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THE SOUTHERN CALIFORNIA NETWORK BULLETIN JULY — DECEMBER, 1987

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INTRODUCTION

The California Institute of Technology together with the Pasadena Office of the U.S. Geological Survey operates a network of approximately 250 remote seismometers in southern California. Signals from these sites are telemetered to the central processing site at the Caltech Seismological Laboratory in Pasadena. These signals are continuously monitored by computers that detect and record thousands of earthquakes each year. Phase arrival times for these events are picked by human analysts and archived along with digital seismograms. All data aquisition, processing and archiving is achieved using the CUSP system. These data are used to compile the *Southern California Catalog of Earthquakes*; a list beginning in 1932 that currently contains more than 160,000 events. This data set is critical to the evaluation of earthquake hazard in California and to the advancement of geoscience as a whole.

This and previous Network Bulletins are intended to serve several purposes. The most important goal is to make Network data more accessible to current and potential users. It is also important to document the details of Network operation, because only with a full understanding of the process by which the data are produced can researchers use the data responsibly.

NETWORK CONFIGURATION

New Stations. Several new sites have been added since publication of the last Network Bulletin. As in past Bulletins reports of network changes are not restricted to those that occured during the reporting period but are as current as possible. An explanation of the conventions used for full station codes can be found in Given *et al.* (1987).

In addition to the new sites listed below, plans are underway to telemeter TIN and CWC, two long established sites in Owen's Valley. One or more new sites may also be added in that area.

A new broad-band, high dynamic range site is planned for the vicinity of the new Seven Oaks dam being contructed north of Redlands by the U. S. Army Corps of Engineers. Its design will be very similar to the new Streckeisen that has been installed in Pasadena (see below).

BRA A new site has been instrumented with a short-period vertical seismometer and a triaxial force-balance accelerometer (FBA) in the Imperial Valley. It is located in the office of Unocal Geothermal in the town of Brawley. Because of the high noise level at this location the attenuation of the short-period seismometer is set to 36 db.

Site name:	Brawley	
Latitude:	32° 58.73′ N	(32.9788°)
Longitude:	115° 32.94′ W	(115.5490°)
Elevation:	-33 m	(-108 ft.)
Date installed:	September 15, 1988	

Full Code	Inst.	Orientation
BRACV	L4	vertical
BRACI	FBA	vertical
BRACJ	FBA	north/south
BRACK	FBA	east/west

LUC A new short-period vertical instrument was installed at an existing radio receive site in the Lucerne Valley. This site will help fill a gap left when the Round Mountain (RDM) site was removed on April 20, 1982.

Site name:	Lucerne Valley	
Latitude:	34° 27.29′ N	(34.4548°)
Longitude:	116° 58.79′ W	(116.9798°)
Elevation:	886 m	(2907 ft.)
Date installed:	April 19, 1988	

Full Code	Inst.	Orientation
LUCCV	L4	vertical

PAS (VBB) A Streckeisen very-broad-band digital seismometer was installed at Kresge Laboratory in Pasadena, California in December, 1987. This instrument provides seismic data over a large amplitude and frequency range with a flat velocity response within most of this range. The high dynamic range produces high quality recordings of events ranging from local microearthquakes to teleseisms and free oscillations. The latitude, longitude and elevation are the same as all other instruments at the PAS site.

Site name:	Pasadena (VBB)	
Latitude:	34° 8.95′ N	(34.1492°)
Longitude:	118° 10.29′ W	(118.1715°)
Elevation:	308 m	(1010 ft.)
Date installed:	December, 1988	

Full Code	Inst.	Orientation
PASC1	Streckeisen	vertical
PASC2	Streckeisen	north/south
PASC3	Streckeisen	east/west

The system is made up of a Streckeisen STS-1/VBB three-component very-broad-band sensor set, a three-component set of 24-bit Quantagrator digitizers, and a VME-Bus 68020/68881-based computer. The software provides real-time acquisition of 24-bit VBB data, real-time digital filtration, and remote access to data buffered by the system. Data are recorded at 20 samples/second. In addition to the Streckeisen seismometer, low gain strong ground acceleration is recorded from a three-component Kinemetrics FBA-23. Table 1lists the five data types produced by the Pasadena broad band system and the calibration for each channel.

■ **Table 1. Pasadena Very-Broad-Band Components**

		Band	Sample Rate *samples/sec*	Calibration *counts/m/sec*^{2}
LG (FBA)	–	low-gain	100	3.74×10^3
VBB	–	very broad band	20	1.04×10^9
LP	–	long period	1	4.16×10^9
VLP	–	very long period	0.1	1.66×10^{10}
ULP	–	ultra long period	0.01	6.64×10^{10}

Data are stored in two random access buffers on Winchester disks. The first contains data for events that trigger the detection system. Triggered events are stored for two to three months before they are overwritten by new data. The second buffer holds a continuous record of all seismic data for about two to three days before being overwritten. In addition, all seismic data are continuously recorded on 120Mb cartridge tapes which hold approximately three weeks of data. Those tapes are sent routinely to Albuquerque where the data are integrated into the national data set and made available on the Day Tapes.

These data can be accessed over telephone lines using the on-line data retrieval system developed by Joseph Steim. This is the same system that is used on similar equipment at Harvard, Albuquerque and Hawaii. The phone number of the Pasadena system is (818) 795-6415. The username is "VBB" and the password is "DATA".

This instrument and its recording system are funded by the California Institute of Technology, the University of Southern California, the U.S. Geological Survey, and the Incorporated Research Institutions for Seismology (IRIS). It is maintained by the Pasadena office of the U.S.G.S.

<u>SBP</u> A short-period vertical seismometer and a triaxial force-balance accelerometer (FBA) has been installed at the microwave telemetry relay site on Strawberry Peak in the San Bernardino Mountains.

Site name:	Strawberry Peak	
Latitude:	34° 13.93′ N	(34.2322°)
Longitude:	117° 14.09′ W	(117.2348°)
Elevation:	1872 m	(6142 ft.)
Date installed:	October 18, 1988	

Full Code	Inst.	Orientation
SBPCV	L4	vertical
SBPCI	FBA	vertical
SBPCJ	FBA	north/south
SBPCK	FBA	east/west

Discontinued Stations. A number of instruments have been removed since the last Bulletin was released. These removals are summerized in Table 2. WCX, China Lake Radio, was discontinued because a reorganization of radio telemetry in the area left it alone on a telephone circuit. This arrangement was not cost effective. The instrument on the Cahuilla Indian Reservation, CAH, was removed because the land owner was going to develop the site. A new station will be installed in the area when a suitable site can be found and permitted.

In December 1987 Unocal discontinued its seismic array in the Imperial Valley. That array had been used to monitor then effects of geothermal production at the south end of the Salton Sea. Three of these sites had been telemetered to Caltech; U06, U08, and U13.

▪ Table 2. Discontinued stations

Code	Date Discontinued
CAH	February 5, 1988
WCX	September 15, 1988
U06	December 1, 1987
U08	December 1, 1987
U13	December 1, 1987

Mislocation of Station CAH. Station CAH, Cahuilla Valley, was mislocated at the time it was installed on April 30, 1981. As a result the wrong location has been distributed in copies of the Network station list and in several publications including Presgrave *et al.* (1985), Norris *et al.* (1986), and Klein *et al.* (1988). The correct location is:

$$33^\circ\ 29.54',\ -116^\circ\ 43.41',\ 1341\ \text{m elevation}$$

We thank Jennifer Scott and Frank Vernon of Scripps for bringing this problem to our attention. They discovered the mislocation when P and S residuals for the station showed a systematic variation with azimuth. This illustrates that the interpretation of complex data like those generated by the Network must be considered carefully and all processing artifacts considered before an interpretation is made.

Calibration Pulse Update. A program to record Network station calibration pulses was begun in June of 1987 (Given *et al.*, 1988). Currently calibration pulses have been recorded and saved for approximately 90% of the network stations that produce them. This work is hampered by the tendency of the calibration clocks to drift and be reset by lightning strikes. An effort is being made to reset the calibration clocks during site visits. As a result, about 51% of those recorded are now occurring at the correct times. These figures indicate a significant improvement in both the number of calibration pulses available and the number of pulses occurring at predictable times.

