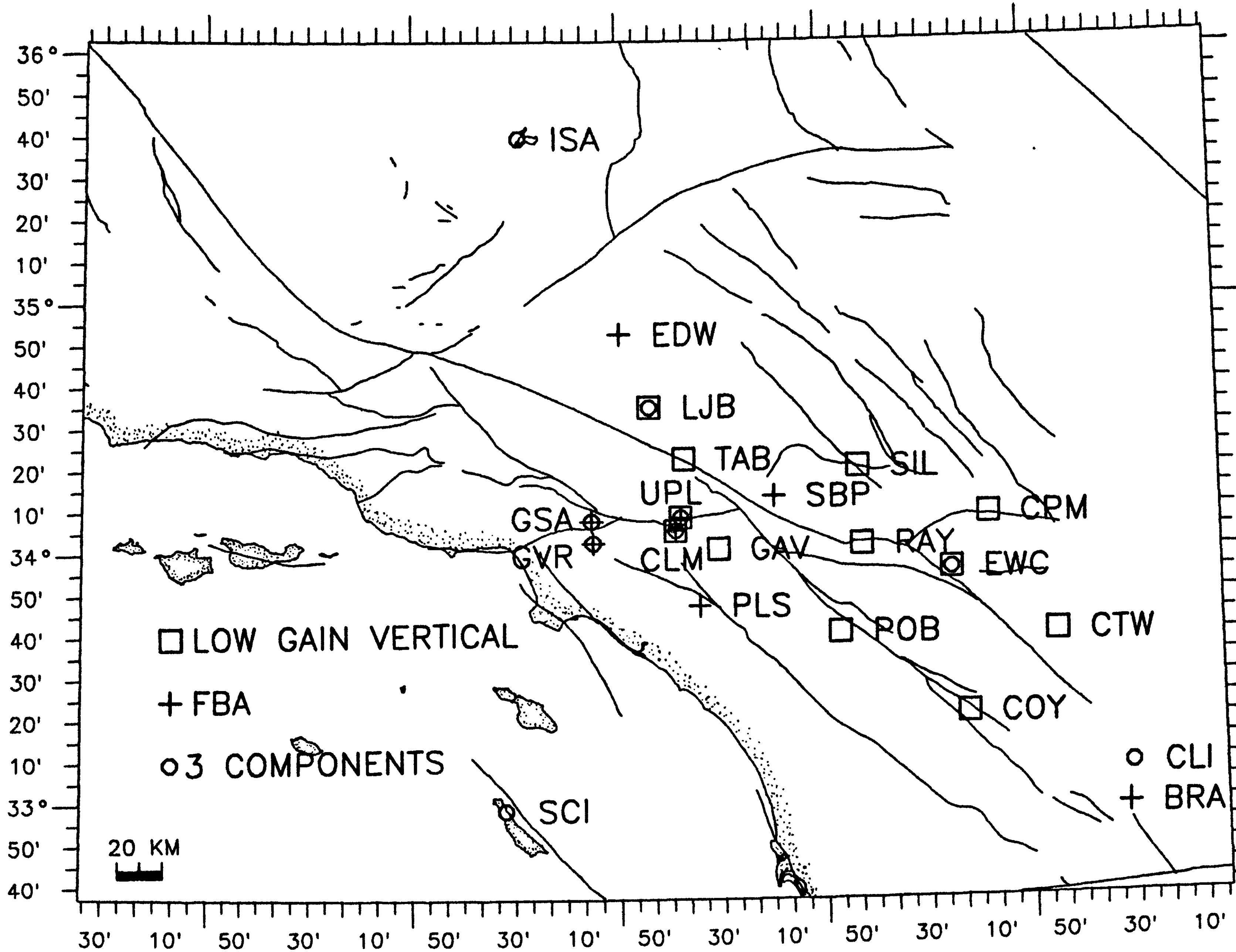

Figure 2. Map showing location of low-gain (triangles) and FBA (squares) sites in the Southern California Seismic Network. All FBA sites also have a low-gain vertical component. GSA has high and low-gain FBA components.

FM telemetry, phone lines and microwave links to the central recording site at Caltech.

Over the last five years we have improved the quality of the waveforms recorded by the short-period instruments. Calibration systems have been added to all stations and routine recording of calibrations signals instituted. Signal quality has been analyzed and the amplification has been decreased at more than 50 stations to improve dynamic range. We have searched for electronic noise and eliminated it whenever possible through repairing and replacing VCO's and discriminators and filtering out high frequency noise in the central recording facility. The average dynamic range of the high gain stations has improved from about 30 dB to 40 dB.

Current information about the configuration of each network station (sensor type, amplifier type, gain settings, etc.) is documented in an easily accessible PC database, which is updated within a few days of any modifications. The database has proved useful to technicians and scientists who wish to obtain detailed instrument information, for example, searching for all sites which have a particular type of electronic amplifier, or tracing the history of gain settings at a particular station. These database files can also be used in a computer program which removes the instrument response from the network waveform data to produce (band-limited) ground displacement or velocity seismograms (Figure 3).

In addition to the remote telemetered sites, Caltech operates 7 stations with on site photographic recording. Caltech is also responsible for field maintenance of 24 of the 220 remote telemetry stations, while the USGS Office maintains 159 remote sites. Fourteen channels of data are received from USC, 18 channels from the USGS in Menlo Park and 8 channels from Department of Water and Power (Table 1).

TABLE 1. Stations and channels digitally recorded by the SCSN

Agency Maintaining Stations	Number of Stations	Number of Components
USGS, Pasadena	159	219
Caltech*	24	30
USGS, Menlo Park	15	18
USC	14	14
DWR	8	8
Total:	220	289

*Caltech also maintains 7 remote sites with photographic recording of Wood-Anderson and other old instruments.

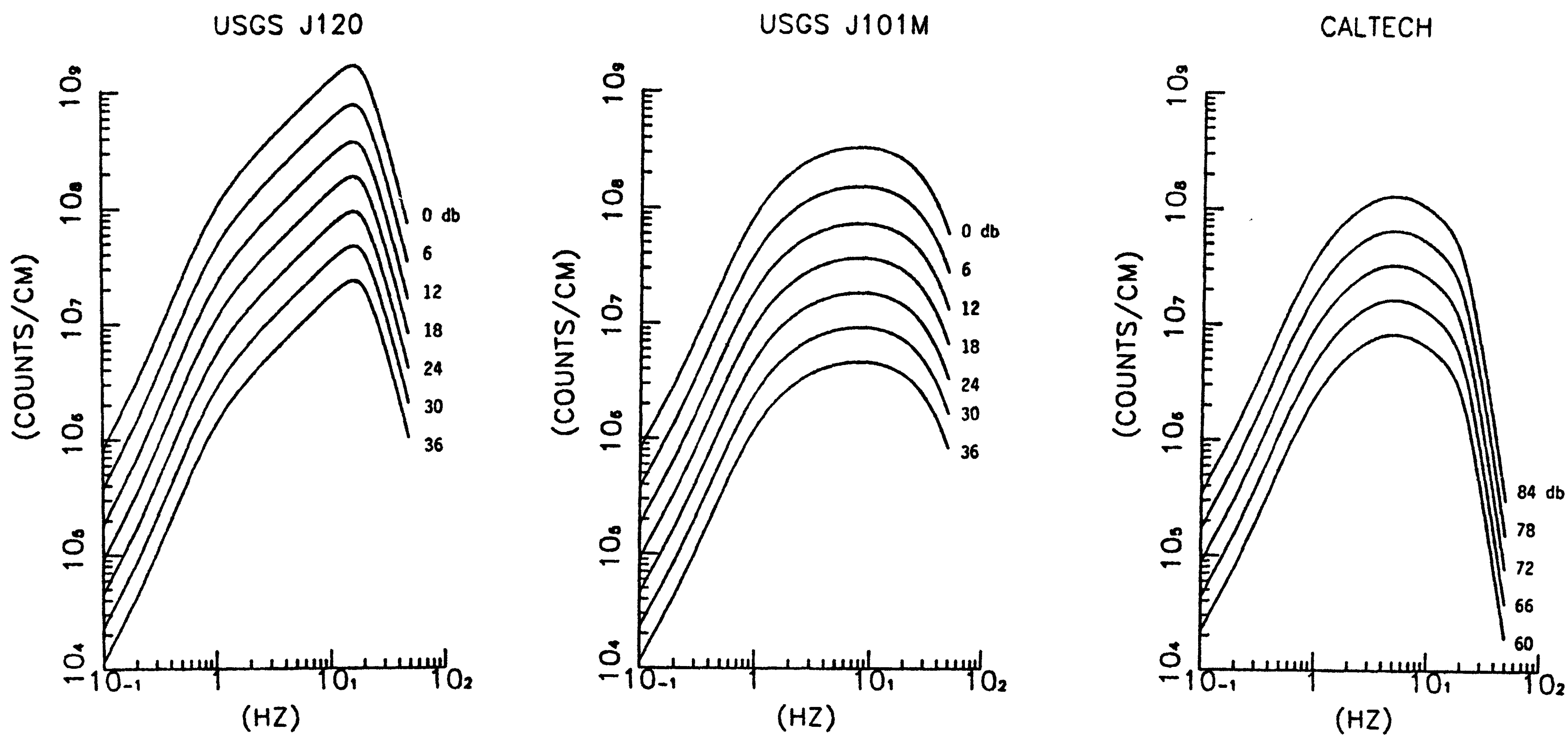

Figure 3. Instrument responses for discriminator types USGS J120, USGS J101M, and Caltech with a variety of attenuation settings.

Central Recording

Data channels arriving at the central recording site at Caltech are demodulated back to analog signals, passed through anti-alias filters at 20 Hz and then converted to 12 bit digital data (±2048 counts) at 100 samples per second by a Tustin digitizer. A DEC MicroVax 3200 computer is used for event detecting and begins recording data when the triggering algorithm signals an earthquake. The waveform data is stored on a 670 megabyte hard disk and periodically down-loaded to a VAX11/750 computer for processing (Figure 4).

A backup recording system consisting of a similar setup but with a completely separate digitizer and PDP11/34 computer is always in operation, parallel with the primary recording system. Further backup is provided by continuous recording of almost half of the channels onto FM tape.

TERRAscope

The California Institute of Technology, in cooperation with the USC, USGS and IRIS, has been operating a very-broad-band seismograph system at the Kresge Observatory in Pasadena. This system has proved extremely useful to study waveforms and source spectra of regional events. In 1988 with the support of the L. K. Whittier Foundation we initiated the TERRAscope project to install about a dozen very broad band seismic stations in southern California. By the end of 1990 we expect to have four stations, in addition to Pasadena, recording in southern California. These four sites will be Goldstone, Santa Barbara, Pinon Flats and Lake Isabella. Also the U.S. Geological Survey is planning to have a very broad band station near San Bernardino in 1990. The combination of the traditional high-density short-period array and the TERRAscope will produce exciting new results toward a better understanding of earthquake mechanics and tectonics in southern California.

Real-Time Seismology-Early Warning System

A future goal of the network operation is developing a Seismic Computerized Alert Network (SCAN). SCAN is intended to give critical facilities early warning (10 - 100 sec) of strong ground shaking from a large earthquake (Heaton, 1985). An array of high dynamic range sensors telemetered to a central processing site could quickly give estimates of an earthquake's location, size and some reliability criterion. This information

Southern California Seismographic Network: Real-Time Data Acquisition System

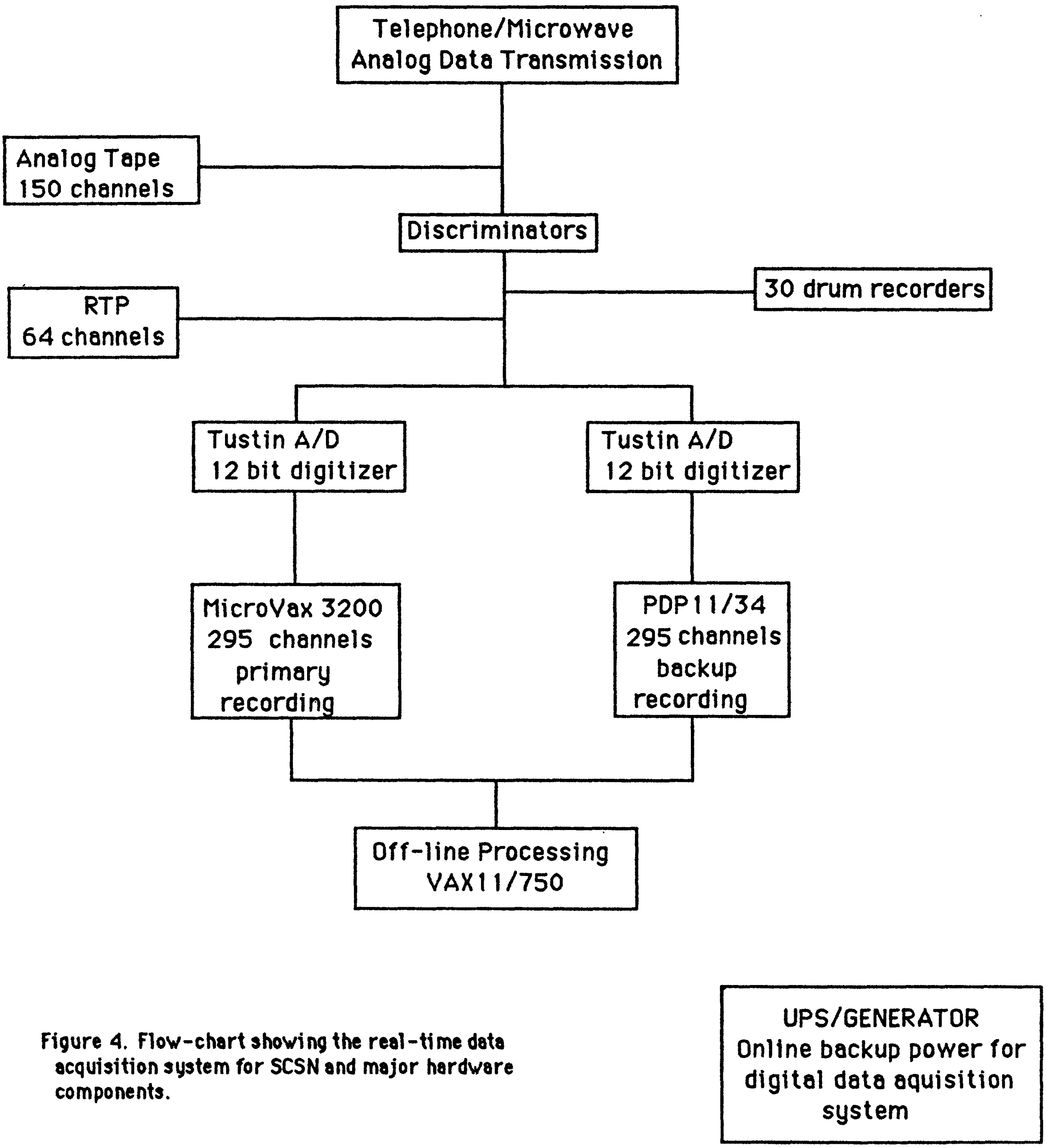

Figure 4. Flow-chart showing the real-time data acquisition system for SCSN and major hardware components.

sent directly by networked computers could arrive before the seismic waves. Agencies such as power companies, emergency services or computer facilities could make use of the short amount of time to initiate safety procedures. Examples might include electric power isolation to avoid widespread blackouts, protection of hazardous chemicals, closing of natural gas valves to minimize fire hazards and warnings to nuclear power plants.