Double Discriminators. The southern California network records some signals for instruments that are owned and maintained by other agencies. This means that we control only a portion of the telemetry path and cannot always know when components or settings are changed that might affect the station gain or response. It also means that the signals are modulated and discriminated twice; once by the telemetry of the owner agency and again to telemeter the signal to Pasadena.

Table 3 lists stations that are modulated twice. The owner agencies are **DWR**, California Department of Water Resources; **USC**, University of Southern California; **Menlo**, U.S.G.S. office in Menlo Park, **Unocal**, Union Oil of California, and **Berkeley**, University of California, Berkeley.

■ **Table 3. Twice modulated signals**

Sta.	Agency	Sta.	Agency	Sta.	Agency
BNP	DWR	PAD	Menlo	PTQ	Menlo
CIWZ	USC	PBI	Menlo	PTR	Menlo
CSP	DWR	PEC	DWR	PYR	DWR
DHBM	USC	PHC	Menlo	RCP	USC
FLA	USC	PMC	Menlo	SAT	USC
FRI	DWR	PMCE	Menlo	SBI	USC
GFPE*	USC	PMCN	Menlo	U06*	Unocal
GFPN*	USC	PMCZ	Menlo	U08*	Unocal
GFPZ	USC	PMG	Menlo	U13*	Unocal
JAS	DWR	PPB	Menlo		
MNP	Menlo	PPR	Menlo		
MTCZ	Menlo	PRI	Berkeley		
MTU	Menl	PSH	Menlo		
ORV	DWR	PSM	Menlo		

* Station no longer active

FBA Calibration. Four sites in southern California have three-component force-balance accelerometers (FBA) installed. The signal from the FBA site at the Pasadena office of the U.S.G.S., GSA, passes through two different amplifiers and is recorded at two different gains. The higher gain signals are called I, J, K and the lower gain signals are called A, B, C. The gains on all the FBA's have been adjusted at various times in an attempt to set their gains to the values that would recover the most useful data from each site. The calibration for each FBA and the date each became effective has been determined by James Mori and is listed in Table 4. The last entry for each FBA is the current calibration. A sample record from the GSA low gain instrument for the Pasadena earthquake of December 3, 1988 (M_L 4.9) is shown in Figure 1.

■ **Table 4. FBA Calibrations**

Site Name	Component Codes	Calibration $counts/(cm/sec^2)$	Beginning Date
GSA	A, B, C	33.456	October 6, 1987
		66.912	December 6, 1988
GSA	I, J, K	4.142	October 6, 1987
		2.071	December 6, 1988
GRV	I, J, K	0.990	October 8, 1987
		1.238	February 22, 1988
		4.188	April 7, 1989
BRA	I, J, K	1.047	September 15, 1987
		4.188	March 7, 1989
SBP	I, J, K	1.047	October 18, 1987
		4.188	March 9, 1989

NETWORK OPERATIONS

Status of Processing. The status of each month of catalog data since the advent of digital recording is described in Table 5. Events for months marked preliminary (**P**) have been timed but have not yet run the gauntlet of quality checking, addition of helicorder amplitudes and rearchiving necessary to become final (**F**). For months marked "pinked" (**Pnk**), larger events ($\approx$ 3.0) have only been timed crudely on a few stations and smaller events are absent. A period in 1980–1981 has actually been timed and digital seismograms are available, but the "pinked" version is still used for any purpose requiring good magnitudes or completeness for large earthquakes; some events and magnitudes are missing otherwise.

■ Table 5. Processing Status of Network Data

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977	P	P	P	P	P	P	P	P	P	P	P	P
1978	F	F	F	F	F	F	F	F	F	F	F	F
1979	P	P	P	P	P	P	P	P	P	P	P	P
1980	P	P	P	P	Pnk	Pnk	Pnk	Pnk	Pnk	Pnk	Pnk	Pnk
1981	Pnk	Pnk	P	P	P	P	P	P	P	P	P	P
1982	P	P	P	P	P	P	P	P	P	P	P	P
1983	P	P	P	P	Pnk	P	P	P	P	F	F	F
1984	F	F	F	F	F	F	F	F	F	F	F	F
1985	F	F	F	F	F	F	F	F	F	P	P	P
1986	F	F	F	F	F	F	P	P	P	P	P	P
1987	P	P	P	P	P	P	P	P	P	P	P	P
1988	P	P	P	P	P	P	P	P	P	P	P	P
1989	P	P										

F = final, Pnk = "pinked", P = preliminary

New On-line Computer System. A new on-line earthquake detection and recording system has been installed in Pasadena. The improved real-time software was developed by Bob Dollar, Peter Johnson and Sam Stewart of the U.S.G.S. Menlo Park office and runs on a DEC MicroVAX II computer. This new machine replaces one of our aging PDP 11/34 computers. The MicroVAX is linked to our existing processing machine, a VAX 750, via LAVc (Local Area VAXcluster) software over an Ethernet cable. The MicroVAX, which is more powerful than its predecessor, removes some of the processing load from the off-line VAX 750 and allows greater throughput on that machine. LAVc allows disk sharing between the computers which speeds file transfer and reduces the time between recording of an event and its availability for analysis. The new real-time software is still in a testing stage but is should result in faster and more reliable data collection and processing.

In addition to the benefits mentioned above the surplus CPU power of the MicroVAX computer will allow real-time, automatic phase picking, location and magnitude determination within minutes of an event. Software to achieve these goals is near completion.

RTP. A hardware real time picker (RTP) was installed in Pasadena in June of 1988. The device was designed and built by Rex Allen in the Menlo Park office of the U.S.G.S. It is based on the Motorola 68000 processor and the VME bus architecture.

The machine continuously monitors 64 stations of the southern California array. It makes individual P-picks using a short-term-average/long-term-average algorithm and associates picks to determine if they might represent an earthquake. If an event is declared, the phase picks and amplitude information are sent over a serial line to the VAX 750 and a DEC PRO350.

On the PRO350 a special version of HYPOINVERSE (Klein, 1984) locates the events, computes magnitudes and plots the results on a screen display. It also produces a hardcopy output of the location parameters. This system produces a result within minutes of the event.

On the VAX 750 a group of programs developed by Peter Johnson converts the data to CUSP format and computes a location, magnitude and quality. RTP events are collected in a catalog which is kept separate from the regular earthquake catalog. This catalog is used to plot a map of seismic activity on a color monitor. The software also checks each event to see if it meets certain alarm criteria. If an event does trigger an alarm, messages can be sent via computer mail and digital pagers to notify laboratory staff. Similar systems are in place in the Menlo Park office of the U.S.G.S.

Routine Crustal Model and Delays. Since the southern California catalog was begun in 1932 several different location methods and crustal models have been used to calculate earthquake hypocenters. Because of these differences the catalog is heterogeneous and studies that span a long time interval should be approached with care.

Hileman *et al.*(1973) recount the early methods used for catalog locations. From 1932 through 1960 graphical location methods were used applying world-wide travel-time curves that had been modified in light of local quarry blast and earthquake data (e.g. Wood and Richter, 1931 and Gutenberg, 1951). In 1961 computer locations were begun using a location program by Nordquist (1962) and a layered velocity model developed by Press (1960). When the U.S.G.S. became directly involved in the southern California network in 1974 the program HYPO71 (Lee and Lahr, 1975) was used to locate earthquakes and different velocity models were used for different areas (Fuis *et al.*, 1978).

Finally the CEDAR system (Caltech Earthquake Detection And Recording) was introduced in 1977 and eventually evolved into the current CUSP system (Caltech U.S.G.S Seismic Processing). Since that time a single velocity model has been used to locate all earthquakes for the southern California catalog. This model is based on work by Kanamori and Hadley (1975) and has been modified to include unpublished data (Fuis *et al.*, 1978). The model represents an average model for the western Mojave, Transverse Ranges, Los Angeles basin and the Peninsular Ranges (Table 6).