Earthquake Hazard Assessment

In addition to recording seismic data for research, the Southern California Seismographic Network monitors the earthquakes in near real time for post earthquake response and short term earthquake hazard assessment. An RTP system ("real time picker"; *Allen*, 1982), scans 64 of the 295 stations of the network for signals it recognizes as earthquakes. The signals are correlated and locations and duration magnitudes are calculated within 4 minutes of the start of the earthquake. These locations and magnitudes are evaluated by an alarm system and network seismologists are notified by electronic mail and radio pagers of all earthquakes above magnitude 3.5 and some smaller earthquakes within selected regions.

The limitations of this system are less accurate locations (with little or no depth control) and no focal mechanisms because less than one quarter of the stations within the network are used. Also no magnitudes above 4.1 are determined because of the limits of the signal duration used to calculate magnitudes in near real time. To overcome these problems, a new software based system within CUSP is being developed to use all of the stations including the low gain instruments and ultra-low-gain forced balance accelerometers. A program is in place to automatically determine magnitudes for the larger earthquakes from the low-gain instruments within 3 or 10 minutes (depending on the type of online computer) which can then be used with the present RTP locations.

At least one network seismologist goes into the laboratory after earthquakes above magnitude 3.5 to insure that equipment is operational and to answer inquiries from government and the public. For larger earthquakes, more staff is called in. Aftershock locations from the RTP and focal mechanisms determined from CUSP data often allow the causative fault to be determined for larger earthquakes within one or two hours. This basic information is important both to scientists planning field investigations and to emergency response officials directing search and rescue operations. For instance, as was discovered after the 1971 San Fernando earthquake, the heaviest damage may be quite a distance from the epicenter of an earthquake when there is significant horizontal rupture propagation.

With the data available from the RTP and CUSP, network scientists also attempt to evaluate the potential for future seismic activity. Recent developments have allowed us to determine the probability of damaging aftershocks given the rate of occurrence and magnitude distribution of a particular aftershock sequence [*Reasenberg and Jones*, 1989]. In some situations we can also determine the probability that a larger earthquake will follow within an ongoing earthquake sequence [*Jones*, 1985; *Agnew and Jones*, 1990]. These probabilities are now being routinely calculated whenever the aftershock sequence is large enough to make it worthwhile. The California OES has twice issued public advisories, for San Diego in 1985 and for the San Gabriel Valley in 1990, based on probabilities calculated from data collected from the southern California seismic network. If the threat is serious enough, staff from the network will consult with the California Earthquake Prediction Evaluation Council (CEPEC) to determine appropriate action, as was done after the Superstition Hills earthquake (M=6.6) of 1987. For the most serious threat, the southern San Andreas fault, which has a 60% chance of rupturing in a M=7.5-8.0 within 30 years [*Working Group on California Earthquake Probabilities*; Agnew 1988], a working group has developed a plan for the most appropriate responses to possible precursors to a San Andreas earthquake (Appendix D; *Jones et al.*, 1990).

Data and Information Transfer to Public and Government

One of the important functions of the Southern California Seismographic Network is to communicate to the public the information gleaned from the monitoring, hazard assessment and research functions. Calling Caltech after an earthquake is a time-honored tradition in Los Angeles. Moreover, as the rate of moderate earthquakes has increased in the Los Angeles metropolitan region in recent years [*Jones and Reasenberg*, 1989], public interest in seismology in southern California has also increased. Caltech and the U. S. Geological Survey coordinate efforts to transfer data and information to the public, including providing information and advice to government officials after moderate or large earthquakes, providing information to the public and press after all felt earthquakes, and general earthquake education.

As discussed above, local government officials need quick assessment of the location, magnitude and, if possible, causative fault of moderate and large earthquakes to coordinate rescue efforts. To fulfill this need, local government agencies can make arrangements to be called as soon as possible after an earthquake. Caltech maintains a "call list" of agencies to be telephoned after earthquakes greater than 4.0, 4.5, and 5.0 that includes the California Governor's Office of Emergency Services (OES), several police departments, electric and gas utilities, and railroads. This list is activated by a magnitude 4.0 or greater about 10 times per year. For earthquakes above magnitude 5.0 (on average once or twice a year), OES usually sends a representative to Caltech with a cellular phone so that the most recent information about causative fault and the probabilities of more damaging earthquakes can be quickly relayed to their headquarters. When necessary, this channel of communication can be used for preparing public statements or earthquake advisories.

With the large populations in the Los Angeles and San Diego metropolitan areas, felt earthquakes generate considerable public interest. Caltech is the primary source of information about southern California earthquakes and the staff of the southern California seismic network and the Caltech public relations office handle many hundreds of interviews with the press every year about specific earthquakes. A moderate earthquake like Whittier Narrows will generate a few hundred requests for information from both the local and national press. Four or five members of the network staff with some experience with the press handle most of these interviews.

People in southern California have always been interested in the earthquakes, so that even without the prod of a recently felt earthquake the staff of the network receive a constant stream of requests for information. Some come through the press; we estimate staff members conduct close to one hundred interviews per year about general earthquake topics. The Caltech public relations office coordinates requests for speakers from community groups and local schools and colleges. About one hundred such talks are given by network staff members each year. Tours of the Seismological Laboratory are also given in special situations. Caltech has also published some information pamphlets that are distributed to the public on request.

Data Products and Access

With over 10,000 earthquakes recorded on 220 seismic stations (289 channels) per year, the Southern California Seismographic Network analyzes and archives a huge quantity of data every year, including catalog listings (time, magnitude, location and location quality), phase data (arrival times, qualities and first motions at each station) and seismograms. These data are used by a wide variety of people - researchers from the U. S. Geological Survey, Caltech and other academic institutions, geotechnical consultants, insurers and lawyers. Because of the limited staff of the network, we have endeavored to make it as easy as possible for users to get the data themselves. The data products available from the network and the mechanisms for accessing them are diagrammed in Figure 5. Bulletins listed in Appendix E provide detailed documentation.

The data from the Southern California Seismographic Network is recorded and processed using the CUSP (Caltech/USGS Seismic Processing) system [*Johnson*, 1983] on a network of four VAX/VMS computers. The data are maintained in CUSP binary data bases, accessible through a series of programs. Individual accounts for outside researchers and general visitor accounts are maintained on the VAX's. Information about limited use accounts and phone numbers for modems have been published in semi-annual network bulletins. Much of the data has also been transferred to the UNIX computers in the Seismological Laboratory and is regularly used from there. In the last six months, the VAX network has been joined to CITNET, the Caltech computer network and through CITNET to INTERNET and NSFNET, providing more general access to the data.

Earthquake Catalog

The earthquake catalog is the most commonly used of the Southern California Seismographic Network data bases. It is complete for events M $\geq$ 3.0 since 1932 and includes over 150,000 events (Figure 6). It provides a unique resource in seismology because it is the only U. S. catalog in which magnitudes of earthquakes above 3.0 have been determined in the same way for this long a period. Because of the variety of people that use the catalog, we provide several avenues to access the data. Printed listings of the earthquakes of magnitude 3.0 and greater have been published for 1932-1973 [*Hileman et al.*, 1973] and 1974-1983 [*Hutton et al.*, 1985] and are for sale by the Caltech bookstore. The complete catalog - complete above magnitude 3.0 since 1932 and above 1.8 since 1981 - is maintained online on the VAX cluster with programs for searching for events that fit different criteria. On request, Caltech will conduct searches of the catalog over specific time, location and magnitude intervals and produce either printouts or computer files. An average of 80-100 requests are received

Southern California Seismographic Network: Data Flow

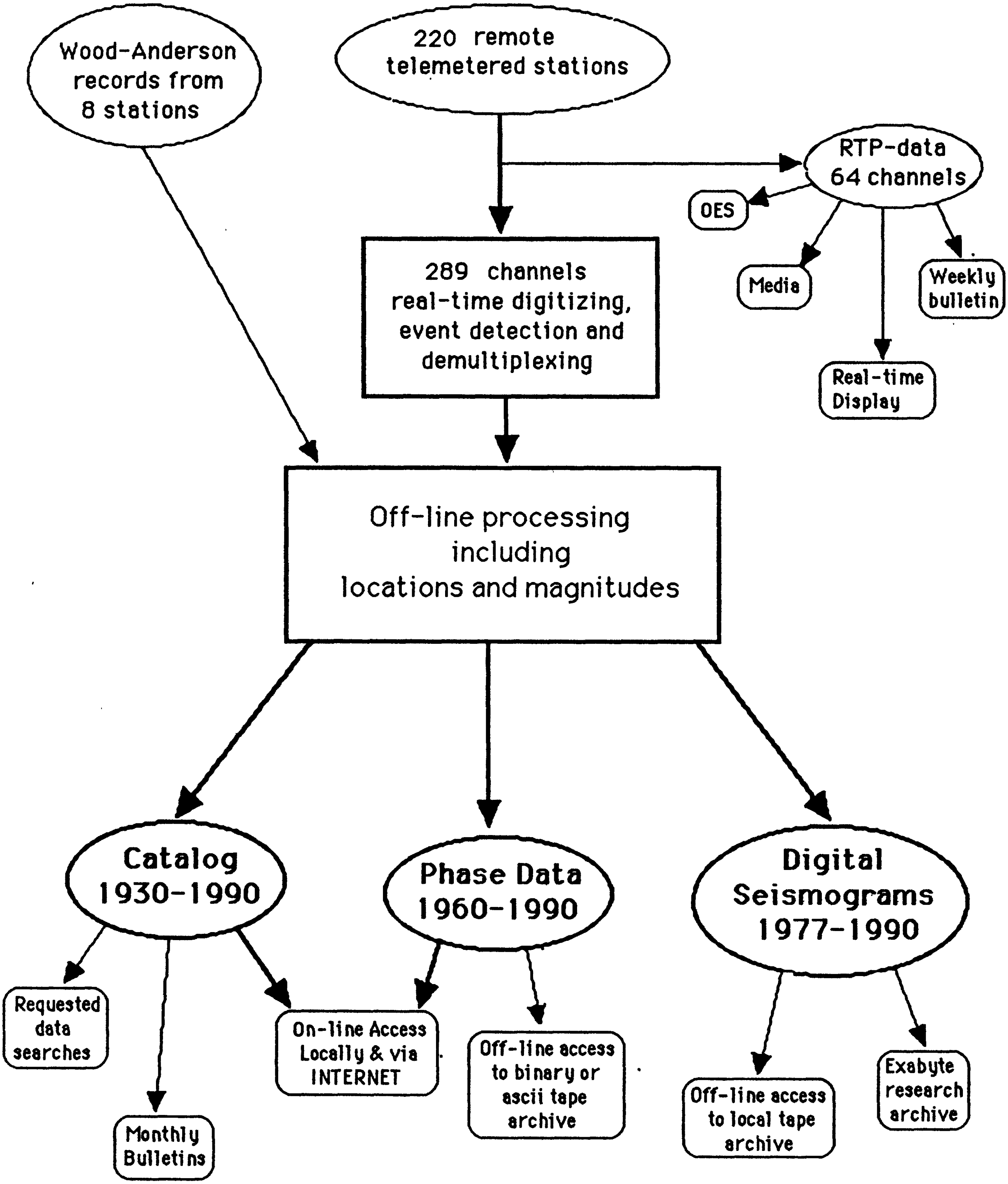

Figure 5. Data flow and access for the Southern California Seismographic Network.

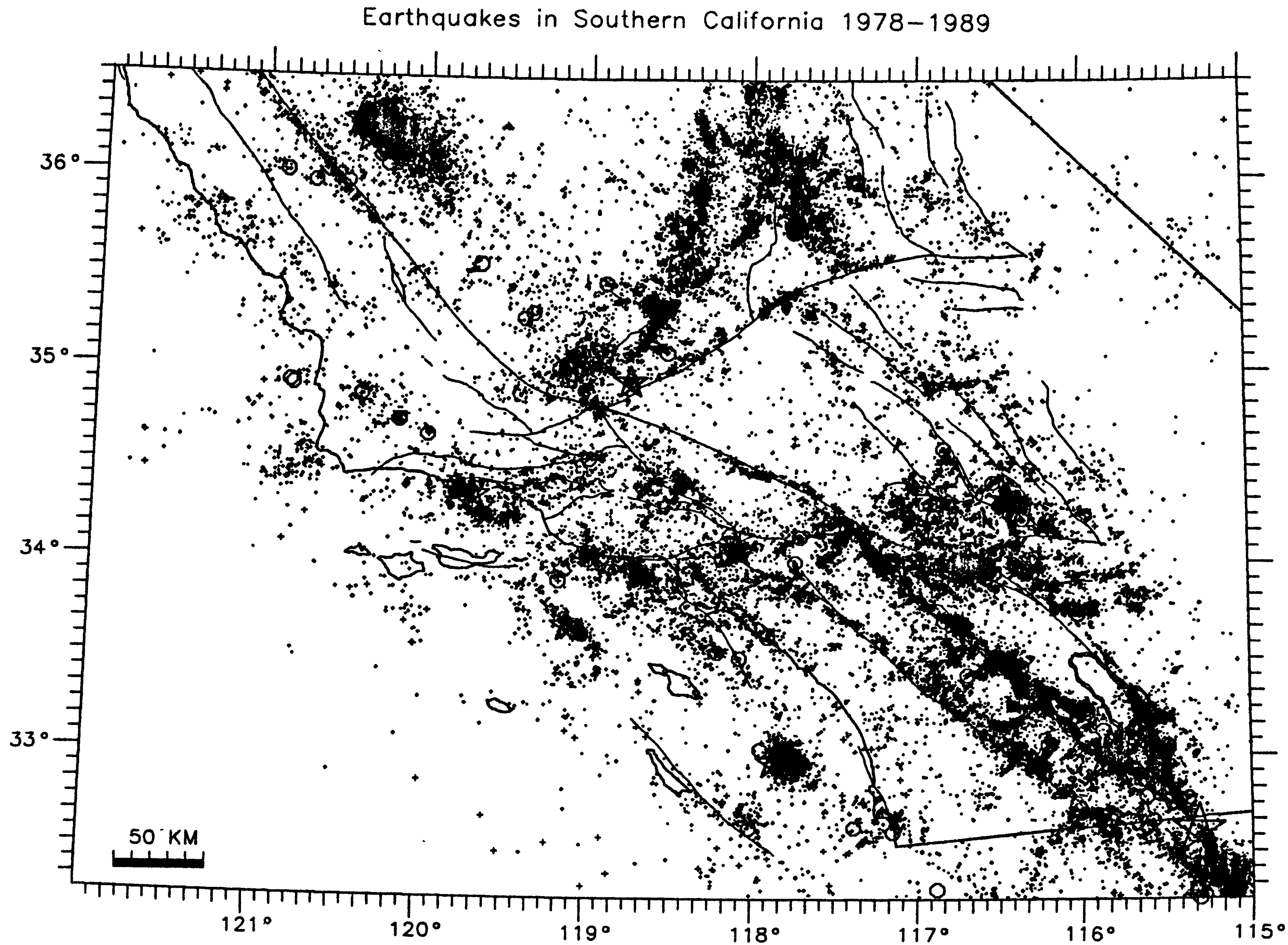

Figure 6. Southern California Seismicity 1978-1989.

per year from researchers (10/yr), geotechnical consultants (40/yr) lawyers and insurers (20/yr) and others (20/yr). Researchers may also access the catalog directly. A limited use account has also been established for catalog searches and the modem telephone number and account information generally published. That account has been used over 250 times in the last 27 months, mostly by researchers, and as of this year can be used through INTERNET/NFSNET. The catalog has also been sent to the Seismology Branch of USGS in Menlo Park and is updated at yearly intervals.