■ **Table 6. "Hadley/Kanamori" Crustal Model**

Depth to Top (km)	Velocity (km/sec)
0.0	5.5
5.5	6.3
16.0	6.7
37.0	7.8

This average model does an acceptable job of locating most events but is not the best model for every area of southern California. Use of a single regional model is a necessary concession made to allow processing of a large volume of data. If more accurate locations are required, it is left to the individual researcher to relocate events using an appropriate velocity model and location technique.

Since 1984 a *priori* delays have been used for some station in the network to improve locations. These delays were arrived at empirically and are listed in Table 7. Positive delays generally were applied to station in deep sedimentary basins such as the Imperial Valley and negative delays to the stations in the southern Sierra and Coso areas. Use of these delays has improved the hypocentral solutions for these areas. Any station not appearing in the table has no delay.

■ **Table 7. Station Delays Used in Routine Processing**

Sta.	Delay (sec.)	Sta.	Delay (sec.)	Sta.	Delay (sec.)
BAT	0.3	IRS	0.3	U15*	0.6
BON	0.6	NW2	0.6	U16*	0.6
BSC	0.3	NWR*	0.6	VPD*	0.4
CAM*	0.4	OBB*	0.6	WBS	-0.3
CLI	0.6	SGL	0.3	WCH	-0.3
COA	0.3	SLT	0.6	WHF	-0.3
COK	0.3	SNR	0.6	WIS	0.6
ECF	0.4	SRT	0.4	WKT	-0.3
ELR	0.6	SUP	0.3	WLH	-0.3
EMS	0.3	TCC	0.4	WLK	0.6
ERP	0.3	TOW	0.4	WML	0.6
FIL	0.4	U06*	0.6	WNM	-0.3
FNK*	0.3	U12*	0.6	WOR	-0.3
FRK	0.3	U13*	0.6	WSC	-0.3
ING	0.3	U14*	0.6	WWP	-0.3

* Station no longer active

SPIGOT. Southern California Seismic Network hypocentral data may be "tapped" via computer modem using a program called SPIGOT. It allows remote users to extract subsets of the southern California catalog. Subsets are defined by specifying the following parameters:

1. Beginning and ending dates
2. Regional box or polygon
3. Magnitude range
4. Location qualities (A, B, C, etc.)
5. Earthquakes, blasts or both

Output files can be written in either CIT or HYPOINVERSE formats or both. The resulting data file can then be downloaded using ASCII transfer or KERMIT. This method of data access is only practical for relatively small data sets. Requests for large data sets should be made to the address below.

Details of SPIGOT login can be obtained by contacting the Pasadena Office of the U.S.G.S. at the following address:

SPIGOT
U. S. Geological Survey
525 So. Wilson Ave.
Pasadena, CA 91106
(818) 405-7811 commercial
961-8711 FTS

RESEARCH NOTES

An Anomalous Long-Period Phase Recorded at Pasadena:
Reported by Hiroo Kanamori. On the seismograms of the 18 June 1988 Gulf of California earthquake (M_S 6.6) recorded at the Kresge Lab, we noticed a prominent long period phase (Figure 2a). This phase is prominent only on the horizontal components, and appears to be one of the multiple G waves from the event. However, a close examination reveals that this phase cannot be the surface waves (Figure 2b). These records are 100–300 ($\times$1500) seismograms simulated by convolving the output from the very-broad-band Streckeisen instrument with the response curve shown in Figure 3. The phase was also recorded with the Press-Ewing instrument and the Benioff LP instrument at the Kresge laboratory (Figure 4). However, no short-period energy was recorded.

Strangely, no such anomalous phase was recorded at Berkeley (Bruce Bolt, personal communication), or at the Piñon Flat observatory (Duncan Agnew, personal communication).

Since the phase was recorded with the Streckeisen, Press-Ewing, and Benioff instruments, it is almost certain that it is not instrumental noise but is a real signal.

The absence of this phase at other stations (Berkeley and Piñon Flat) suggests that it could be due to some local source. The absence of the signal on the vertical component suggests that it could be due to tilt, rather than horizontal ground motion. The particle motion suggests that the incidence azimuth is approximately NE-SW (if it is due to SH motion), or NW-SE (if it is due to tilt).

The estimated ground-motion amplitude or tilt is approximately 1 mm or 3×10^{-8} radians respectively. The latter value is comparable to that of earth tide.

The cause of this signal is mysterious. One possible source is a sudden burst of air motion in the Pasadena area. However, the absence of the vertical motion is somewhat difficult to explain. The complete absence of short-period energy seems to preclude any man-made sources. Another possible source is an episodic tectonic event in the Pasadena area (e.g. fault creep). Of course, this is just a speculation, but it is interesting to note that the "Garlock fault" event, M_L 5.3, occurred on 10 June 1988 and the Upland earthquake, M_L 4.5, occurred on 26 June 1988.

With data from only one site, it is not possible to pin down the source of this mysterious phase, but this is another example that illustrates the importance of this type of instrumentation in regional seismology.

SYNOPSIS OF SEISMICITY

During the last half of 1987, 9,067 earthquakes and 710 blasts were recorded and cataloged in southern California (Figure 5). Two large earthquakes shook the region during the reporting period; the Whittier Narrows earthquake of October 1, 1987 (M_L 5.9) and the Superstition Hills earthquakes of November 24, 1987 (M_S 6.2 and 6.6). Including the aftershock sequences of these events, there were 254 earthquakes of M_L 3.0 or larger (Appendix A). Focal mechanisms for eighteen earthquakes are shown in Figure 6.

A quiescence at the M_L 4.0 level in southern California (exclusive of Baja California) began in November 1986 and lasted eleven months before it was ended by the Whittier Narrows earthquake of October 1, 1987. Such rate changes are not necessarily precursory; a similar quiescence in 1976-77 lasted seven months but was not terminated by a large event.

The overall rate of seismicity in southern California was largely unchanged after the Whittier Narrows earthquake, however, there was a regional increase following the Superstition Hills sequence (Figures 8a and 8b).

As in previous Bulletins, southern California has been divided into eleven sub-regions (Figure 7). This practice is arbitrary, but useful in discussing characteristics of seismicity in a manageable context. Figures 8a and 8b summarize the activity of each sub-region over the past four years. The two large earthquakes of the reporting period are discussed first, followed by discussion of those sub-regions that have been of seismic interest.

Whittier Narrows Earthquake. The M_L 5.9 Whittier Narrows mainshock occurred about 15 km east of downtown Los Angeles on October 1, 1987. This was the most destructive earthquake in the Los Angeles metropolitan area since the San Fernando earthquake (M_L 6.6) on February 9, 1971. According to Person (1988a), the Whittier Narrows event killed eight people, injured many and left 2,200 homeless. It damaged more than 10,400 buildings and caused an estimated $358 million in property damage.

Seismological aspects of the Whittier Narrows earthquake have been discussed by Jones and Hauksson (1988). In map view the aftershocks form a ring with a diameter of 4 to 5 km centered around the epicenter of the mainshock (Figure 9). In north-south cross section, the aftershocks define a plane dipping shallowly to the north. This is consistent with the focal mechanism of the mainshock which has one nodal plane striking east-west and dipping 25° to the north (Figure 9). Therefore, the spatial distribution of the hypocenters of the mainshock and its aftershocks, as well as the focal mechanism of the mainshock, indicate that the causative fault is a gently dipping thrust fault with an east-west strike, located at depths from 11 to 16 km. The motion on this fault was pure thrust with no strike-slip component. The mainshock ruptured a previously unrecognized thrust fault located just north of the Whittier Narrows at depths between 11 and 16 km (Hauksson *et al.*, 1988).

Several features of this aftershock zone are unusual. First, no earthquakes occurred near the surface; the shallowest aftershock was 10 km deep. Most earthquakes of this size in California have aftershock zones that extend to shallower depths, often producing measurable surface offset. Second, the 4 to 5 km diameter of the aftershock zone is very small. By comparison, the 1986 North Palm Springs earthquake (M_L 5.6) that also occurred on a dipping fault had an aftershock zone of 16 by 9 km (Jones *et al.*, 1986); an aftershock area more than six times larger than that of the larger Whittier Narrows earthquake. The number of aftershocks was also unusually low. Finally, aftershocks appear to have occurred on faults of at least two different orientations.

The largest aftershock (M_L 5.3), which occurred about three days after the mainshock, was located 3 km to the northwest of the mainshock's epicenter. The focal mechanism of the largest aftershock is significantly different from the focal mechanism of the mainshock (Figure 9). It shows mostly strike-slip movement on a steeply dipping, northwest-trending plane with a small reverse component. The focus of the largest aftershock is located at a depth of about 12 km, within the hanging wall of the thrust sheet and 2-3 km above the rupture surface of the mainshock. The locations of this and numerous smaller aftershocks define a north-northwest-striking, steeply dipping fault, which forms the western edge of the aftershock distribution of the mainshock. The spatial distribution of aftershocks indicates that the steeply dipping fault exists both within the hanging wall and the foot wall of the buried thrust. Therefore, the mainshock rupture may have terminated against this fault. The stress loading from the mainshock may have triggered the largest aftershock on this steeply dipping fault.

This steeply dipping cross fault probably represents the extension of the Whittier fault at depth. The surface trace of Whittier fault terminates in the Puente Hills about 10 km to the southeast of the mainshock. There it is dominantly a northeast-dipping strike-slip fault with a small reverse component.

The seismic evidence and the absence of surface rupture suggests that this earthquake occurred on a thrust fault that does not reach the surface. This buried thrust fault is responsible for the overlaying anticline that forms the Puente and Montebello Hills. In fact the Montebello Hills rose 5 cm as a result of the coseismic slip (Lin and Stein, *in press*). A system of similar thrust faults capable of generating moderate-sized, destructive earthquakes may extend westward from Whittier to Santa Monica, along the northern edge of the Los Angeles basin (Davis and Hayden, 1987). This 10-20 km wide zone of shallow thrust faults south of the southern margin of the Transverse Ranges has also been suggested on the basis of seismotectonic analysis of small earthquakes (Hauksson, 1987).

Since 1970 seven other M_L 5.0 or larger earthquakes have occurred west of the San Andreas fault in southern California. These earthquakes are distributed over a large geographic area and are usually associated with low-slip-rate faults (Ziony and Yerkes, 1985). Over the last century, these moderate-sized earthquakes have occurred more frequently on thrust faults of the Transverse Ranges than along northwest striking strike-slip faults that strike subparallel to the San Andreas fault, such as the Elsinore-Whittier fault system and the Newport-Inglewood fault zone.

Current estimates of earthquake hazards in the Los Angeles basin are based mostly on studies of reverse and strike-slip faults exposed at the surface. The occurrence of the 1987 Whittier Narrows earthquake demonstrates that the existing estimates of earthquake hazards need to be reevaluated to include quantitative estimates of the earthquake potential of these buried thrust faults.

Superstition Hills Earthquakes. The Superstition Hills earthquake sequence produced two mainshocks and caused surface rupture along two orthagonal fault zones on the west edge of the Salton trough. The first mainshock (M_L 5.8, M_S 6.2) occurred on November 24 at 01:54 gmt. It was preceded by six recorded foreshocks clustered about 2 km southwest of the mainshock. The first foreshock (M_L 4.2) occurred 21 minutes before the mainshock. It was followed ten minutes later by four events, all smaller than M_L 2.1. The final foreshock (M_L 4.0) was slightly nearer to the epicenter of the mainshock and occurred one minute before it. The first motions of the mainshock were obscured by the coda of this foreshock; however, its focal mechanism appears to match that of the foreshock (Figure 6, event 12). It indicates left-lateral strike-slip on a northeast trending vertical fault. This plane is also supported by the lineation of the aftershock zone (Figure 10a). The strike is consistent with the broad complex zone of surface ruptures along the newly named Elmore Ranch fault. The routine catalog locations of these events put them at depths of 5 km or less, however, relocation using a velocity model more appropriate to the area indicates depths of about 10 km (Magistrale *et al.*, 1989).

The second, larger mainshock (M_L 6.1, M_S 6.6) occurred 11.4 hours later at 13:15 gmt. According to Person (1988) the second event injured 94 people, caused $4 million damage in Imperial County, California and left 3,000 homeless in the Mexicali area of Mexico. It was felt throughout the southern California area.

This event occurred at the junction of the Elmore Ranch and Superstition Hills faults (Figure 10) and broke unilaterally to the southeast rupturing the Superstition Hills fault for its entire mapped length of 28 km (Budding and Sharp, 1988). Right-lateral strike-slip offset of up to 80 cm was measured in the day after the event but significant afterslip doubled the total offset in the months following the event. The focal mechanism of the second mainshock is consistent with the sense and orientation of the surface rupture (Figure 6). The aftershocks do not, however, delineate a well defined trend. Rather, they form a cloud of events between the Superstition Hills and Superstition Mountain faults (Figure 10b). The focus of the second mainshock was at a depth of 2.4 km and was unusually shallow for an event of this size. This earthquake appears to have included three subevents; the initial rupture was followed by a larger event 3 seconds later and by a still larger event

10 seconds after the beginning (Frankel and Wennerburg, 1988; and Wald and Somerville, 1988).

Because the two mainshocks were within 11.4 hours and 10 km of one another, speculation about their physical relationship is enticing. The orthagonal orientation of the faults involved naturally leads to the suggestion that the first event triggered the second by reducing normal stress on the Superstition Hills fault thus weakening it (Given and Stuart, 1988; Hudnut *et al.*, 1989). Given and Stuart (1988) have suggested that the 11.4 hour delay between the two events was a result of continued weakening of the Superstition Hills fault by post-seismic slip due to stress relaxation in the viscous portion of the Elmore Ranch fault. Hudnut *et al.* (1989) have proposed that the delay might be due to recovery of the pore pressure on the Superstition Hills fault.

The stress changes that accompanied this earthquake sequence had wide ranging secondary effects in the region. Some "aftershocks" of the first mainshock occurred in a small cluster off the Elmore Ranch trend, near Obsidian Butte on the southeast shore of the Salton Sea (Figure 10a). This is a persistent site of swarm activity at the south end of the Salton Sea. It seems likely that this activity was stimulated by the stress changes of the first mainshock. Another secondary increase of seismicity about 30 km to the southwest, at the north end of the Laguna Salada fault, is discussed in the section for Region 3 below. Several nearby faults showed "triggered" slip either coseismically or shortly after the Superstition Hills earthquakes. McGill *et al.* (1989) documented slip of about 8 mm on the Imperial fault and of about 3 mm on the southern San Andreas fault using creepmeters. Clark and Hudnut (1988) found surface cracks with a maximum displacement of about 15 mm along a 3 km section of the Coyote Creek fault that had broken in 1968 during the Borrego Mountain earthquake (M_L6.4).

The Superstition Hills-Superstition Mountain area had been identified as being one of 15 sites in California with the potential to produce an earthquake of $M_L \geq 5.7$ between 1986 and 1996 (Wesson and Nicholson, 1987).

South Elsinore – Region 3. The area at the southern end of the Elsinore fault zone became active immediately following the Superstition Hills earthquakes in November. The surface trace of the Elsinore fault zone ends here to be resumed after a gap of about 13 km by the Laguna Salada fault (Figures 5 and 10b). The Laguna Salada fault continues into Baja California for another 70 km with the same southeasterly strike (Kahle *et al.*, 1984).

Activity was distributed over a broad area and was not restricted to the mapped surface faults. Events tended to occur in spatial and temporal clusters, some of which delineated linear trends. This dramatically higher rate of activity continued well into 1988.

The proximity of this activity in space and time to the Superstition Hills sequence strongly suggest a causal relationship. Just as the M_S 6.6 event of that sequence may have been triggered by stress changes caused by the preceding M_S 6.2 event, so this increase in activity may have been induced by the stress changes caused by the Superstition Hills sequence.