To increase the usefulness of the catalog, the staff of the Southern California Seismographic Network prepares weekly and monthly digests of the recorded seismicity. A listing of all earthquakes above 2.5 is prepared monthly within 2 weeks of the end of the month and mailed to over 200 recipients (see Appendix C), many in industry. An analysis of the activity including focal mechanisms of earthquakes above magnitude 3.0 was sent monthly to a smaller group, primarily researchers. This year we began distribution of a weekly summary of seismicity issued every Thursday afternoon about the earthquakes from Thursday through Wednesday that includes a list of the earthquakes above 2.5 and a description and short analysis of the interesting earthquakes of the week. This report is faxed to about 23 recipients each Thursday (see Appendix B). This report is used by one major network television station in Los Angeles (KNBC) to show a weekly earthquake map as a part of their weather forecast in the late afternoon every Thursday. A monthly epicenter map of M>2.5 earthquakes is published by the Los Angeles Times. In addition, a month's worth of these reports with focal mechanisms for the earthquakes above magnitude 3.0 have replaced the previous monthly analyses.

Phase Data

The phase data, arrival times and first motions at all timed stations, are more voluminous than the catalog with about 100-150 megabytes of data now created per year. A sample of the data is shown in Figure 7, where first-motion focal mechanisms for M>3.5 events that occurred in 1989 is shown.

The data from 1932 to 1959 are kept on printed cards. The data from 1960 onwards have been entered into computer data bases. Two data gaps exist in this time period for which the digital seismograms have not yet been processed: May 1980 - Feb 1981 and Mar - June 1983. A subset of the stations were timed off of paper records for earthquakes $M \geq 2.5$ in these time periods and these data are available.

The phase data have been kept on magnetic tapes in the CUSP data base format ("FREEZE tapes") and ASCII format ("HYPOINVERSE tapes"). On

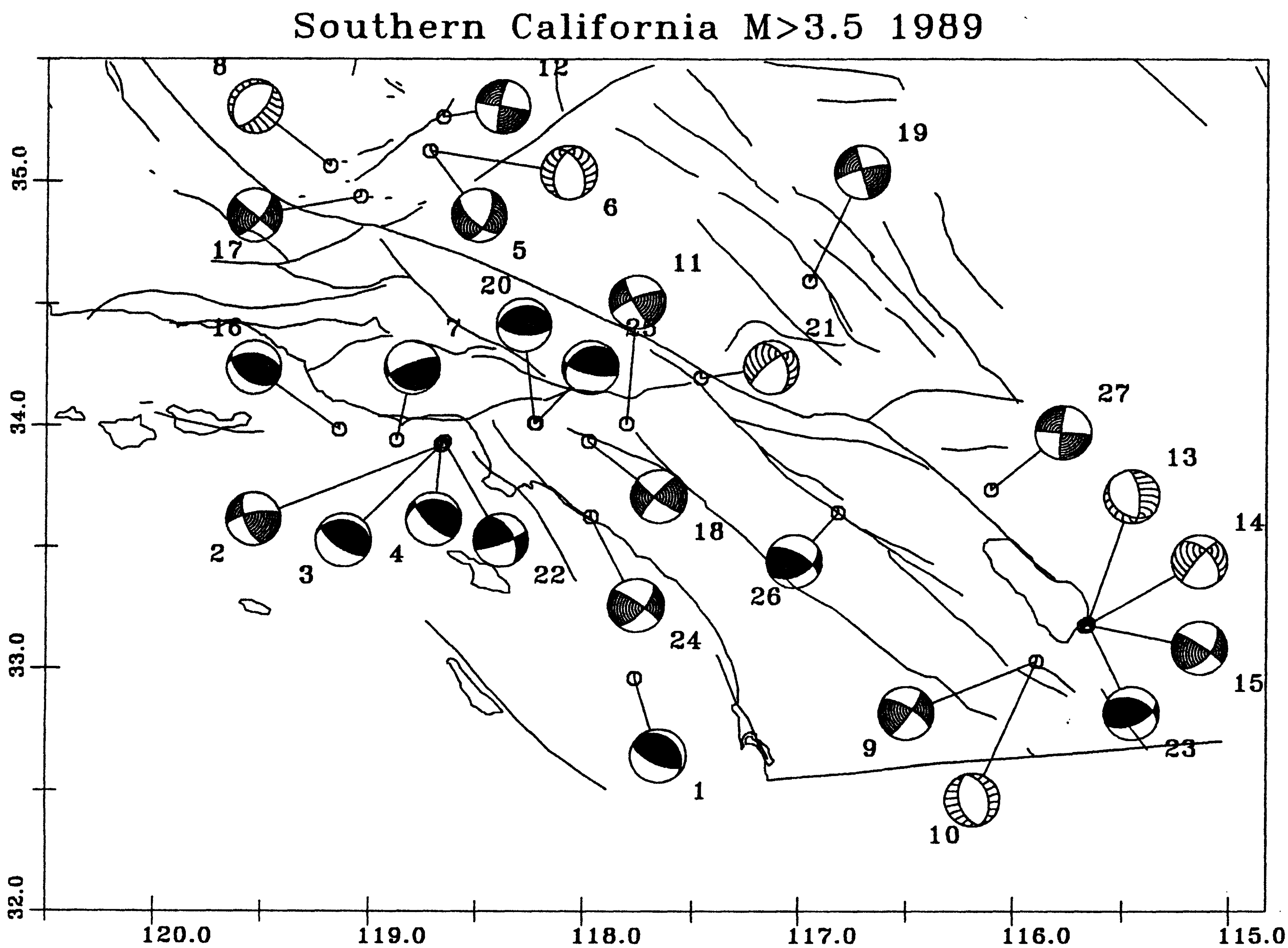

Figure 7. Focal mechanisms of M>3.5 earthquakes in 1989.

request (10-20/year), the USGS Pasadena office distributes copies of the HYPOINVERSE tapes. Many researchers from Caltech, USGS, UC San Diego, USC, UC Santa Barbara, and CICESE (a seismological laboratory in Ensenada, Mexico) maintain accounts on the VAX cluster in part for utilizing phase data. The complete (at the time) set of phase data were given to Lamont-Doherty Geological Observatory and the USGS in Menlo Park in 1986 and 1987. This summer, the accessibility of phase data was greatly improved by the addition of a new magnetic disk to the VAX cluster on which all of the post-1960 phase data are stored. Access to phase data by INTERNET (from both UNIX and VMS based computers) is now available and loading of magnetic tapes is no longer required. A separate phase data base on the UNIX computers in the Seismological Laboratory has also been developed and at present, includes phase data from 1984 to 1989.

Seismogram Data Base

Seismograms are recorded on paper and computer. About 7 sites (20 components) are recorded and archived on paper in addition to the 220 sites that are recorded digitally by the Southern California Seismographic Network. Of these, 14 components are standard Wood-Anderson seismographs which are, mechanical, not electronic instruments, and therefore cannot be recorded by computer. These instruments have been operated since the 1920s and provide continuity with the recordings of older earthquakes, especially in magnitude determination.

All other seismic signals, except for the Wood-Anderson instruments have been recorded on computer since 1977 (see Technical Configuration, above). Because of their size (an *average* of 10-20 megabytes of data per earthquake), seismograms are stored on magnetic tape within one or two days of being recorded. In addition, the data since 1981 are being copied to Exabyte tapes to facilitate use of large quantities of seismic data. Because of staffing limitations, the network does not distribute digital seismograms on request, but rather provides the computing resources and documentation for researchers who come to Pasadena. At present, about 5-10 people per year use the seismogram data. In the near future we plan to install an optical disk reader and transfer the seismograms to optical disks. In addition, we have begun a program to reformat the array data onto high-density media specifically for tomographic projects. It is expected that the thousands of 9-track tape archive will be reduced to a few tens of 8 mm tapes. So far the 75 Gbytes of data recorded by the array from 1984 to 1989 has been copied onto 40 8 mm tapes. We hope that the easier access this will provide, together with the improvements to the quality of the seismic signals that have been effected in the last few years will lead to greater use of the seismograms

Real Time Data

A Real Time Picker (RTP) is connected to 64 channels of the data to determine and correlate P-wave arrival times. The picks are sent to another computer where locations are determined within a few minutes of the earthquake occurrence. This automated location procedure gives fast reliable locations for events within the network and is used to send magnitude and location information to pagers carried by USGS and Caltech personnel. Preliminary magnitudes for smaller events are estimated from coda durations recorded on the RTP. For larger earthquakes ($M \geq 4.0$), preliminary magnitudes are estimated from an on-line program which automatically calculates Wood-Anderson response seismograms from the low gain seismometer and FBA data channels. Amplitudes from these simulated Wood-Andersons are used with the RTP location to get a local magnitude (M_L).

Scientific Research

The Southern California Seismograph Network has been a steady source of data for a wide range of innovative research projects. The results of those studies by researchers at Caltech, USGS and other institutions have been described in over 200 publications over the last 20 years. Below we discuss the results of some of the more recent projects.

Earthquake Statistics

The southern California earthquake catalog is one of the longest and most complete in the world and as such is an important tool for the study of the statistics of earthquakes and earthquake sequences. Over 150,000 events have been catalogued since 1932 which provides enough data to determine meaningful statistics. Moreover, the method for determining magnitudes above 3.0 by the network (local magnitudes from Wood-Anderson amplitudes) has remained the same since 1932. The magnitudes for smaller earthquakes are always calibrated against the Wood-Anderson magnitudes. *Habermann* [e.g., 1987] has shown that changes in magnitude determination can cause artificial changes in rate and clustering characteristics to appear in the analysis. The consistency in the southern California catalog eliminates many problems when working with statistics.

Aftershock statistics. The most noticeable feature of any catalog is the non-random clustering of events after large earthquakes, called aftershocks. Various statistical techniques have been used to define aftershocks in the southern California and examine their properties [*Gardner and Knopoff*, 1974; *Reasenberg and Jones*, 1989]. *Reasenberg and Jones* [1989] determined the parameters of Omori's Law and the Gutenberg-Richter relation for 65 aftershocks from the southern and northern California catalogs and from these defined a generic California aftershock sequence. They also show that knowledge of these parameters can be used to determine the probability of damaging aftershocks within an ongoing sequence. *Kisslinger and Jones* [1990] have suggested that the decay rate of aftershock sequences may be related to heat flow. *Jones* [1989] analyzed the distribution of largest aftershocks and showed that Båth's Law does not apply in southern California but rather that all magnitudes within 2.5 units of the mainshock are equally likely for the largest aftershock.

Foreshock statistics. It has long been recognized that smaller earthquakes often, but not always, precede large events [e.g., *Richter*, 1958, pg. 67]. *Jones* [1985] and *Kagan and Knopoff* [1978] have used the southern California catalog to define foreshock sequences in time and space. *Jones* [1985] used these results to determine that the generic probability that an earthquake in southern California will be followed by a larger event within 5 days and 10 km to be 6%. *Agnew and Jones* [1990] have refined the probability analysis to consider the chance that an earthquake near a major fault will be a foreshock to the characteristic mainshock of that fault. This has already been used to develop a short term earthquake alert system for the southern San Andreas fault [*Jones et al.*, 1990]. The probabilities for the southern San Andreas fault are shown in Figure 8.

The details of several individual foreshock sequences have also been studied [*Lindh et al.*, 1978; *Jones*, 1984; *Jones*, 1988], suggesting some intriguing characteristics of foreshocks such as similarity of focal mechanisms between foreshock and mainshock and occurrence at complications in the faults but nothing yet has been shown to be a discriminating characteristic.

<u>Seismotectonics</u>

Below we discuss the results of a few selected seismotectonic analyses that used the seismic network data. The list of papers in Appendix A also covers other studies not discussed here.

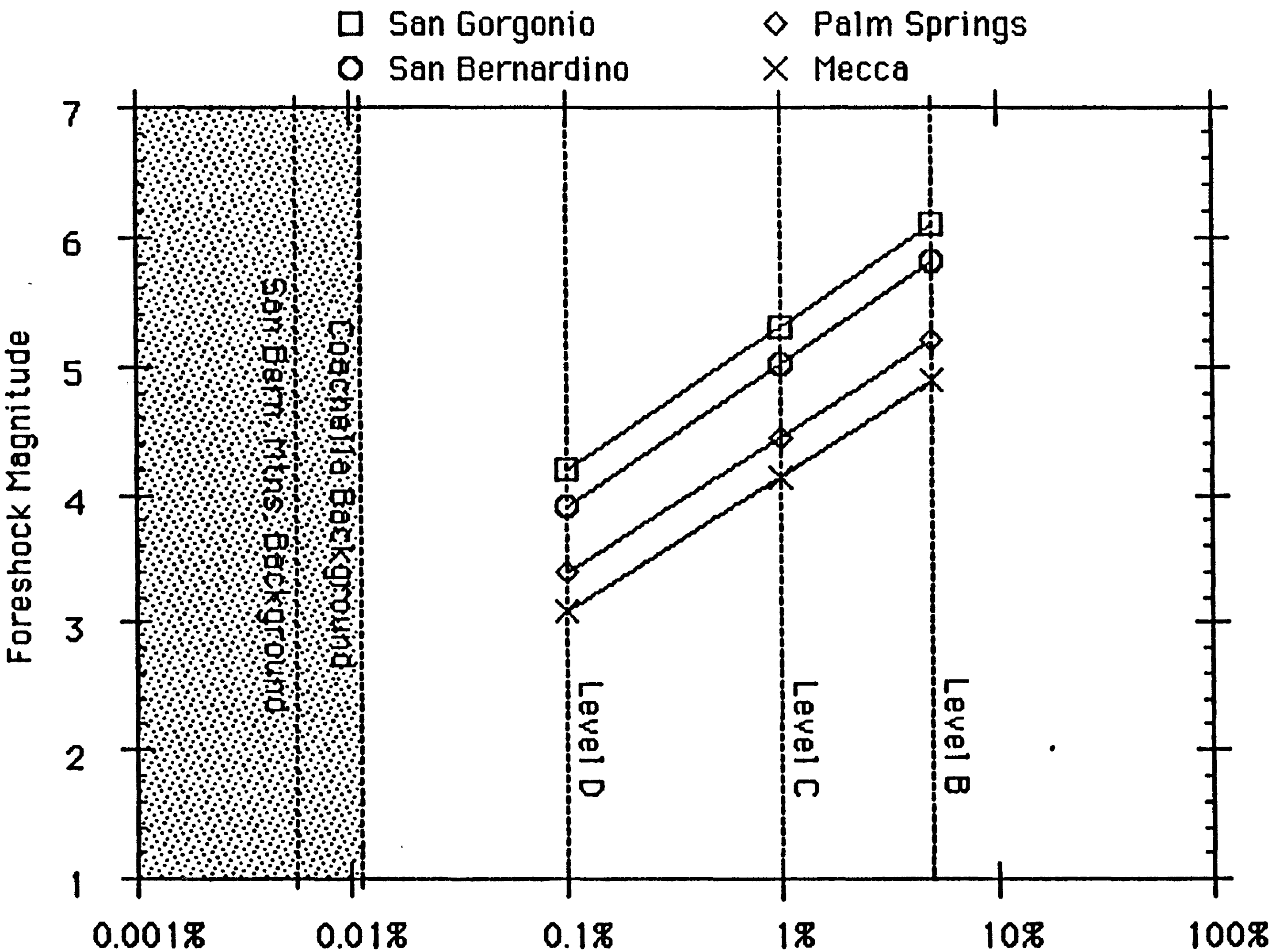

Figure 8. The probability of a major earthquake occurring on the southern San Andreas fault within 72 hours after a potential foreshock versus the magnitude of the potential foreshock for the four microseismic regions, San Bernardino (circles), San Gorgonio (squares), Palm Springs (diamonds), and Mecca Hills (crosses). The background probabilities for 72 hours based on the long-term probabilities of WGCEP (1988) are also shown for the Coachella Valley and San Bernardino Mountains segments.

Los Angeles Basin. Hauksson [1990] summarized the earthquake activity, types of faulting and state of stress in the Los Angeles basin. Since 1920 fourteen moderate (M_L=4.9-6.4) earthquakes have been reported in the Los Angeles basin. These events are associated with both mapped surficial faults and concealed faults beneath the basin sediments. To determine the style of faulting and state of stress in the basin, single-event focal mechanisms for 244 earthquakes of $M \geq 2.5$ from 1977 to 1989 were calculated. Fifty-nine percent of the events are strike-slip and are mostly located near two of the major, northwest striking right-lateral strike-slip faults in the basin, the Newport-Inglewood fault and the Palos Verdes fault. The 1988 Pasadena and the 1988 Upland earthquakes showed left-lateral strike-slip on northeast striking faults. Numerous small earthquakes in the eastern part of the basin show left-lateral strike-slip faulting and form a northeast trend near Yorba Linda. Thirty-two percent of the events have reverse mechanisms and are distributed along two broad zones. The first, the Elysian Park fold and thrust belt, coincides with anticlines along the eastern and northern flank of the Los Angeles basin extending into Santa Monica Bay. The second, the Torrance-Wilmington fold and thrust belt, coincides with anticlines mapped on the southwest flank of the basin and extends from offshore Newport Beach to the northwest into Santa Monica Bay (Figure 9). The coexistence of zones of thrusting and large strike-slip faults in the basin suggests that the thrust and strike-slip movements are mostly decoupled. The trend of the maximum horizontal stress varies from N1°W to N31°E across the basin and consistently forms high angles with the fold axes. This stress field and ongoing folding and thrusting suggest that tectonic deformation is concentrated along the flanks of the deep central basin. Today the deformation of the basin consists of uplift and crustal thickening and lateral block movement to accommodate the north-south compression across the basin.

Santa Monica Bay - offshore area. One of the more difficult problems in southern California seismotectonics is the relationship between reverse and oblique left-lateral slip in the northern Los Angeles basin and the Transverse Ranges and ongoing right-lateral strike-slip faulting in the southern L.A. basin and adjacent offshore areas. To investigate this relationship we have examined the seismicity from 1973 to 1986 for Santa Monica Bay and find numerous thrust focal mechanisms that coincide spatially with mapped anticlinal axes [*Hauksson and Saldivar*, 1989]. The tectonics in Santa Monica Bay are dominated by compression, with thrust, reverse and strike-slip faulting. The coexistence of thrust and strike-slip

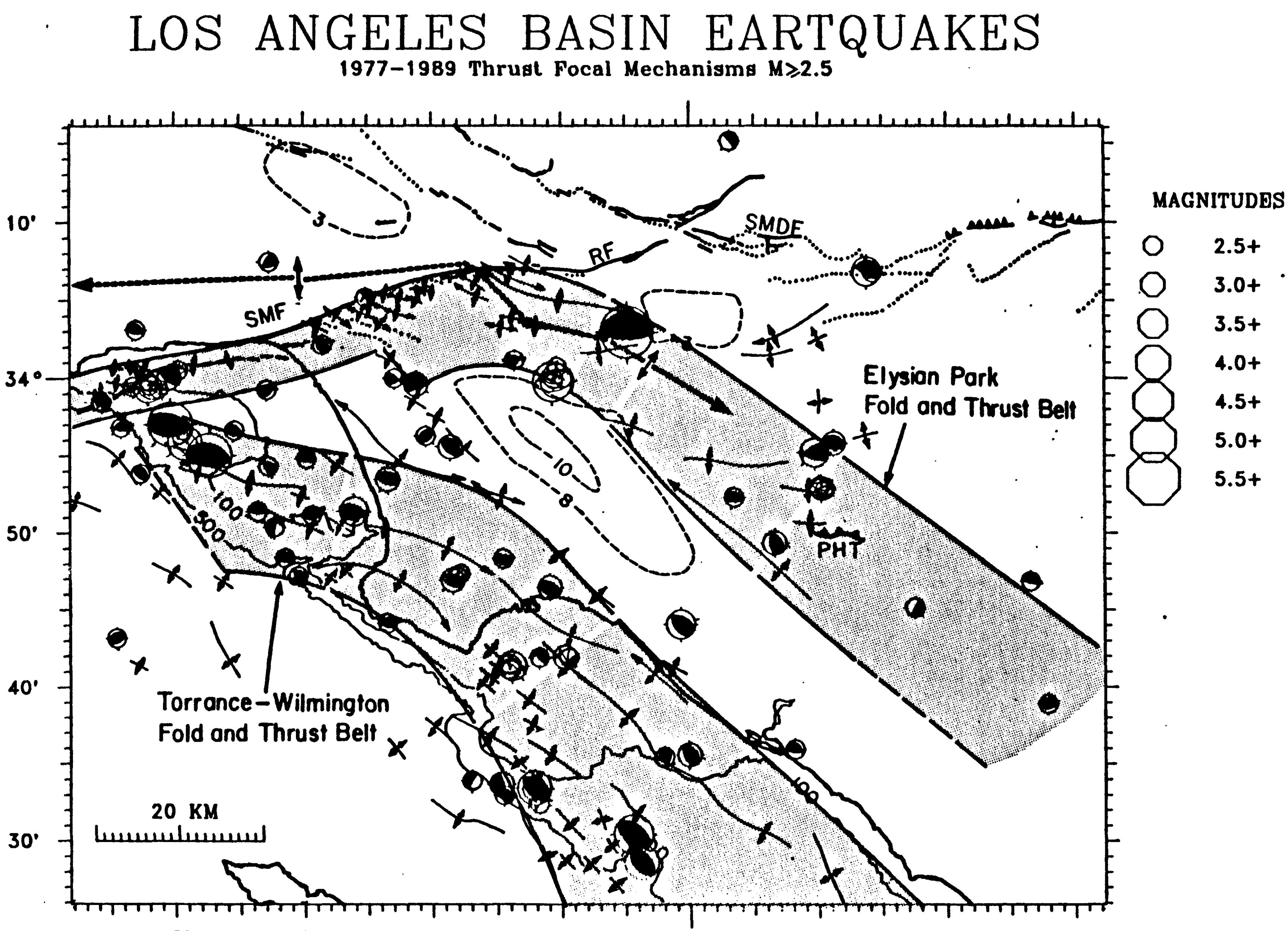

Figure 9. Fold and thrust belts in the Los Angeles basin.

faults suggests that the bay is not a part of the Peninsular Ranges terrain, but forms a transition zone that accommodates the change from strike-slip in the Peninsular Ranges to the south, to reverse faulting in the Transverse Ranges to the north. Mapped anticlines and the previously unrecognized thrust faults beneath the bay form two fold and thrust belts that present additional seismic hazards to Los Angeles and the southern California coastal zone through seismic shaking and possible generation of small tsunamis.

Ventura basin. *Bryant and Jones* [1990] analyzed earthquakes occurring at depths of 20-30 km beneath the Ventura Basin and showed that the epicentral distribution of deep seismicity outlines an east-trending ellipse which corresponds closely with the mapped Santa Clara Syncline, the main structural element of the Ventura basin with 15 km thickness of sediments. Clear Pn and Pg phases are seen for even the deepest earthquakes which demonstrate that these earthquakes are occurring within the crust. Travel time curves from shallow and deep earthquakes in the western Transverse Ranges require that the depth to the Moho under the Ventura basin must be depressed by 5-7 km relative to the surrounding area. Other researchers have shown that the Ventura basin has the lowest heat flow in western California. Thus low heat flow, very thick (15 km) sediments, the deep earthquakes, and a depressed Moho all coincide within a small area, strongly suggesting a common cause for all four phenomena in the rapid shortening of the Ventura basin. The confinement of the deep earthquakes and depressed Moho to the Ventura region suggests that the very rapid shortening of the Ventura basin is not representative of the rate of shortening across all of the western Transverse Ranges.

San Andreas fault. The seismotectonics of the San Andreas fault have been analyzed using data from SCSN. *Jones* [1988] determined from P wave first motion polarities focal mechanisms for 138 small to moderate earthquakes. Using these mechanisms the southern San Andreas fault was divided into five segments with different stress regimes. The results of inverting for the state of stress within each segment show that the stress state varies significantly between regions. The most significant change in the stress state was found near the end of the rupture zone of the 1857 Fort Tejon earthquake. Thus the stress state determined by using data from small earthquakes may be important in controlling the rupture propagation for large earthquakes.

Using composite focal mechanism, *Nicholson et al.* [1986] studied deformation along the San Andreas fault in San Gorgonio Pass and adjacent areas. They identified a number of left-lateral faults that strike northeast and a systematic pattern of normal and reverse focal mechanisms. They interpreted this pattern of deformation as the clockwise rotation of crustal blocks located within a zone of right-lateral shear stress. They also suggested that the distribution of deep seismicity was consistent with a detachment surface at depth extending beneath the San Bernardino mountains. Thus the analysis of the local network data have provided new insight into the tectonics of this important segment of the San Andreas fault.

San Jacinto fault. The San Jacinto fault is the most seismically active fault in southern California. The distribution of seismicity along the fault shows areas of high activity bracketed by areas of low activity. An area of low activity at the northern end of the fault is of particular interest because it is very similar to the lack of seismicity along the San Andreas fault that was later ruptured by the M=7.1 Loma Prieta earthquake. *Sanders* [1986] used data from the modern network to redetermine the epicenters for large historical events that occurred in 1937, 1942, and 1954. The location of these and other older events and the 1968 Borrego Mountain event have reconfirmed the presence of the Anza seismic gap, which was initially identified by *Thatcher et al.* [1975]. *Sanders* [1986] and Doser [1986] also showed that the depth of seismicity is inversely correlated with heat flow along the San Jacinto fault.

Studies of individual earthquake sequences. Although analysis of background microseismicity is a powerful tool for studying tectonic structures, many of active faults, especially those that produce large earthquakes have little or no microseismicity. The study of aftershock sequences is an important, and in the case of offshore and buried faults, often the only source of information about these fault structures. Several moderate earthquakes have occurred in southern California in the last five years and studies of these earthquakes using SCSN data has contributed significantly to our understanding of the seismotectonic structures.

The October 1, 1987 Whittier Narrows earthquake (M_L=5.9) has been extensively studied [*Hauksson et al.*, 1988; *Jones and Hauksson*, 1988; *Hauksson and Jones*, 1989]. It was located at a depth of 14.6 +0.5 km beneath the northeastern Los Angeles basin. The spatial distribution of the mainshock and aftershocks as well as the focal mechanisms of the mainshock indicate that the causative fault was a 25° north-dipping thrust fault striking west, although no thrust had previously been recognized in the area. This earthquake conclusively demonstrated that a previously unrecognized buried fault system runs along the northern flank of the Los

Angeles basin and poses a substantial seismic hazard. By contrast, analysis of the Dec., 3 1988 Pasadena earthquake (M_L=4.9) which occurred only 10 km north of the Whittier Narrows earthquake at 16 km depth beneath the City of Pasadena demonstrated that the Raymond fault, which many had thought to be a reverse fault, is dominantly a left-lateral strike-slip fault [*Jones et al.*, 1990].

The Whittier Narrows and Pasadena earthquakes are part of an increase in seismic activity within the Los Angeles basin that began in March 1986 [*Jones and Reasenberg*, 1989]. In the Los Angeles basin the rate has increased from one M>4.5 event every four years to one M>4.5 event every four months. The area of increased activity extends east into the San Gabriel Valley where the February 28, 1990 Upland (M 5.5) earthquake occurred. Preliminary analysis suggests that this earthquake was caused by left-lateral strike-slip faulting on a northeast trending fault coinciding with the San Jose fault, that has been mapped from ground water barriers. Relocations of the aftershocks and background seismicity suggest that an asperity large enough for a M 5.5-6.0 earthquake remains unbroken on this fault (Figure 10).

The increase in activity in the Los Angeles basin has prompted a reanalysis of one of the regions largest historic events, the 1933 Long Beach earthquake. Reanalysis of regional seismographic network and teleseismic data [*Hauksson and Gross*, 1990] confirms that the causative fault was probably the Newport-Inglewood fault. The teleseismic focal mechanism had a strike of 315°, dip of 80° to the northeast and rake of -170°. Relocation of the sequence using modern events as fixed reference events, shows that the rupture extended unilaterally to the northwest for a total length of 13-16 km. The centroidal depth was 10±2 km and the seismic moment was $6*10^{25}$ dyne-cm, which corresponds to an energy magnitude of M_W=6.4. Both the spatial distribution of aftershocks and inversion for the source time function suggest that the earthquake may have consisted of at least two subevents. When the slip estimate of 100-150 cm from the seismic moment is compared with the long term geological slip rate of 0.1-1.0 mm/yr along the Newport-Inglewood fault, the 1933 earthquake has a repeat time on the order of a few thousand years.

The Oceanside earthquake (M_L 5.3) occurred offshore from San Diego county on July 13, 1986. The epicenter of the mainshock is located at the northern end of the north-northwest striking San Diego Trough fault zone. The focal mechanism of the mainshock and the spatial distribution of aftershock hypocenters are consistent with a mainshock rupture on a south dipping and east-west striking reverse fault. Hence this sequence appears to have ruptured a small fault that provides for a left offset in the San

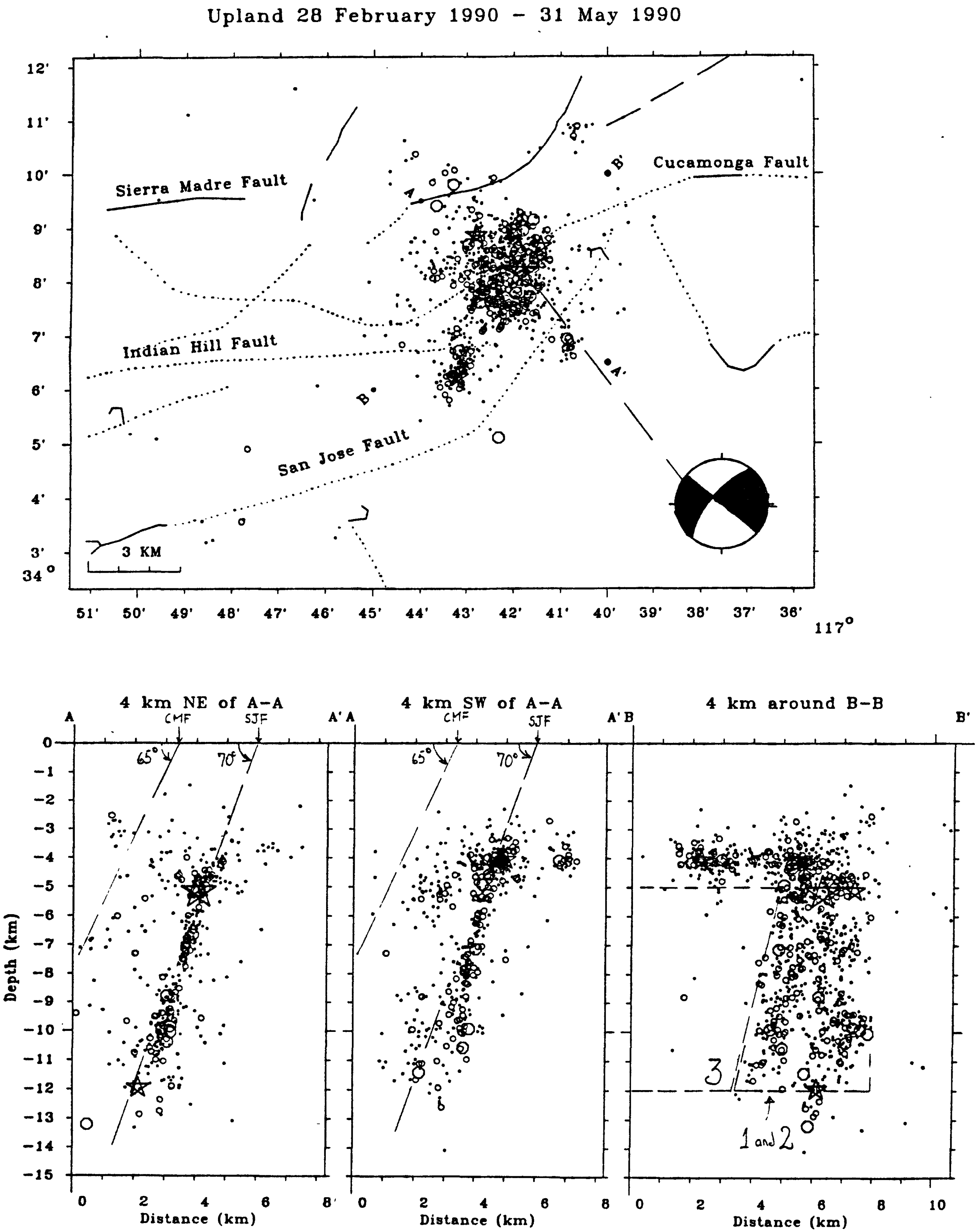

Figure 10. The 1990 Upland earthquake sequence. (top) Map view including the focal mechanism of the M = 5.5 mainshock. (Bottom) Cross sections orthogonal and parallel to the fault. The parallel cross section B-B' shows the area of the fault to the southwest that has not yet ruptured.