San Diego – Region 4. A swarm of small earthquakes occurred in August and September under San Diego Bay (Figure 5). There were twelve events between magnitudes 2.0 and 2.8. This was the site of two larger swarms, one in June 1964 (M_L 3.7, 3.6) and the other on June 18, 1985 (M_L 3.9, 4.0 and 3.8). Activity in the the San Diego area has been unusually high since the occurrence of the Oceanside earthquake (M_L 5.3) on June 13, 1986 (Heaton, 1987; Given *et al.*, 1987).

Los Angeles Coast – Region 5. Two small clusters of activity occurred in July (Figure 5). The first began on July 7 on the Newport-Inglewood fault zone. It produced about 6 events in less than 24 hours. The largest event had an M_L of 3.2 and involved normal slip on planes oriented nearly north-south (Figure 6, event 3). About 20 hours later a second cluster of seismicity began 18 km to the southwest off of Point Fermin. It included events of M_L 3.6 (Figure 6, event 4) and 3.3.

South Sierra Nevada – Region 9. There were several swarms in the south Sierra Nevada region during the last half of 1987 (Figure 11). Such swarms are characteristic of the Sierra seismic lineation (Jones and Dollar, 1986).

The first of the moderate swarms occurred just northeast of Lake Isabella from August 1–14 and included five events of M_L greater than 3.0. The frequency of events during the swarm was rather irregular. Minor bursts of activity continued in the area of the swarm through December. The focal mechanism indicates predominently normal slip (Figure 6, event 6), consistent with Basin and Range extension.

An intense swarm about 45 km to the north began around September 6 that eventually produced more than 300 events. This swarm was centered under Monache Mountain, a 2.4 million year old rhyolite dome (Bacon and Duffield, 1981). The swarm defined a column of seismicity plunging 65° to the northwest from about 6 to 15 km depth. The largest member of the swarm was a M_L 3.4 event on September 9. The swarm appeared to taper-off after two weeks but showed a renewal of activity at the end of the month and continued into October. The sequence had a high b-value ($b = 1.3$) which is typical of earthquake swarms.

A M_L 4.1 event that was not part of a swarm occurred 40 km southwest of Lake Isabella on December 15. Its focal mechanism is shown in Figure 6 (event 14).

A small swarm about 20 km south of Lake Isabella began on December 21 and stopped abruptly after six days. The largest event was a M_L 3.1 event at the midpoint of the swarm. The swarm was preceded by about two weeks by a M_L 3.1 event 8 km to the east.

Santa Barbara – Region 11. A small swarm occurred just off shore near Ventura on July 19-23. It included eight events between M_L 2.5 and 3.2. The focal mechanism of the largest event shows thrusting on an east-west striking plane, consistent with the mapped faults in the area (Figure 6, event 5).

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APPENDIX A.

SIGNIFICANT SOUTHERN CALIFORNIA EARTHQUAKES

All event of $M_L \geq 3.0$ for the period July to December 1987. Times are GMT, RMS is the root-mean-squared of the location error, NPH is the number of phases picked. The CUSPID is the unique number assigned to the event by the CUSP system. FM denotes the number of the accompanying focal mechanism in Figure 6.

DATE	TIME	SEC	LAT	LON	Z	Q	M	TYP	RMS	NPH	CUSPID	FM
1987 JUL 1	17:55	34.83	33.7417	-119.9473	6.00	C	3.1	M_{CA}	0.26	29	725234	
1987 JUL 3	6:52	19.14	33.8605	-116.1861	4.82	A	3.1	M_{CA}	0.07	23	132883	
1987 JUL 3	6:52	21.79	33.8571	-116.1810	1.32	A	3.0	M_{CA}	0.10	20	725345	
1987 JUL 5	4:57	4.07	33.1766	-115.6525	1.56	A	3.1	M_{CA}	0.10	36	725483	1
1987 JUL 6	2:23	46.35	33.9781	-116.6501	7.00	A	3.1	M_{CA}	0.08	44	725536	
1987 JUL 7	13:18	26.08	34.9013	-117.0652	9.63	A	3.1	M_{CA}	0.04	33	725630	2
1987 JUL 7	21:07	11.43	33.8304	-118.1836	13.95	A	3.2	M_{CA}	0.17	57	725667	3
1987 JUL 8	16:55	59.46	33.6992	-118.2723	7.75	A	3.6	M_{CA}	0.09	21	725689	4
1987 JUL 8	18:34	21.17	32.9328	-117.7655	6.00	C	3.1	M_{CA}	0.20	26	725697	
1987 JUL 9	0:42	14.82	33.6977	-118.2736	6.00	A	3.3	M_{CA}	0.09	26	725725	
1987 JUL 9	16:45	35.92	36.3238	-118.3715	6.00	C	3.2	M_{CA}	0.06	23	725754	
1987 JUL 19	5:01	43.42	34.3350	-119.4446	6.85	A	3.2	M_{CA}	0.05	20	726345	5
1987 JUL 23	15:01	1.37	34.3325	-119.4414	6.00	A	3.0	M_{CA}	0.06	21	726710	
1987 JUL 26	17:15	28.62	33.0188	-117.8538	6.00	C	3.0	M_{CA}	0.35	32	726881	
1987 AUG 4	2:40	10.29	32.9650	-117.7788	6.00	C	3.0	M_{CA}	0.29	18	727392	
1987 AUG 6	7:53	49.02	35.7625	-118.3606	7.57	A	3.0	M_{CA}	0.04	33	133513	
1987 AUG 9	3:12	43.33	35.7664	-118.3671	6.18	A	3.1	M_{CA}	0.06	68	133105	
1987 AUG 9	3:13	56.87	35.7798	-118.3395	6.00	C	3.1	M_{CA}	0.13	8	133107	6
1987 AUG 9	3:14	39.41	35.7688	-118.3597	5.95	C	3.0	M_{CA}	0.16	21	620426	
1987 AUG 13	10:24	43.66	35.7435	-118.3613	9.08	A	3.1	M_{CA}	0.04	8	620796	
1987 AUG 14	10:57	31.00	35.4206	-118.7238	9.97	A	3.1	M_{CA}	0.10	48	620853	
1987 AUG 17	18:37	2.32	34.2970	-116.9294	2.99	A	3.1	M_{CA}	0.15	64	621074	
1987 AUG 19	9:40	2.77	33.5826	-118.0034	13.50	A	3.0	M_{CA}	0.19	63	621215	
1987 AUG 23	23:18	58.73	35.9453	-117.0268	6.00	C	3.3	M_{CA}	0.23	36	621553	
1987 AUG 24	0:12	25.28	33.9795	-116.9740	15.64	A	3.0	M_{CA}	0.09	65	621557	
1987 AUG 25	6:27	26.62	34.3567	-117.5771	9.31	A	3.6	M_{CA}	0.10	111	621670	7
1987 AUG 28	19:22	4.18	33.6525	-118.5604	11.03	A	3.1	M_{CA}	0.14	36	621997	
1987 AUG 31	21:04	25.72	35.5439	-116.7665	6.00	C	3.1	M_{CA}	0.08	35	622266	
1987 SEP 9	8:57	20.79	36.2139	-118.1765	9.15	A	3.4	M_{CA}	0.09	20	133640	
1987 SEP 15	2:06	42.42	36.1245	-119.8702	6.00	C	3.2	M_{CA}	0.24	21	623380	
1987 SEP 15	10:48	38.11	36.3054	-120.3587	6.00	C	3.1	M_{CA}	0.12	17	623399	
1987 SEP 18	9:40	50.99	36.2838	-120.3220	6.00	C	3.1	M_{CA}	0.11	15	623564	
1987 SEP 20	18:42	20.49	34.3046	-119.5834	8.85	A	3.4	M_{CA}	0.15	37	623706	
1987 SEP 30	19:25	39.53	32.0222	-114.3292	6.00	D	3.1	M_{CA}	0.61	12	624522	
1987 OCT 1	14:42	20.02	34.0613	-118.0785	9.50	A	5.9	M_L	0.18	176	731691	8
1987 OCT 1	14:43	4.34	34.0667	-118.0833	9.00	C	3.6	M_L	0.16	2	134363	
1987 OCT 1	14:45	15.33	34.0667	-118.0833	9.00	C	3.7	M_L	0.00	1	134364	
1987 OCT 1	14:45	41.45	34.0488	-118.1005	13.55	A	4.7	M_L	0.05	32	624578	
1987 OCT 1	14:48	3.11	34.0763	-118.0901	11.66	A	4.1	M_L	0.14	54	731693	
1987 OCT 1	14:48	24.32	34.0500	-118.0833	10.00	C	3.6	M_L	0.00	1	134366	