Diego Trough fault as it curves toward the west around the Santa Cruz-Catalina escarpment *[Hauksson and Jones*, 1988]. The main conclusion of this study is that reverse faulting on west-striking faults may be as important as strike-slip faulting on northwest striking faults within the Continental Borderland.

The most recent earthquake to occur within the San Jacinto fault system was the 1987 M_S=6.6 Superstition Hills earthquake [*Magistrale et al.*, 1989]. This earthquake was preceded by a M_S=6.2 foreshock that occurred on a northeast trending fault between the San Jacinto and San Andreas faults. This caused considerable debate at the time between network staff, CEPEC, and OES as to the possibility of triggering further seismic activity. especially on the San Andreas fault. During this crisis the seismic network proved to be very important and provided the necessary data to evaluate the ongoing activity. The seismic network data have been used to determine the distribution of aftershocks of the 1987 earthquake and to improve our understanding of the tectonics of the region.

Tomographic Studies

In addition to its use in locating seismicity and focal mechanisms, the SCSN has generated important datasets for determining the lateral variations in velocity and structure in the crust and upper mantle. In the last decade there have been several studies that have utilized this data.

Upper Mantle Structure. Humphreys [1985] and Humphreys et al., [1984], utilizing the travel times of teleseismic events recorded on the SCSN imaged a fast (cold) slab-like feature beneath the Transverse Ranges that descends to a depth of 250 km., and a shallow slow (hot) anomaly beneath the Salton Trough. One hypothesis is that these two features form the source and sink of a small convection cell. The coincidence of the slab-like anomaly with the "Big Bend" in the San Andreas Fault has fueled speculation that it has developed from lithospheric material forced down by the convergence in this region (Figure 11).

Crustal Structure. Hearn [1984] and Hearn and Clayton [1986a,b] examined the crustal phases Pg and Pn which bottom at approximately 10 and 30 km respectively, for lateral variations in travel times. The map of lateral variations in Pg velocities reveals a striking similarity to the surface tectonic features such as the San Andreas Fault and Garlock Faults. Perhaps the most intriguing result is the the San Jacinto block appears to belong the the North American side rather than the Pacific side at a depth of 10 km.

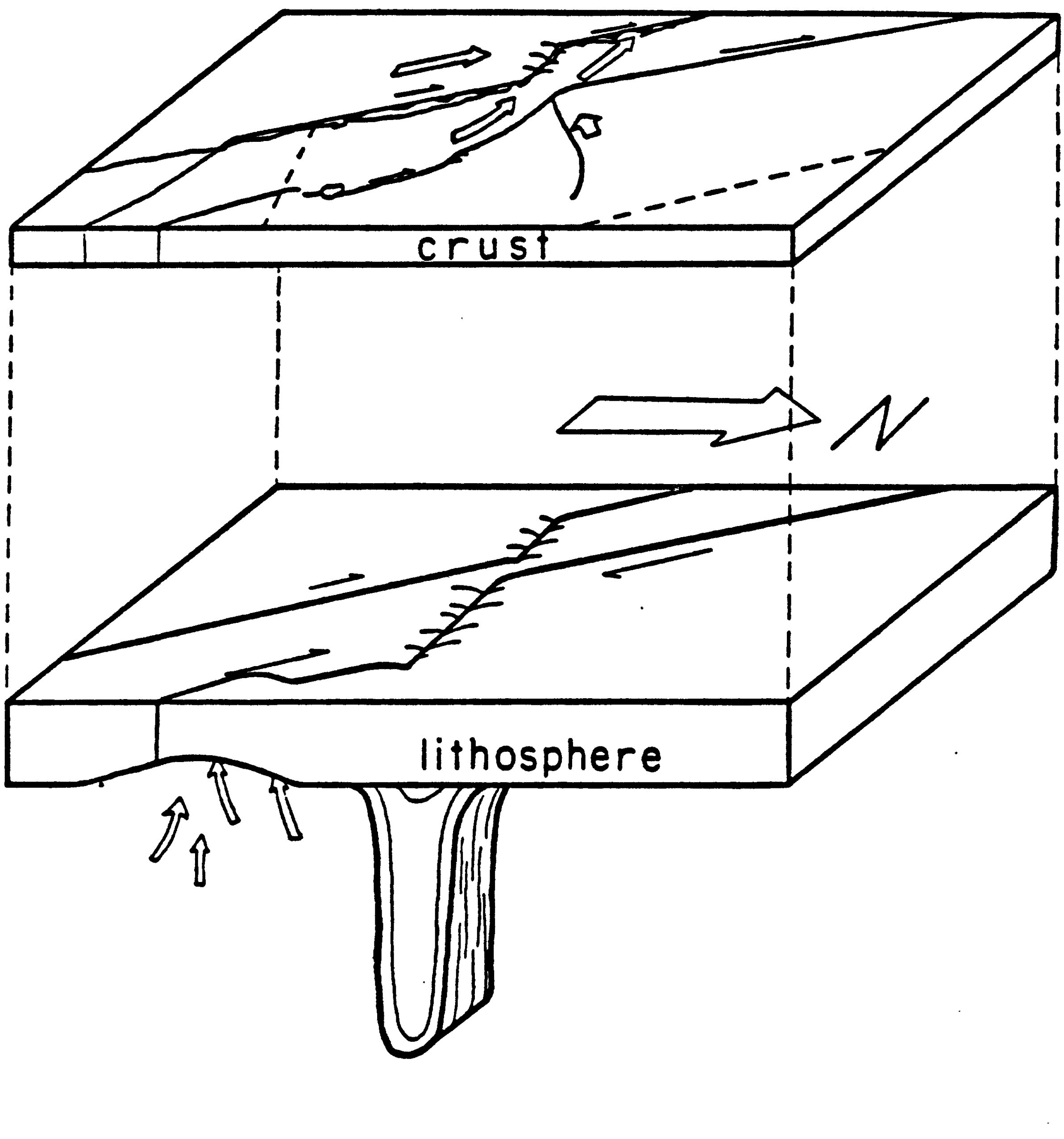

Figure 11. Simplified model of the lithospheric kinematics for southern California. The mantle lithosphere does converge in the big bend region and sinks there. Also shown is mantle upwelling and lithospheric divergence in the Salton Trough region.

3-D Velocity Structure. Magistrale [1990] has determined 3-D crustal structure in southern California from forward and inverse modelling of travel time data from about 1000 earthquakes recorded with the network. A midcrustal depth slice is shown in Figure 12 An improved 3-D crustal structure model will improve the location accuracy of earthquakes in southern California, which in turn help us to identify possible seismogenic structures in the Los Angeles basin and to assess long-term seismic potential of the area.

Attenuation Studies. Using amplitude ratios of P and S waves, details of the shear wave attenuation structure were studied in the Imperial Valley and the Coso volcanic area, two areas of anomalously high attenuation in Southern California. Walck and Clayton [1987] inverted both P and S wave travel times in the Coso Region to determine the existence of a magmatic body 3-5 km deep beneath Indian Wells Valley. This analysis included both traditional P wave tomography, but also Vp/Vs tomography which indicated the feature was magmatic rather than hydrothermal. Sanders et al. [1988], Sanders [1986] and Ho-Liu et al. [1988] used travel times and apparent attenuation of P to S wave amplitudes to map a zone of increased attenuation in the Imperial Valley at a depth of 10-12 km.

Keiti Aki and his students (Jin and Aki, 1989) have determined coda amplitude decay to map zone of low and high Q in S. Calif. The low Q zone tend to associate themselves with fault zones. There is some hope that temporal changes in Q may indicative changes in stress, possibly leading to a rupture event.

Short Period Waveforms

The Southern California Seismographic Network has one of the best collections of organized waveforms collected by a dense regional array over a large area. Although the frequency-band and dynamic range of the telemetered data is limited, there is much information to be learned from the seismograms. Recent studies have focused on ways to use the data from local events to estimate local velocity structures and earthquake source parameters. Also, waveforms from teleseismic sources recorded across the network have been used to study characteristics of the crust and upper mantle. With the increased accessibility of the well-calibrated short-period network data and availability of the broadband TERRAscope data, we expect much more use of the waveform data for local and regional studies in the near future.

Layer 5, 14 to 20 km depth

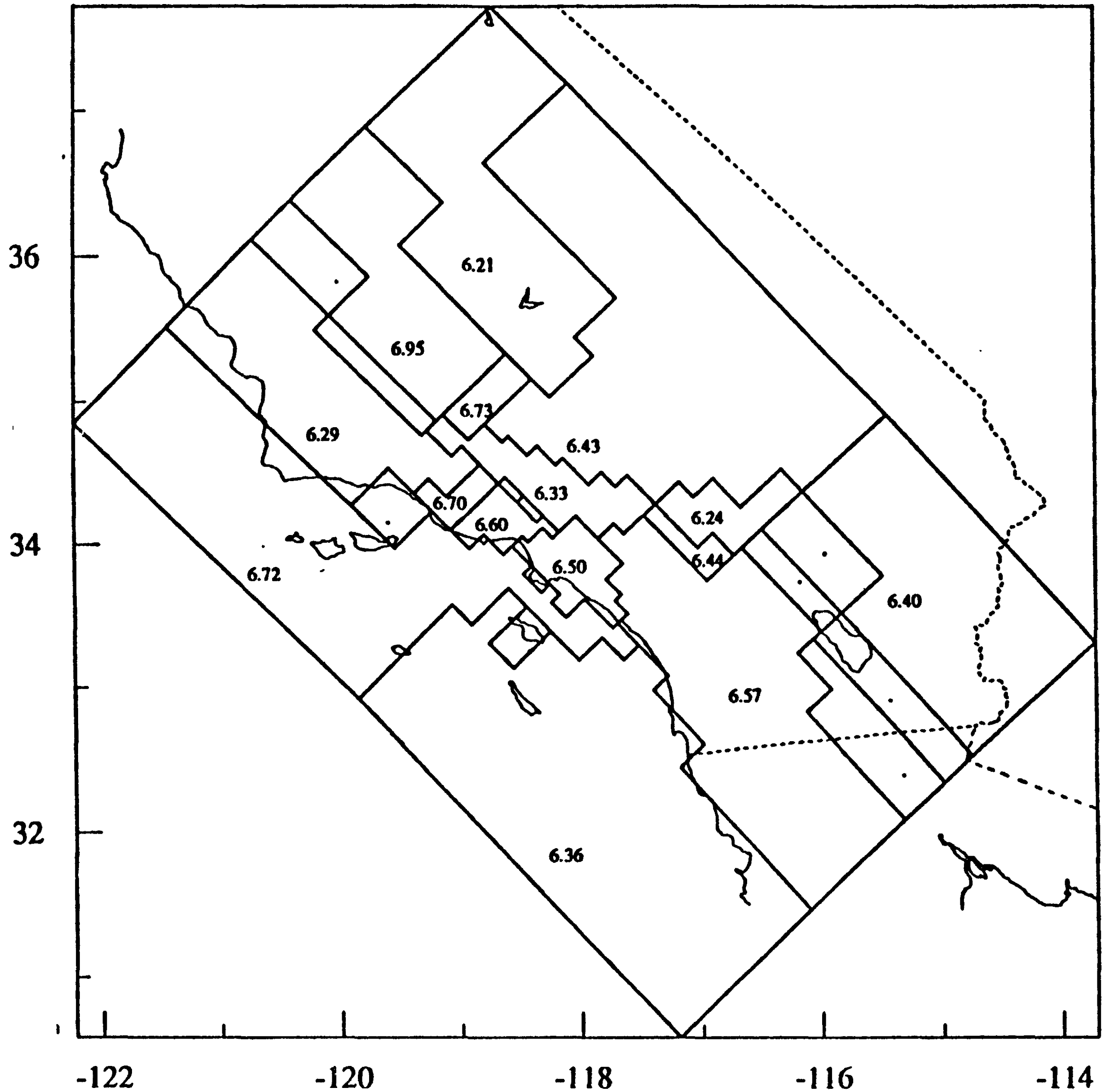

Figure 12. Results of the inversion (run with station corrections). This section represents a 14 to 20 km depth and shows P-wave velocities in km/sec in the appropriate superblock. Blocks with no velocity shown were not inverted.

Estimates of Velocity Structure and Source Depth from Multiple P-waves. P waves recorded at distances of 10 to 50 km in the Imperial Valley often show multiple (up to 3) free-surface reflections. By combining data from 40 - 50 events recorded at 4 stations, event record sections were constructed (Figure 13). Although the waveforms of individual seismograms can be difficult to interpret, these event record sections show that the multiple P waves are a coherent feature across this distance range. Event record sections for the 1987 Elmore Ranch and Superstition Hills earthquakes were modeled using synthetics for flat-layered models to estimate the local velocity structure and the earthquake source depths (Mori, 1990).

Determining Source Parameters using Empirical Green Functions. Source parameters such as moment and stress drop were determined from P waves of M 3.5 to 4.5 earthquakes that are well-recorded on the low-gain components of some of the short-period network. In general, the seismograms are quite complicated by path and site effects so that it is difficult to directly obtain source parameters from the waveforms. To separate out the path, site and instrument effects from the source, we use a small event (M 2.0 -3.0) as an empirical Green function. The waveform of the Green function event is deconvolved from the larger event, resulting in a simple waveform which is interpreted as the far-field source time pulse. An example of the deconvolution is shown in Figure 14 This procedure was used to estimate stress drops for aftershocks of the 1986 Palm Springs earthquake (Mori and Frankel, 1990). Also, this technique was used to study P waves of the 1988 Upland earthquake (M 4.6), where directivity in the waveforms was used to determine which one of focal-mechanism nodal-planes was the fault plane (Mori and Hartzell, 1990).

Attenuation Studies. The average attenuation as determined from shear-wave coda decay over regional distances in Southern California was estimated to be 280. Using the same method to compare the attenuation to the Eastern US and cratonic South Africa, Southern California was found to have significantly higher attenuation then the other two areas (Frankel et al., 1990).

Upper Mantle Structure from Teleseismic P waves. Regional and teleseismic waveforms recorded on the SCSN from events to the south from the East Pacific Rise, and from the north from events from the Alaskan Trench have been used in previous studies (Walck and Minster, 1982;

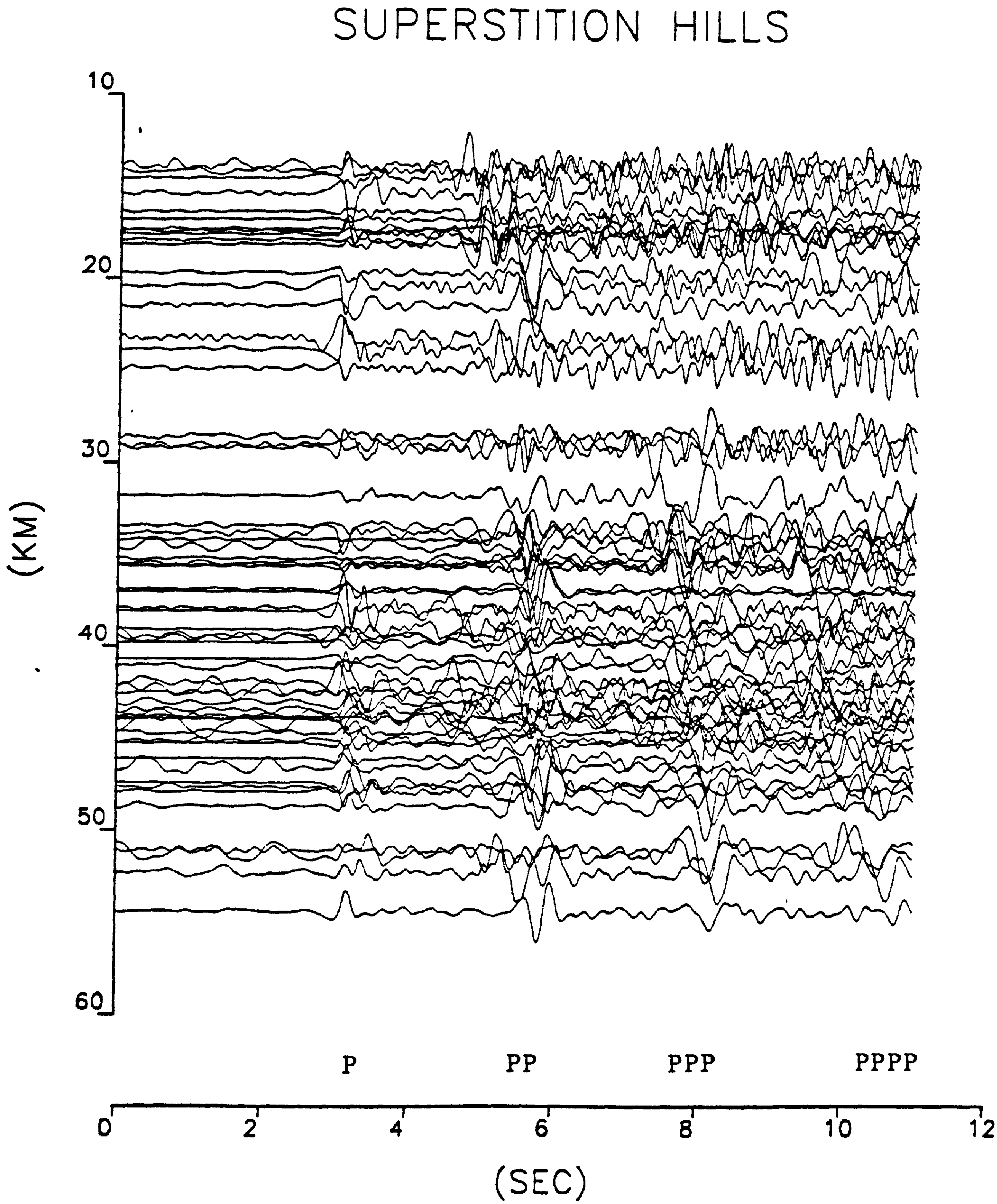

Figure 13. Event record section of P waveforms for the Superstition Hills aftershocks, recorded at the four stations. Data have been corrected to displacement and band-passed between 1 and 5 hz. Seismograms are lined up on the initial P arrival, normalized to the maximum value of each trace, and plotted as a function of epicentral distance.

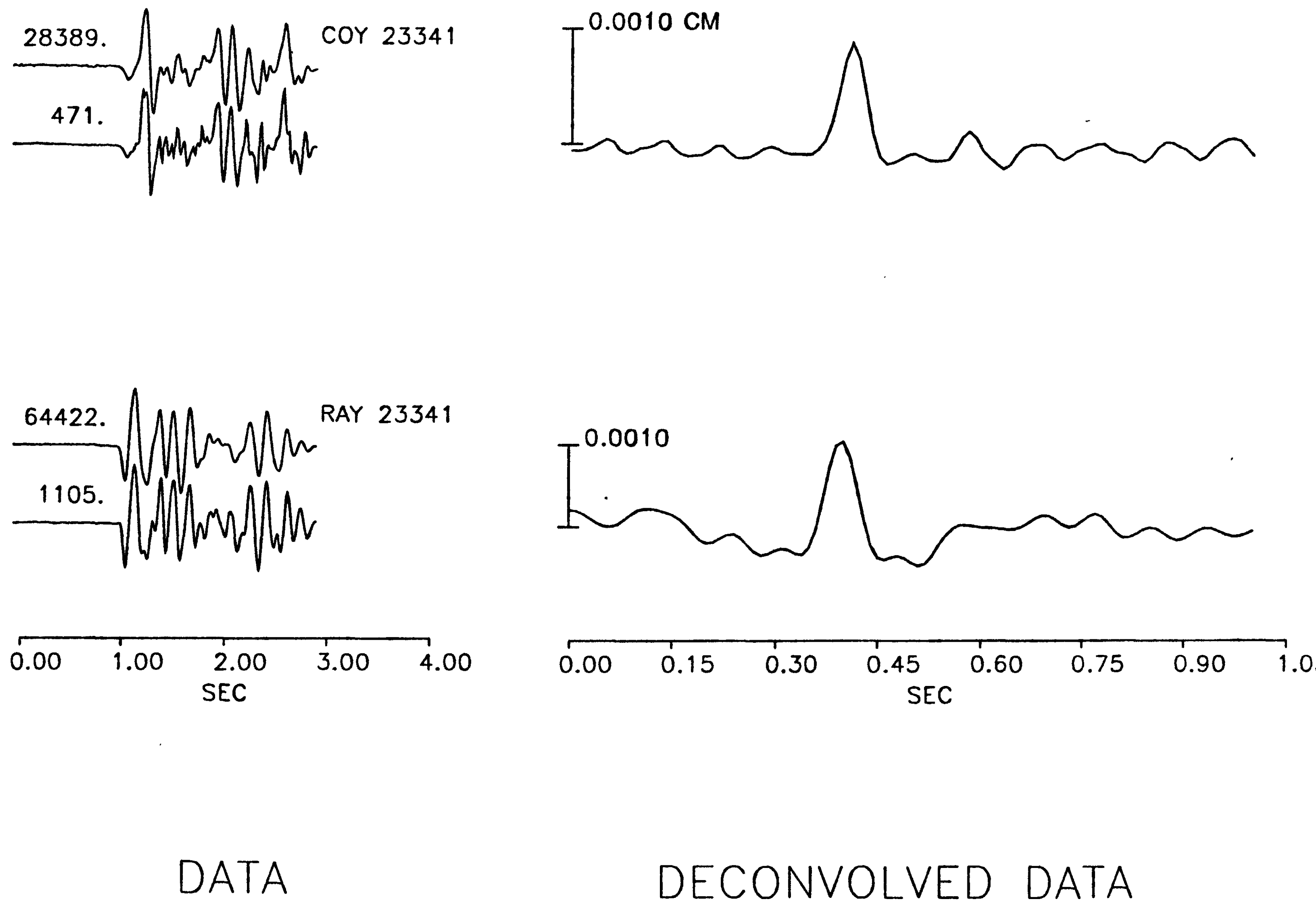

Figure 14. Data from event 23341 used to demonstrate the deconvolution method. The seismograms on the right show the P waves as recorded at stations COY and RAY. The upper trace of each pair is an M_L 3.4 event for which source parameters were determined and the lower trace is an M_L 2.1 event that was used as the empirical Green function. The numbers to the left give the relative peak amplitudes of the seismograms in digital counts. Deconvolution of the smaller event from the larger event gives the resultant displacement pulse shown on the right.

Walck and Clayton, 1987) to determine upper mantle velocity structures. At this distance range the triplications due to the 400 and 600 km discontinuities can be seen in the data. The primary difference appears to be in the strength (significance) of the 400 km discontinuity, with it being strong to the south and weak to the north. Re-examination of this data reveals no evidence for a 500-550 km discontinuity (Figure 15).

Regional Variation of Rg and Lg waves. Surface waves from large teleseismic events can be well-recorded on the short-period network stations. Although these waves do not trigger the usual event-detection system, the data can be retrieved from the continuous FM recording system. Current studies (Wald and Heaton, 1990) of 1 to 10 sec surface waves across the network show a variation of waveform and amplitude that can be correlated with some geologic features.

Earthquake Studies with Broadband Instruments

The short-period instruments of the SCSN have been a powerful research tool providing high quality locations and focal mechanisms and a dense distribution of travel times and short-period waveforms. However, especially for the larger earthquakes with lower corner frequencies the narrow band width of the instruments have been a limitation. The addition of the TERRAscope station at Pasadena has expanded the range of possible research for the SCSN.

Source Heterogeneity. Green's functions developed using the broad-band, high dynamic range seismograms recorded at Pasadena for two 1988 Upland earthquakes have been used to study the source characteristics of the February 28, 1990 Upland mainshock (M_L=5.5) [Dreger and Helmberger, 1990b]. Comparisons of the broad-band displacement and high-frequency Wood-Anderson data for the three events indicates that the 1990 mainshock was a complicated event with at least two asperities. Point source models indicate that the rupture initiated at 6 km depth and extended down-dip to 9 km depth where 29% of the moment was released. The rupture duration was 0.75 seconds. We obtain a moment estimate of $(1.7\pm0.4)\times10^{24}$ dyne-cm from the point source model (Figure 16).

Stress Drops. Recording of the 1988 Pasadena earthquake (M 4.9) on a broad-band TERRAscope station at an epicentral distance of about 3 km (15 km hypocentral distance) showed clear P, S and near-field displacement. The records could be modeled to obtain the focal mechanism and moment. The waveforms showed two subevents that were interpreted

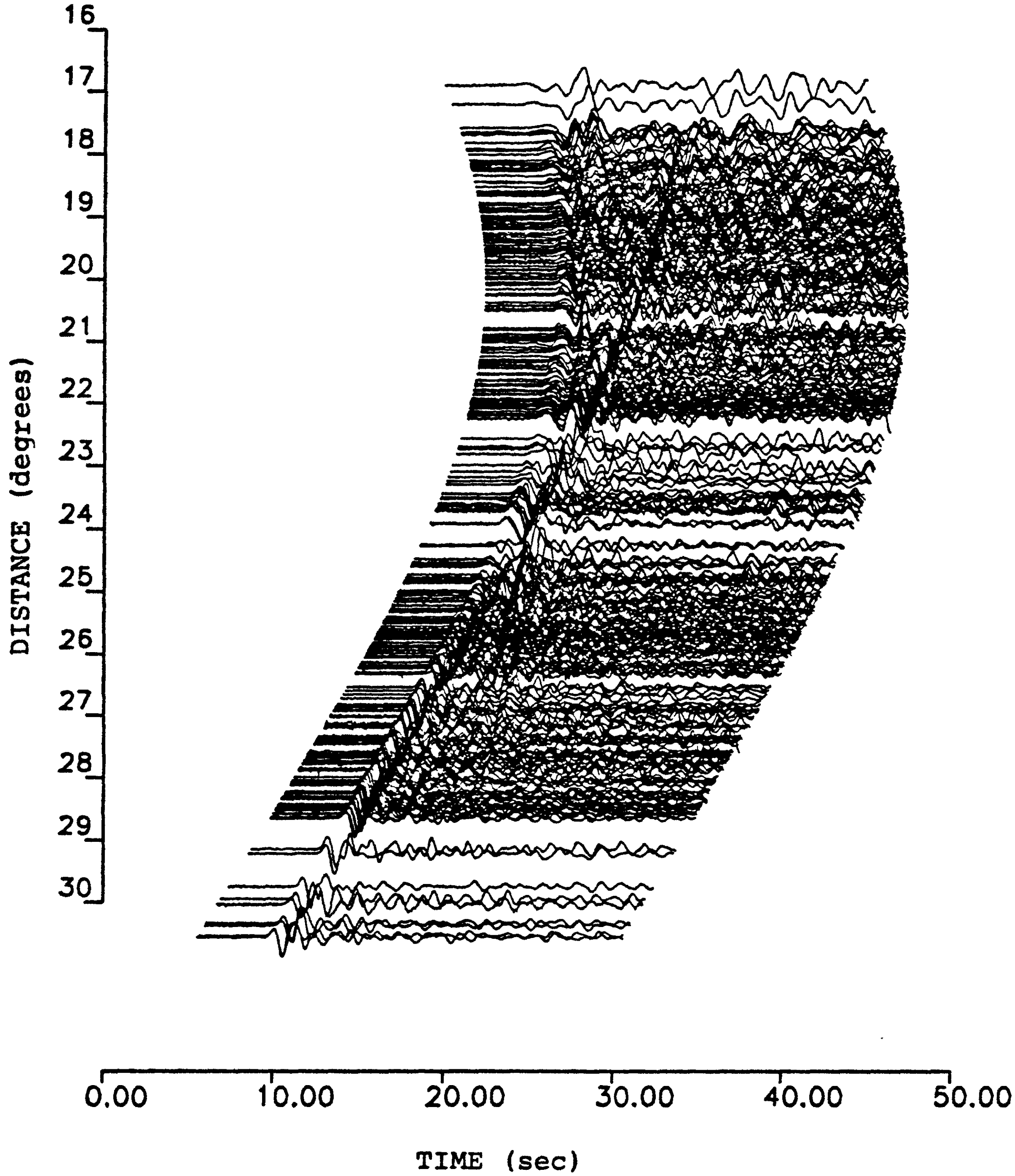

Figure 15. Record section formed by combining P-wave arrivals from 4 events in Mexico as recorded on the Southern California Seismic Network. The traces were initially lined up on the P wave arrival and then offset assuming a Herrin velocity structure. Note the triplications, caused by the 450 and 670 km upper mantle discontinuities, which have cross over points near 17 and 23 degrees, respectively.