DATE			TIME	SEC	LAT	LON	Z	Q	M	TYP	RMS	NPH	CUSPID	FM
1987	OCT	1	14:49	5.91	34.0599	-118.0998	11.70	A	4.7	M_L	0.05	46	624580	
1987	OCT	1	14:51	29.22	34.0811	-118.0832	12.42	A	3.6	M_L	0.18	74	731695	
1987	OCT	1	14:52	18.85	34.0746	-118.0543	14.55	A	3.2	M_L	0.14	16	134085	
1987	OCT	1	15:05	34.30	34.0623	-118.0902	11.47	A	3.0	M_L	0.16	72	731698	
1987	OCT	1	15:08	7.69	34.0444	-118.0826	9.45	A	3.2	M_L	0.14	48	731699	
1987	OCT	1	15:12	31.76	34.0517	-118.0906	10.80	A	4.7	M_L	0.19	162	134294	
1987	OCT	1	15:13	59.33	34.0532	-118.0961	9.92	A	3.2	M_L	0.15	41	731700	
1987	OCT	1	15:14	51.69	34.1119	-118.0449	10.00	C	3.2	M_L	0.08	4	134379	
1987	OCT	1	15:17	46.65	34.0514	-118.0911	12.43	A	3.4	M_L	0.19	101	731701	
1987	OCT	1	15:20	2.90	34.0644	-118.0535	10.00	A	3.0	M_L	0.19	78	731702	
1987	OCT	1	15:22	21.31	34.0449	-118.0790	10.82	A	3.2	M_L	0.16	101	731703	
1987	OCT	1	15:29	47.23	34.0593	-118.0916	10.42	A	3.1	M_L	0.14	83	731706	
1987	OCT	1	15:54	36.96	34.0738	-118.0916	11.43	A	3.0	M_L	0.18	73	731715	
1987	OCT	1	15:59	53.55	34.0499	-118.0867	10.41	A	4.0	M_L	0.16	127	731717	
1987	OCT	1	16:21	10.90	34.0817	-118.0617	13.31	A	3.4	M_L	0.17	116	731723	
1987	OCT	1	16:32	50.84	34.0592	-118.0476	11.18	A	3.0	M_L	0.31	85	731726	
1987	OCT	1	16:33	33.23	34.0484	-118.0897	11.72	A	3.3	M_L	0.20	95	134295	
1987	OCT	1	17:20	15.30	34.0568	-118.0926	10.79	A	3.4	M_L	0.16	101	134296	
1987	OCT	1	17:20	48.72	34.0674	-118.0697	13.57	A	3.1	M_L	0.16	33	731744	
1987	OCT	1	17:47	26.25	34.0508	-118.0933	11.89	A	3.6	M_L	0.19	132	731751	
1987	OCT	1	19:11	37.96	34.0607	-118.1003	12.21	A	3.6	M_L	0.16	116	731768	
1987	OCT	1	20:40	20.66	34.0763	-118.0641	12.66	A	3.3	M_L	0.19	105	731778	
1987	OCT	2	2:42	19.27	34.0504	-118.0673	10.69	A	3.0	M_L	0.18	76	731817	
1987	OCT	3	3:03	41.53	34.0625	-118.0587	10.15	A	3.1	M_L	0.19	75	731911	
1987	OCT	3	23:23	17.21	34.0568	-118.0512	7.98	A	3.0	M_L	0.20	92	731992	
1987	OCT	4	2:56	16.61	34.0507	-118.0864	10.71	A	3.0	M_L	0.17	84	732011	
1987	OCT	4	10:59	38.19	34.0736	-118.0978	8.22	A	5.3	M_L	0.17	187	732031	9
1987	OCT	4	11:08	42.00	34.0781	-118.0985	8.13	A	3.0	M_L	0.17	62	732033	
1987	OCT	4	14:05	52.47	34.0758	-118.1078	10.96	A	3.5	M_L	0.16	126	732056	
1987	OCT	5	7:05	11.52	34.0758	-118.1004	9.26	A	3.2	M_{CA}	0.17	111	732128	
1987	OCT	13	15:59	4.26	33.9585	-117.2127	14.08	A	3.6	M_{CA}	0.09	100	732742	10
1987	OCT	13	15:59	4.28	33.9581	-117.2129	13.91	A	3.6	M_{CA}	0.12	124	625589	
1987	OCT	24	23:58	33.10	33.6756	-119.0707	11.88	A	3.7	M_{CA}	0.28	151	626287	11
1987	OCT	24	23:58	33.12	33.6758	-119.0583	12.17	A	3.7	M_{CA}	0.18	94	733642	
1987	OCT	31	3:27	5.52	36.1051	-120.1479	6.00	C	3.1	M_{CA}	0.25	16	734071	
1987	NOV	2	19:21	24.92	35.3402	-117.8069	7.25	A	3.3	M_{CA}	0.12	69	734186	
1987	NOV	6	23:36	45.24	32.9973	-117.7834	6.00	C	3.1	M_{CA}	0.15	27	734567	
1987	NOV	10	12:21	9.69	34.3015	-116.3386	0.79	A	3.0	M_{CA}	0.11	48	734784	
1987	NOV	15	3:46	55.19	36.0102	-117.8727	5.17	A	3.6	M_L	0.04	11	735083	
1987	NOV	17	8:17	46.42	35.8250	-121.1401	12.46	B	3.2	M_{CA}	0.07	17	735235	
1987	NOV	24	1:32	48.10	33.0672	-115.7806	3.96	A	4.2	M_L	0.14	55	735661	
1987	NOV	24	1:34	19.95	32.3816	-118.8497	6.00	D	3.0	M_{CA}	0.35	12	134893	
1987	NOV	24	1:53	3.16	33.0718	-115.7820	4.24	A	4.0	M_L	0.19	50	134849	12
1987	NOV	24	1:54	14.51	33.0825	-115.7752	4.91	A	5.8	M_L	0.15	46	134894	
1987	NOV	24	1:58	53.47	33.1045	-115.7897	6.00	C	3.3	M_L	0.18	12	735665	