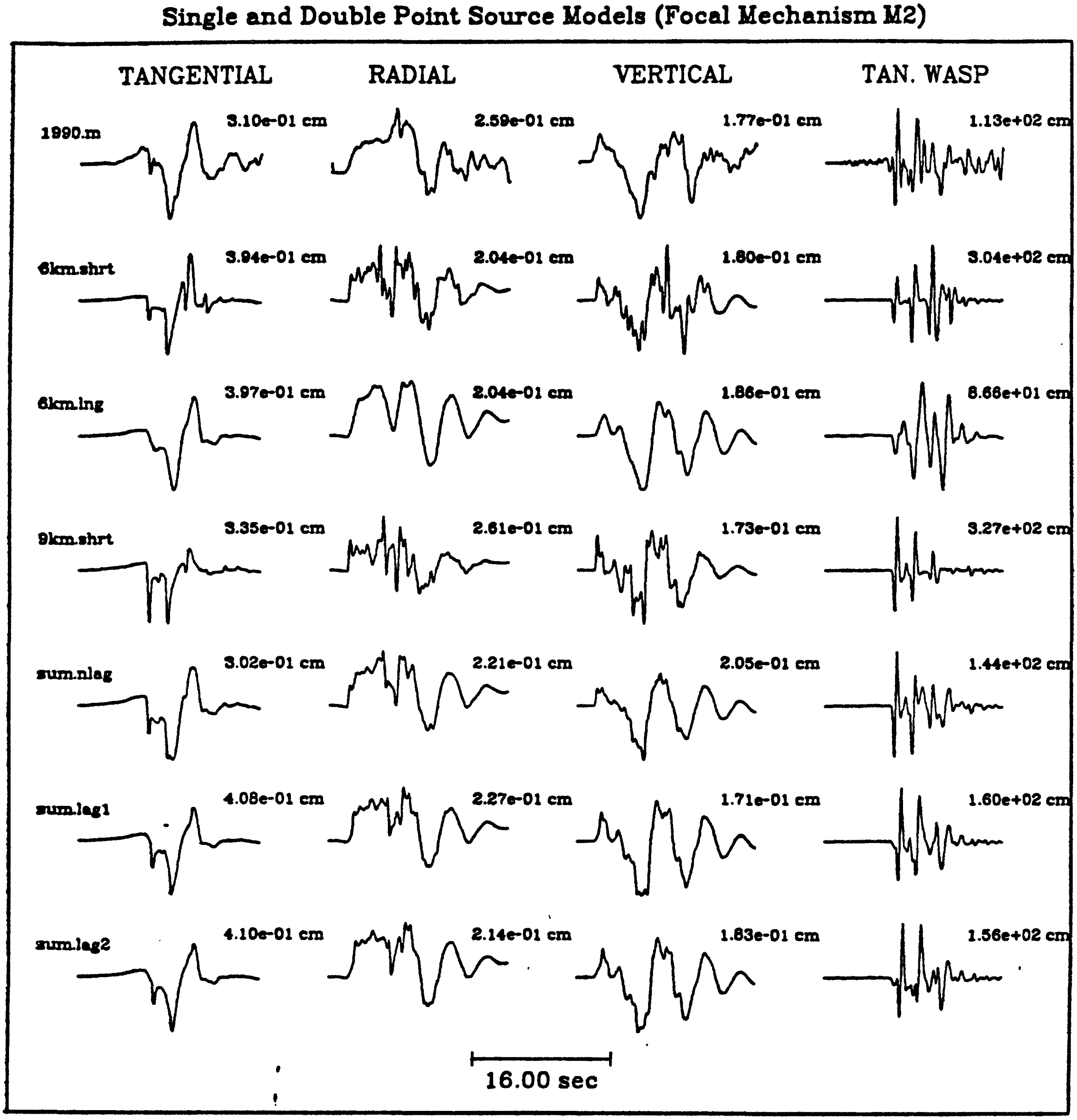

Figure 16. Three component displacement and tangential component Wood-Anderson data for the 1990 Upland mainshock, and single and double point source models (Dreger and Helmberger, 1990).

to be asperities with kilobar stress drops (Kanamori et al., 1990). Similar analysis of the aftershocks show a variety of focal mechanisms with a total moment release that is small compared to other aftershock sequences.

One of the most notable results we have obtained so far is that the stress drops of earthquakes inferred from the pulse width vary substantially from event to event. Figure 17 shows the P and SH pulses from the four larger earthquakes, the Pasadena earthquake of December 3, 1988, an earthquake in the Whittier Narrows (an aftershock of the October 1, 1987 Whittier Narrows earthquake), the Malibu earthquake of Jan. 19, 1989, and the Montebello earthquake of June 12, 1989. The three of them are about the same size (M_w=4.9), and the Montebello event is slightly smaller (M_w=3.9). However, the SH pulse width is very different between the Pasadena, Whittier Narrows, and the Malibu earthquakes. The narrow pulse of the Pasadena earthquake indicates a local stress drop of about 2 kbars. The pulse width of the Whittier Narrows aftershock is about 2.5 times wider than that of the Pasadena earthquake. For the Montebello earthquake, the SH wave is nodal but the source pulse width can be determined from the P wave. The P pulse width of this earthquake is very narrow, narrower than that of events with M_L=2.5 event at a comparable distance. These results indicate that the stress drop is very high for the Pasadena and the Montebello earthquakes, while it is low for the Malibu earthquake. The stress drop for the Whittier Narrows earthquake is intermediate between these two groups. Although these results are still preliminary, the observation that stress drops of regional events vary by almost two orders of magnitude appears well substantiated. The stress drops can be related to the strength of fault, and these results can be interpreted as indicating large variations in the strength of fault zones in southern California.

Future Directions

We expect research to continue in all the areas outlined above. In addition, we are attempting several projects to improve the quality of the data that should expand the scope of possible research projects. One of our major projects is to recover all the old data backlogs and to enter all of the old phase and amplitude data into the computer data base. Once this is done, we will relocate and redetermine magnitudes, leading to a more complete and consistent catalog that will facilitate earthquake statistic studies. We plan to emphasize long term seismicity rate changes for insight into the possible causes of the present increased rate in Los Angeles. Online phase data will also greatly facilitate all seismotectonic and tomographic studies, eliminating days or weeks of work that can be involved in assembling a data set for a particular study.

Comparison of Pulse Width for 3 "M=5" Earthquakes

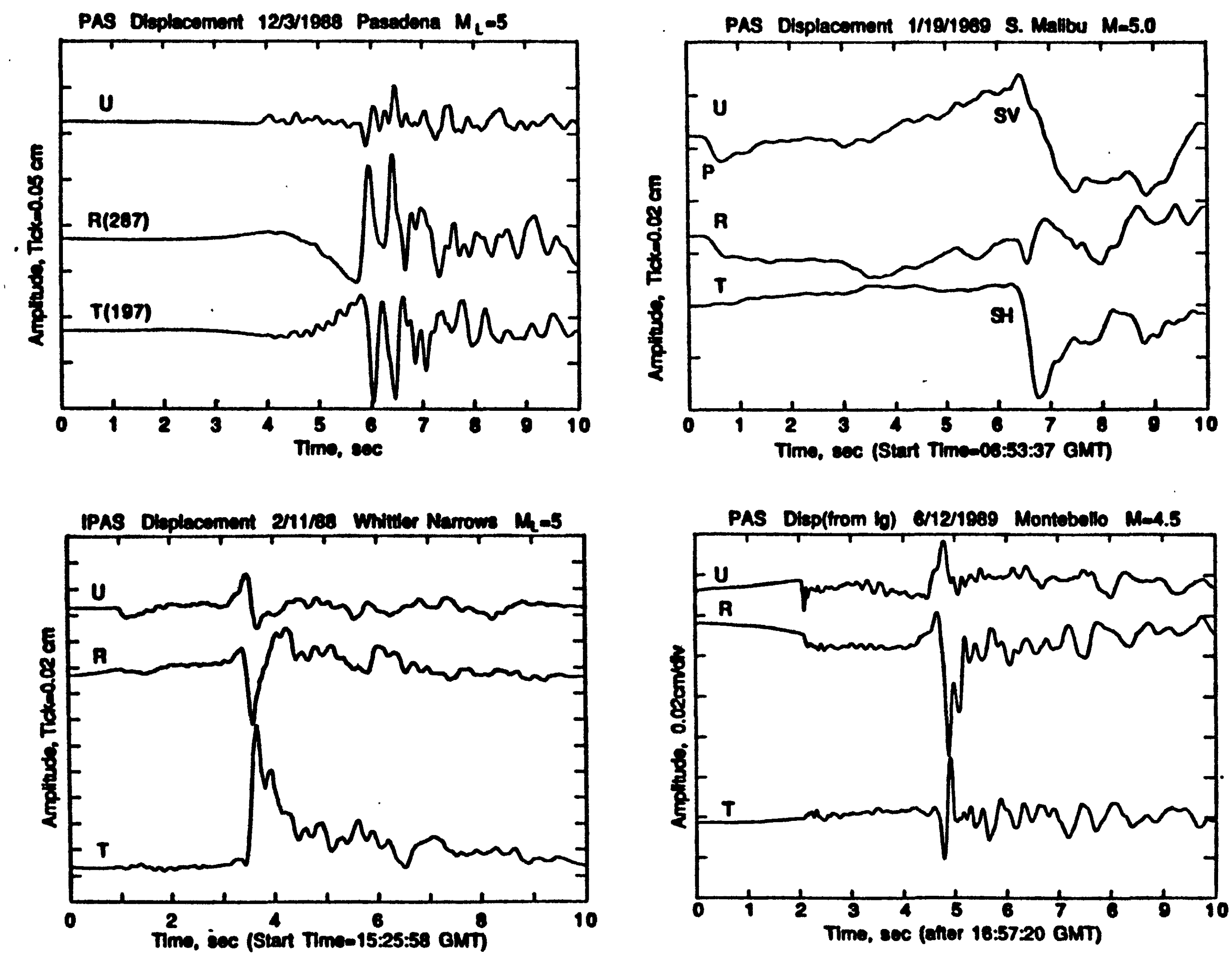

Figure 17. Comparison of pulse width for four M=5 earthquakes in the Los Angeles area.

The improvements in the quality and accessibility of short-period and broad band waveforms should greatly increase the research possible with the SCSN. With four broad band stations installed by the end of the year, the short-period and broad band systems should complement each other and lead to a range of new projects. The short period system, with 220 sites, provides a great density and extensive spatial coverage for examining spatial variations. The broad band system with large frequency and dynamic ranges will allow more detailed studies and greater use of teleseismic waveforms. In addition, we will complement the network with portable broadband instruments. The use of portable instruments will give flexibility to the research programs using the TERRAscope. Planned projects include standard dispersion studies and numerical waveform modelling of regional and teleseismic surface waves for local structure, analysis of the phases PmP and SmP, which are primary reflections from the Moho to map the lateral continuity and depth of this important interface analysis of detailed travel time observations in specific regions to determine local structure.

Need for Improved Instrumentation

As the accessibility of SCSN data has improved over the last decade, research using the data has expanded accordingly. However, the level of funding has stayed the same (and thus has decreased substantially in real dollars) over the same time. The network has continued to operate but improvements have not been possible and several aspects of network operations have suffered. We see several areas in which increased funding would significantly improve the quality of data and our ability to fulfill the objectives of the network. The following recommendations are preliminary and priorities would depend on the availability of funds.

Real-time Analysis. At present, only a small subset of data is easily available in real-time from the Southern California Seismographic Network. A 64-channel real-time processor (RTP) is now used to determine real-time earthquake locations and magnitudes. Because signals from only 64 of the 220 stations (289 channels) are being used to determine the locations, so that depths cannot be determined accurately; focal mechanisms are unreliable or indeterminate; and the location errors of the epicenters are large. The hardware is old and the system is maintained from Menlo Park, leading to delays when repairs are needed.

Recommendation 1: Upgrade the real-time earthquake processing capability for southern California from 64 to all 289 channels of seismic data. This should preferably be done through software on the online data acquisition computer that can be maintained and upgraded by local personnel.

Data Access. Continued upgrading of both on-line and off-line software is needed to ensure the quality of data being produced. Software also needs to be developed and maintained to record the TERRAscope data and to improve research access to the short-period data. Old phase data (1930-1960) need to be entered into a computer to make it possible to improve the quality of both locations and magnitudes in the catalog. Data processing gaps in the data collected from 1975-1983 need to be closed. Some outside requests for data must be declined because of insufficient manpower to fulfill them.

Recommendation 2: Two full time computer programers (one with USGS and one with Caltech) should be hired. Two additional full-time data analysts at Caltech are needed to close data gaps and enter old data into the computer and help with outside requests for data.

Central Recording. The off-line data processing and the scientific research by USGS personnel is done using two 10-year-old VAX11/750 computers. The real-time recording of 289 channels is done with a MicroVax 3200 that is 6 months old. Presently it is performing well, but it needs to have its memory upgraded from 16 Mbytes to 32 Mbytes. This memory upgrade would allow continued development of software for improved real-time locations and separate detection of teleseisms. The backup real-time data recording is done with a 20-year-old PDP11/34 that is very expensive to maintain. Interactive timing of the earthquakes is done on two 20-year-old Tektronics graphics terminals with hand wired high speed graphics boards.

Recommendation 3. Replace two VAX11/750 (one operated by Caltech and the other by the USGS Pasadena office) with one VAX4000 computer to provide computer power for both off-line processing and scientific research. Add one more VAX 3200 with 32 Mbytes of memory and 2 Giga bytes of disk space for backup recording to replace the PDP11/34. Add 3 VAX3100 workstations for interactive analysis of seismograms.

Telemetry Cost. We have installed one microwave trunk-line that brings signals from east of the Sierra Nevada through Edwards Air Force Base to Pasadena. This has saved significant telemetry costs. However, less than half of the network stations are transmitted through the microwave system. The telemetry system is 20 years old.

Recommendation 4: Two new microwave links, one extending down to Imperial Valley and a second extending to Santa Barbara would realize significant additional savings in telemetry cost. The process of switching the telemetry system to modern digital telemetry should be begun.

Remote Sites. Equipment such as seismometers, VCOs and radios at about 30-50% of the 220 remote sites is old and requires extensive maintenance. Some of the old VCOs do not have calibration capability. Most of the stations have only high gain vertical seismometers.

Recommendation 5: Old VCO's, old seismometers and radios that are unreliable should be replaced to make the instrumentation and calibration procedures uniform. More three-component and lower gain seismometers should be installed.

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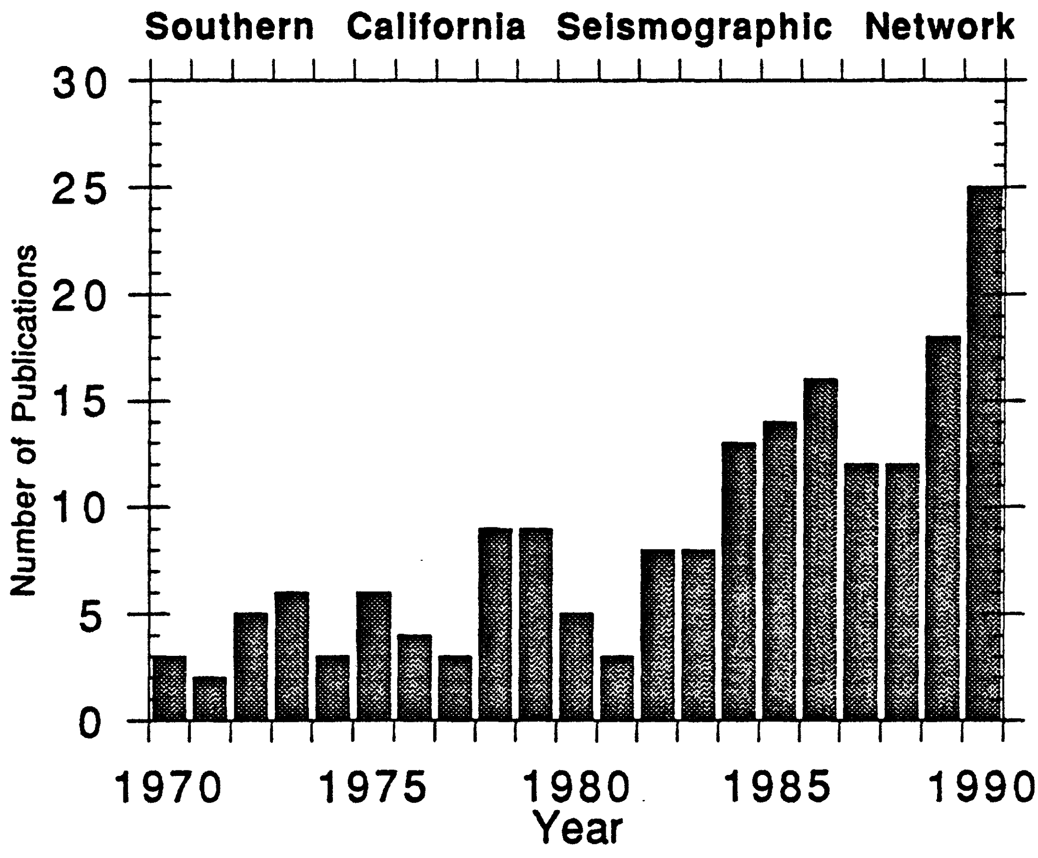
Appendix A

List of Publications, 1970-1990, Excluding Abstracts.