DATE	TIME	SEC	LAT	LON	Z	Q	M	TYP	RMS	NPH	CUSPID	FM
1987 NOV 24	2:01	46.80	33.0675	-115.7913	1.01	A	3.8	M_L	0.17	33	134895	
1987 NOV 24	2:05	19.80	33.1612	-115.7201	0.01	A	3.6	M_L	0.09	29	134896	
1987 NOV 24	2:05	52.00	33.0885	-115.7811	0.38	C	3.1	M_L	0.05	13	134897	
1987 NOV 24	2:06	45.12	33.0444	-115.8212	2.55	A	3.7	M_L	0.17	13	134898	
1987 NOV 24	2:07	15.72	33.0500	-115.8000	6.00	C	3.2	M_L	0.00	1	135122	
1987 NOV 24	2:11	35.83	33.0686	-115.7998	0.01	A	3.3	M_{CA}	0.19	23	735669	
1987 NOV 24	2:14	35.45	33.0357	-115.8197	4.73	A	4.5	M_L	0.17	53	735670	
1987 NOV 24	2:15	23.17	33.0478	-115.7985	5.03	A	4.8	M_L	0.18	10	134901	
1987 NOV 24	2:16	47.18	33.0500	-115.8000	6.00	C	4.0	M_L	0.00	1	135124	
1987 NOV 24	2:21	59.59	33.0330	-115.8136	4.49	A	4.0	M_L	0.23	56	627852	
1987 NOV 24	2:25	13.16	33.1777	-115.6654	0.01	A	3.0	M_{CA}	0.10	9	627853	
1987 NOV 24	2:25	52.68	33.1644	-115.6561	3.00	C	3.5	M_L	0.24	25	627854	
1987 NOV 24	2:35	4.63	33.0127	-115.7960	3.48	A	3.0	M_{CA}	0.03	7	138353	
1987 NOV 24	2:46	0.62	33.0243	-115.8140	3.23	A	3.2	M_{CA}	0.13	21	138377	
1987 NOV 24	2:46	1.42	33.0500	-115.8000	6.00	C	3.4	M_L	0.00	1	135125	
1987 NOV 24	2:53	0.74	33.0397	-115.8121	3.49	A	4.7	M_L	0.21	58	627860	
1987 NOV 24	2:59	59.94	33.1082	-115.7505	2.70	A	3.3	M_{CA}	0.12	36	138379	
1987 NOV 24	3:00	1.60	33.0500	-115.8000	6.00	C	3.3	M_L	0.41	2	135126	
1987 NOV 24	3:05	47.64	33.0125	-115.8107	1.17	A	3.2	M_{CA}	0.08	15	138391	
1987 NOV 24	3:06	39.53	33.0136	-115.8079	2.41	A	3.2	M_{CA}	0.07	24	627864	
1987 NOV 24	3:07	56.83	33.0280	-115.8185	1.55	A	3.3	M_{CA}	0.13	32	627865	
1987 NOV 24	3:07	57.67	33.0500	-115.8000	6.00	C	3.3	M_L	0.11	2	135128	
1987 NOV 24	3:13	31.46	33.0327	-115.8121	2.22	A	3.2	M_{CA}	0.11	29	138395	
1987 NOV 24	3:13	32.47	33.0500	-115.8000	6.00	C	3.4	M_L	0.11	2	135133	
1987 NOV 24	3:14	16.77	33.1746	-115.6522	1.00	C	3.1	M_{CA}	0.15	14	627867	
1987 NOV 24	3:21	10.31	33.1735	-115.6608	1.07	A	3.0	M_L	0.14	13	735680	
1987 NOV 24	3:23	24.73	33.1782	-115.6512	0.01	A	3.2	M_L	0.18	26	134952	
1987 NOV 24	3:24	13.85	33.1815	-115.6589	0.01	A	3.4	M_L	0.23	21	735681	
1987 NOV 24	3:28	57.95	33.0195	-115.8056	1.18	A	3.1	M_{CA}	0.13	32	134956	
1987 NOV 24	3:43	55.18	33.0568	-115.8105	5.54	C	3.8	M_L	0.12	36	735688	
1987 NOV 24	3:56	28.23	33.2041	-115.6796	1.05	A	3.5	M_L	0.10	22	735693	
1987 NOV 24	4:00	45.00	33.1579	-115.7089	1.89	A	3.3	M_L	0.10	38	134963	
1987 NOV 24	4:04	36.88	33.1772	-115.6481	0.00	A	3.6	M_L	0.11	22	735695	
1987 NOV 24	4:30	52.25	33.1027	-115.7617	2.27	A	3.1	M_{CA}	0.11	24	627878	
1987 NOV 24	4:40	40.96	33.1239	-115.7341	0.00	A	3.0	M_{CA}	0.06	14	135019	
1987 NOV 24	5:42	54.18	33.0598	-115.7977	1.43	A	3.2	M_{CA}	0.07	28	134980	
1987 NOV 24	6:21	54.59	33.2089	-115.6670	1.59	A	3.2	M_{CA}	0.11	39	134911	
1987 NOV 24	6:23	23.12	33.0220	-115.8085	3.38	A	4.0	M_L	0.08	51	735729	
1987 NOV 24	6:32	2.41	33.0877	-115.7814	0.06	A	3.3	M_L	0.17	31	735731	
1987 NOV 24	6:32	49.63	33.2102	-115.6650	0.09	A	3.2	M_{CA}	0.11	22	627919	
1987 NOV 24	8:37	14.53	33.0241	-115.8121	1.50	A	3.0	M_{CA}	0.10	33	735768	
1987 NOV 24	10:12	37.61	33.0563	-115.7947	1.98	A	3.1	M_{CA}	0.09	24	735797	
1987 NOV 24	13:15	56.46	33.0127	-115.8384	2.40	A	6.0	M_L	0.16	71	628016	13
1987 NOV 24	13:18	48.93	33.0139	-115.8151	6.00	C	4.1	M_L	0.05	3	135136	
1987 NOV 24	13:20	44.06	33.0169	-115.8374	6.00	C	3.9	M_L	0.00	2	135137	

DATE	TIME	SEC	LAT	LON	Z	Q	M	TYP	RMS	NPH	CUSPID	FM
1987 NOV 24	13:21	0.15	33.0078	-115.7863	6.00	C	4.1	M_L	0.00	2	135138	
1987 NOV 24	13:24	3.34	33.0500	-115.8000	6.00	C	3.6	M_L	0.00	1	135140	
1987 NOV 24	13:24	53.92	33.0500	-115.8000	6.00	C	3.4	M_L	0.00	1	135141	
1987 NOV 24	13:32	59.89	32.9933	-115.8718	0.01	C	4.2	M_L	0.20	31	134914	
1987 NOV 24	13:33	55.76	33.1332	-115.8731	0.00	C	4.0	M_L	0.38	17	735841	
1987 NOV 24	13:34	39.93	32.9424	-115.7628	14.00	C	4.8	M_L	0.13	16	134915	
1987 NOV 24	13:37	50.74	33.0500	-115.8000	6.00	C	3.3	M_L	0.00	1	135142	
1987 NOV 24	13:42	11.36	33.0828	-115.8471	0.00	D	3.2	M_{CA}	0.23	22	135048	
1987 NOV 24	13:46	13.41	33.0119	-115.8630	4.06	A	3.9	M_L	0.12	22	134920	
1987 NOV 24	13:46	55.54	33.0234	-115.8048	0.00	A	3.6	M_L	0.18	21	735844	
1987 NOV 24	13:50	32.61	32.9918	-115.7888	2.18	A	3.2	M_{CA}	0.17	35	135049	
1987 NOV 24	13:51	22.02	32.9944	-115.7991	0.01	A	3.1	M_{CA}	0.53	10	735845	
1987 NOV 24	13:52	17.10	33.0072	-115.8315	4.25	A	3.6	M_L	0.13	20	134921	
1987 NOV 24	13:53	40.94	32.9884	-115.8354	0.01	A	3.9	M_L	0.19	18	735846	
1987 NOV 24	14:01	11.96	33.0067	-115.7987	4.65	A	3.6	M_L	0.08	32	134925	
1987 NOV 24	14:02	10.37	32.9933	-115.8168	4.52	A	3.3	M_{CA}	0.16	18	134926	
1987 NOV 24	14:03	41.01	32.9809	-115.7714	3.52	A	3.3	M_L	0.08	27	134922	
1987 NOV 24	14:04	10.54	32.9649	-115.7702	0.00	B	3.4	M_L	0.11	11	134923	
1987 NOV 24	14:09	32.02	33.0248	-115.8919	3.45	A	3.3	M_L	0.18	16	134928	
1987 NOV 24	14:17	41.64	33.0001	-115.8615	12.98	C	3.1	M_{CA}	0.26	14	628031	
1987 NOV 24	14:21	10.28	32.9750	-115.7974	2.81	A	3.0	M_{CA}	0.09	24	138402	
1987 NOV 24	14:21	41.62	33.0127	-115.8253	3.35	A	3.2	M_{CA}	0.09	19	138401	
1987 NOV 24	14:24	39.57	32.9933	-115.8169	6.94	C	3.5	M_L	0.20	51	628034	
1987 NOV 24	14:27	22.85	32.9839	-115.8271	2.57	C	3.2	M_{CA}	0.19	13	138404	
1987 NOV 24	14:28	37.78	32.9867	-115.8365	0.60	A	3.3	M_{CA}	0.17	14	628036	
1987 NOV 24	14:28	39.00	33.0190	-115.8212	6.00	C	3.4	M_L	0.00	2	135146	
1987 NOV 24	14:32	10.82	33.1536	-115.7138	6.00	C	3.0	M_L	0.31	18	134935	
1987 NOV 24	14:34	32.37	33.0056	-115.8537	1.99	A	3.1	M_L	0.11	31	628040	
1987 NOV 24	14:36	29.93	33.0467	-115.8077	0.00	A	4.0	M_L	0.22	46	628041	
1987 NOV 24	14:56	16.45	33.0148	-115.8620	2.16	A	3.2	M_{CA}	0.09	16	628045	
1987 NOV 24	15:06	57.72	33.0225	-115.8694	2.55	A	3.3	M_{CA}	0.15	45	628048	
1987 NOV 24	15:14	17.03	33.0213	-115.8319	3.46	A	3.0	M_{CA}	0.07	27	138411	
1987 NOV 24	15:15	27.81	33.0243	-115.8379	3.23	A	3.2	M_{CA}	0.12	28	628051	
1987 NOV 24	15:23	52.11	33.0126	-115.8221	3.30	A	3.0	M_{CA}	0.10	26	628053	
1987 NOV 24	15:26	39.90	33.0081	-115.8226	2.27	A	3.6	M_L	0.14	53	628054	
1987 NOV 24	15:34	15.32	32.6126	-115.5670	16.02	A	3.3	M_L	0.11	39	628058	
1987 NOV 24	15:34	47.69	33.0435	-115.8067	2.93	A	3.2	M_L	0.11	17	134930	
1987 NOV 24	15:47	16.52	33.0029	-115.8542	2.17	A	3.3	M_{CA}	0.14	46	135051	
1987 NOV 24	16:02	4.73	33.0036	-115.8351	1.15	A	3.1	M_L	0.06	19	735862	
1987 NOV 24	16:27	27.77	32.9138	-115.7064	4.46	A	3.0	M_{CA}	0.07	24	735869	
1987 NOV 24	16:41	16.13	32.9897	-115.8075	2.62	A	3.2	M_{CA}	0.07	14	135076	
1987 NOV 24	16:54	37.68	32.8976	-115.6900	5.83	C	3.3	M_{CA}	0.03	13	135083	
1987 NOV 24	16:56	52.42	32.9635	-115.7587	4.27	A	3.2	M_L	0.06	27	735880	
1987 NOV 24	17:56	42.57	32.9414	-115.7879	3.00	C	3.0	M_{CA}	0.03	6	138413	
1987 NOV 24	18:05	44.39	33.0266	-115.8558	1.15	A	3.1	M_{CA}	0.16	35	628084	