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Appendix B

Weekly Fax Distribution List of Data, Illustrating How Network Data is being Distributed in a Timely Fashion to Emergency Response Agencies and Other Users.

<u>DAY FAX</u>:

Dick Andrews, OES	714-391-3984
Claudia, CDMG	916-324-1396
Bill Bakun, USGS	8-459-5163
Rob Wesson, USGS	8-959-6717
Jim Davis, CDMG	916-445-5718
SCEPP	818-795-2030
David Garcia, KNBC	818-840-3535

<u>NIGHT FAX:</u>

Ed Kiessling, CDMG	213-628-3691
City News Service	213-465-7236
Marty Stephens, L.A. Times	213-237-7190
Claes Andreasson (writer)	818-799-6784
Rick Hazlett, Pomona Col.	714-621-8403
Duncan Agnew, UCSD	619-534-5332
Doug Morton, UCR	714-787-4324
Kei Aki, USC	213-747-2015
Dave Jackson, UCLA	213-825-2779
Dick Kerr, Science Magazine	202-682-0816
Ray Weldon, Univ of Oregon	503-346-4692
Mike or Greg, Ch. 39	619-279-1076
R. Monastersky, Science News	202-785-2527
Craig Weaver, UW	206-442-8350
LA Fire Dept., Disaster Div.	213-485-9884
Phil Van Horn, Pac Bell	714-739-3401

Appendix C

Monthly Distribution List of Data, CIT/Caltech, Illustrating the Use of the Network Data by the Public.

APPENDIX C: Monthly distribution list for catalog data.

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4. Dr. Paul C. Jennings, California Institute of Technology
5. Dr. Greg Lyzenga, Jet Propulsion Laboratory
6. Douglas Smith, California Institute of Technology
7. Dr. Jason Saleeby, California Institute of Technology
8. Dr. Kerry E. Sieh, California Institute of Technology
9. Randy Sear, Solar Physics, California Institute of Technology
10. Steven Vass, California Institute of Technology

11. Lorryn Abbott, Escondido, CA
12. Arturo Aburto, Seismological Laboratory, University of Nevada, Reno NV
13. Dan Eberle, Director, Office of Disaster Preparedness, San Diego CA
14. Marsha Adams,Time Research Institute,Woodside, CA
15. Lyn Adelstein, Altadena, CA
16. Duncan Agnew, Univ. of Calif., San Diego, La Jolla, CA
17. D. Aguilera, Yorba Linda, CA
18. Dr. Keiiti Aki, University of Southern California, Los Angeles, CA
19. Jose Alonso, South El Monte, CA
20. American Geotechnical, Anaheim, CA
21. Mr. David Anderson,Woodland Hills, CA
22. Phil Anderson,Walnut, CA
23 Anza Valley Outlook, Anza, CA
24. James Artherton, Nichols Research Corporation, Newport Beach, CA
25. Dennis Ashley, Southern California Edison, Orange, CA
26. Rod Ballard, Escondido, CA
27. James Beene, Grand Marque Ltd., Export, PA
28. Geology Library, Bechtel, Inc. , San Francisco, CA
29. Mike Belmonte, Baltimore, Ohio
30. Jim Berkland, County Geologist, San Jose, CA
31. Ralph K. Jeffery, American Geotechnical, San Diego CA
32. Gregg E. Brandow, Los Angeles, CA
33. Sue Troup, Hughes Laboratories, Malibu, CA
34. Dale Brown, McDonald Douglas, Huntington Beach, CA
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36. Mr. John C. Burton, San Diego Gas & Electric Co., San Diego, CA
37. Calif. Dept. of Transportation, Sacramento, CA
38. Library, Calif. Div. of Mines & Geology, Sacramento, CA
39. C. Hallstrom, Calif. Div. of Mines & Geology, Sacramento, CA
40. Calif. Div. of Mines & Geology, Los Angeles, CA
41. J. A. Ryan, Calif. State University, Fullerton, CA
42. David Kessler, EQ Engineering, Water Resources, Sacramento, CA
43. Cal State L.A., Geology Department, Los Angeles, CA
44. Mr. William Campbell, Woodland Hills, CA
45. David Castillo, Geophysics, Stanford Univ., Stanford, CA
46. David K. Cecil, Factory Mutual Eng. Assoc., Orange, CA
47. Lloyd S. Cluff, Geosciences Dept., P G & E, San Francisco, CA
48. Peter Cooper, Sherman Oaks, CA
49. Edward J. Corbett, Reno, NV
50. Cristy Craig Hunter, Division of Oil and Gas, El Centro, CA

51. Bill Cumming, Unocal Geothermal, Indio, CA
52. The Earth Technology Corporation, Inc., Long Beach, CA
53. C. B. Crouse, Project Engineer, Dames and Moore, Seattle, WA
54. Dames and Moore, Library, Los Angeles, CA
55. Dames and Moore, Ms. Eugenia Sangines, San Diego CA
56. Decoma Industries, Mr. Steve Notaro, Los Angeles, CA
57. Disaster Preparedness Spec., Naval Air Station, Pt. Magu, CA
58. Earthquake Engineering Research Center, Library, Univ. of Calif., Richmond, CA
59. Yutaka Abe, Earthqk. Res. Inst., Tokyo Univ.,Tokyo, JAPAN
60. Eberhart & Stone Inc., Attn: R. Gregorek, Orange, CA
61. Paul Edie, Hughes Aircraft, Ground Systems Group, Fullerton, CA
62. Michael Ellis, MacKay School of Mines, Reno, NV
63. William J. Elliott, Solana Beach, CA
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66. Carl Faris, La Crescenta, CA
67. Ms. Carolita Feiring, The Press-Enterprise, Riverside, CA
68. Jim Fisher, Woodland Hills, CA
69. Ms. Sharon Frank, City of Santa Ana Fire Department, Santa Ana, CA
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72. John Gaffey, Irvine, CA
73. James Gallagher, San Mateo, California
74. Eric Chael, Sandia National Labs, Albuquerque, NM
75. James Gates, Division of Structures, Sacramento, CA
76. Sam Gazdik, Oakland, CA
77. Geotechnical Exploration Inc., San Diego, CA
78. Grover-Hollingsworth & Assoc., Westlake Village, CA
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83. Karen Guidi, Ventura Co. Office of Emer. Serv.,Ventura, CA
84. Micki Hall, Riverside, CA
85. Dr. Walter Haenggi, Dow Chemical U.S.A., Houston, TX
86. Tom Hall, Raymond Company, Orange, CA
87. Dr. Tom Hanks, U.S. Geological Survey, Menlo Park, CA
88. Dr. Tom Hartnett, Sci. & Tech. Dept., Santa Ana College, Santa Ana, CA
89. Patty Shea, Geology Department, Pasadena City College, Pasadena, CA
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100. Mark Johnson, Orange Co Emergency Mgmt. Div., Orange, CA
101. Tom Johnson, Palm Springs Desert Museum, Palm Springs, CA
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119. Gordon Lewis, Desert Water Agency, Palm Springs, CA
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Appendix D

Summary of Southern San Andreas Report, Illustrating Ongoing Earthquake Hazard Assessment Efforts.

8/1/90

Short-Term Earthquake Alerts for the Southern San Andreas Fault

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Mark Ghilarducci[5], Bradford Hager[2,6], Egill Hauksson[7,8]
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Executive Summary

The historically dormant southernmost 200 km of the San Andreas fault (from Cajon Pass, northwest of San Bernardino, southeast to Bombay Beach on the Salton Sea) is the segment most likely to produce an earthquake of magnitude 7.5 or greater within the near future. Such an earthquake would cause widespread damage in San Bernardino, Imperial, Riverside, Orange and Los Angeles counties, which together have over 12 million inhabitants. If anomalous earthquake or other geophysical activity were to occur near the southern San Andreas fault, scientists would be expected to advise government officials on the likelihood that a major earthquake is forthcoming. The primary purpose of this report is to present a system for quantifying and communicating information about short term increases in the earthquake hazard from the southern San Andreas fault.

We use a system of four alert levels (A, B, C and D) similar to that adopted for the Parkfield earthquake prediction experiment in central California. The alert levels are defined so that the responses of the U. S. Geological Survey (USGS) will be similar to those defined for the Parkfield experiment. The probabilities that the predicted earthquake will occur within the 72 hours of the alerts are comparable to the probabilities defined for the alerts at Parkfield, but the criteria for reaching each alert level necessarily differ from those at Parkfield. The defined alert levels are:

Alert level	Response	Probability of M>7.5 earthquake in next 72 hours	Anticipated interval between alerts
D	Alert scientists involved in data collection and OES in Ontario	0.1 to 1%	6 months
C	Alert Communications Officer of OES in Sacramento, OEVE chief and response for Level-D	1 to 5%	5 years
B	Alert Director USGS, Calif. State Geologist, CDMG, start intensive monitoring and response for Level-C	5 to 25%	28 years
A	Issue Geologic Hazards Warning and response for Level-B	>25%	Not attainable at this time

The alert levels can be triggered by earthquakes, creep events (rapid aseismic surficial slip on faults) and strain events (anomalous deformation of the crust).

Our alert system is based primarily upon the observation that half of magnitude 5.0 or greater strike-slip earthquakes in California have been preceded by immediate foreshocks (defined as earthquakes within 3 days and 10 km of the mainshock). Therefore, the next major earthquake produced by the southern San Andreas could well be preceded by one or more foreshocks. This report describes a method for estimating the probability of the next major earthquake, given the occurrence of a possible foreshock. To be considered a possible foreshock, the rupture zone of the earthquake must come within 10 km of the southern San Andreas fault. The table below gives the magnitude of possible foreshock needed to reach a specified probability (or alert level) for four microseismic regions of the southern San Andreas fault.

Alert level Probability of M7.5 in 72 hr	B 5-25%	C 1-5%	D 0.1-1%
San Bernardino	5.8	5.0	3.9
San Gorgonio	6.1	5.3	4.2
Palm Springs	5.2	4.5	3.4
Mecca Hills	4.9	4.2	3.1

Anomalous creep and strain episodes are also possible precursors to the next major earthquake along the southern 200 km of the San Andreas fault. Exact probabilities cannot be calculated for these possible strain precursors, because the data are inadequate to quantify the relationship between precursory slip or strain and large earthquakes. Moreover, unlike Parkfield where several types of strain and creep meters are densely arrayed along the fault, only one strainmeter and four creepmeters are deployed near the southern San Andreas fault. Therefore, only one alert level is defined for strain and aseismic slip; this is arbitrarily set equal to the lowest level (D) seismic alert. The threshold for producing such an alert is an amount of aseismic slip or strain unprecedented in the history of recording along the southern San Andreas fault.

The reliability of any short-term alert is limited by inadequacies in the data now being recorded along the southern San Andreas fault. For example, continuous measurements of ground deformation are limited to one strainmeter and four creepmeters. Because seismic stations are sparsely distributed and the automatic processing rudimentary, the depth and rupture size of most earthquake sources cannot be resolved, earthquakes above about magnitude 3.5 are not recorded on scale, and their spectral characteristics cannot be determined properly. Furthermore, the available data are not all recorded in one place. Therefore, this report recommends improvements in data management, instrumentation, and research that would increase the ability of scientists to issue a short-term warning for a great southern California earthquake. We should:

Implement centralized recording and analysis. A chief scientist for the southern San Andreas fault should be appointed and supported by the chief of the Office of Earthquakes, Volcanoes and Engineering (USGS) with the authority to issue the warnings described here. Deformation data now available from southern California should be given in real time to the Pasadena office of the USGS and Caltech to be evaluated together with the seismic data. Such evaluation will be an assigned task of the Pasadena office of the USGS and the Seismological Laboratory;

Improve seismic data. Expand the real-time earthquake analysis system to cover all the existing seismic network, add procedures for quickly estimating the magnitudes of large earthquakes, and improve the quality and quantity of seismic stations along the southern San Andreas fault.

Improve creep and strain data. An increased number of telemetered creepmeters along the southern San Andreas fault and auxiliary faults would enhance the evaluation of possible precursors. Additional deformation measurements would also be desirable, but will require careful planning. We suggest that a group of university and USGS scientists develop such a plan.

Improve our fundamental understanding of the fault. Better data would improve our ability to issue short-term warnings, as would a better understanding of the behavior of the fault. We therefore recommend that additional geodetic, paleoseismic, and seismologic research be undertaken to better understand the nature of the fault zone.

Appendix E

List of Recent Bulletins that Contain Detailed Information about the SCSN Data.

Hileman, J. A., C. R. Allen, and J. M. Nordquist, Seismicity of the southern California region, 1 January 1932 to 31 December 1972, pp., Seismology Laboratory, California Institute of Technology,, Pasadena, 1973.

Friedman, M. E., J. H. Whitcomb, C. R. Allen, and J. A. Hileman, Seismicity of the Southern California Region; 1 January 1972 to 31 December 1974, pp., Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 1976.

Fuis, G. S., M. E. Friedman, and J. A. Hileman, Preliminary Catalog of Earthquakes in Southern California, July 1974 - September 1976, U. S. Geol. Surv. Open File Rep. 77-181, pp., 1977.

Hutton, L. K., C. R. Allen, and C. E. Johnson, Seismicity of Southern California; Earthquakes of ML 3.0 and Greater, 1975 through 1983., pp., Seismological Laboratory, California Insitute of Technology, Pasadena, CA, 1985.

Norris, R., C. Johnson, L. Jones, and L. K. Hutton, The Southern California Network Bulletin, January-June, 1985, Open-File Report 86-96, U. S. Geological Survey, Pasadena, 46, 1986.

Norris, R., L. M. Jones, and L. K. Hutton, The Southern California Network Bulletin, July-December, 1985, Open-File Report 86-337, U. S. Geological Survey, Pasadena, 26, 1986.

Given, D. D., R. Norris, L. M. Jones, L. K. Hutton, C. E. Johnson, and S. Hartzell, The Southern California Network Bulletin, January through June, 1986, Open-File Report 86-598, U. S. Geological Survey, Pasadena, 28, 1986.

Given, D. D., L. K. Hutton, and L. M. Jones, The Southern California Network Bulletin, July - December, 1986, Open-File Report 87-488, Pasadena, 43, 1987.

Given, D. D., L. K. Hutton, L. A. Stach, and L. M. Jones, The Southern California Network Bulletin, January - June, 1987, Open-File Report 88-409, U. S. Geological Survey, Pasadena, 45, 1988.

Given, D. D., L. A. Wald, L. M. Jones, and L. K. Hutton, The Southern California Network Bulletin, July - December 1987, Open-FIle Report 89-323, U. S. Geological Survey, Pasadena, 37, 1989.

Wald, L. A., D. D. Given, J. Mori, L. M. Jones, and L. K. Hutton, The Southern California Network Bulletin, January-December, 1988, Open-File Report 90-XXX, U. S. Geological Survey, Pasadena, 48, 1989.

Wald, L. A., D. D. Given, J. Mori, L. M. Jones, and L. K. Hutton, The Southern California Network Bulletin, January-December, 1989, Open-File Report 90-XXX, U. S. Geological Survey, Pasadena, xx, 1990.