DATE	TIME	SEC	LAT	LON	Z	Q	M	TYP	RMS	NPH	CUSPID	FM
1987 NOV 24	18:47	24.66	33.0659	-115.9306	3.49	A	3.9	M_L	0.16	62	628101	
1987 NOV 24	18:50	40.31	33.0165	-115.8809	0.01	A	4.3	M_L	0.12	23	628102	
1987 NOV 24	18:53	59.81	32.9743	-115.7832	3.31	A	3.3	M_{CA}	0.11	31	628103	
1987 NOV 24	18:54	0.63	32.9931	-115.7719	6.00	D	3.2	M_L	0.28	5	135150	
1987 NOV 24	20:23	22.47	32.8395	-115.6099	9.03	A	3.4	M_L	0.10	14	135151	
1987 NOV 24	20:41	39.42	33.7120	-116.8339	16.13	A	3.1	M_{CA}	0.09	49	735916	
1987 NOV 24	21:28	12.30	32.8662	-115.9247	9.53	A	3.1	M_{CA}	0.13	26	135121	
1987 NOV 24	22:05	1.02	32.9771	-115.7799	2.75	A	3.0	M_{CA}	0.08	16	735948	
1987 NOV 24	23:09	58.80	32.9928	-115.8663	2.12	A	3.1	M_{CA}	0.12	23	628192	
1987 NOV 24	23:44	53.17	32.9907	-115.7936	2.10	A	3.2	M_{CA}	0.10	33	735963	
1987 NOV 25	0:33	2.12	32.9822	-115.8135	2.88	A	3.0	M_{CA}	0.10	31	135207	
1987 NOV 25	0:33	49.41	33.0649	-115.9280	1.90	A	3.1	M_{CA}	0.17	24	735981	
1987 NOV 25	0:48	55.73	33.0251	-115.8605	2.04	A	3.3	M_{CA}	0.12	34	135211	
1987 NOV 25	0:50	28.62	33.0703	-115.9349	2.60	A	3.0	M_{CA}	0.10	24	735985	
1987 NOV 25	1:02	16.37	32.9397	-115.7890	3.11	A	3.1	M_{CA}	0.10	23	135213	
1987 NOV 25	1:33	29.99	32.9864	-115.8128	2.20	A	3.1	M_{CA}	0.08	28	736000	
1987 NOV 25	2:08	30.90	33.0688	-115.9318	1.62	A	3.1	M_{CA}	0.08	30	736011	
1987 NOV 25	2:14	59.73	33.0148	-115.8523	0.00	A	3.0	M_{CA}	0.33	40	135219	
1987 NOV 25	2:23	39.71	32.9698	-115.7970	2.78	A	3.1	M_{CA}	0.15	33	736016	
1987 NOV 25	2:47	57.75	33.0113	-115.8671	3.03	A	3.3	M_{CA}	0.09	36	736023	
1987 NOV 25	3:46	51.72	33.0144	-115.8489	1.94	A	3.4	M_{CA}	0.13	38	736039	
1987 NOV 25	4:17	33.16	33.0550	-115.9323	2.07	A	3.5	M_{CA}	0.20	49	736052	
1987 NOV 25	4:25	3.84	32.9569	-115.8002	3.53	A	3.0	M_{CA}	0.11	31	135254	
1987 NOV 25	4:30	17.89	32.9801	-115.8182	0.46	A	3.4	M_L	0.12	43	736056	
1987 NOV 25	5:42	20.65	32.9897	-115.8233	1.36	A	3.3	M_{CA}	0.09	33	736077	
1987 NOV 25	6:07	3.70	32.9935	-115.8518	2.28	A	3.4	M_{CA}	0.10	36	736083	
1987 NOV 25	8:46	17.51	33.1904	-115.6314	1.24	A	3.1	M_L	0.08	13	135165	
1987 NOV 25	13:54	10.00	32.9791	-115.8160	0.58	A	4.2	M_L	0.12	44	736235	
1987 NOV 25	14:09	14.36	33.0017	-115.8253	1.03	A	3.0	M_{CA}	0.12	35	736240	
1987 NOV 25	15:01	37.15	32.9898	-115.7949	1.41	A	3.2	M_{CA}	0.10	38	736256	
1987 NOV 25	17:24	12.36	33.0186	-115.8348	0.41	A	3.3	M_{CA}	0.14	25	736286	
1987 NOV 25	20:07	31.58	32.9071	-115.6944	5.03	A	3.0	M_{CA}	0.09	27	736330	
1987 NOV 25	20:56	5.59	33.0012	-115.8436	0.70	A	3.0	M_{CA}	0.17	29	736347	
1987 NOV 25	22:45	56.32	33.0123	-115.8432	0.76	A	3.1	M_{CA}	0.18	20	736376	
1987 NOV 25	22:51	46.78	32.9926	-115.8418	2.55	A	3.3	M_{CA}	0.10	20	736378	
1987 NOV 26	0:19	31.60	32.9967	-115.8501	1.42	A	3.7	M_L	0.16	43	736397	
1987 NOV 26	0:22	15.02	32.9981	-115.8475	1.63	A	3.5	M_L	0.17	37	736398	
1987 NOV 26	1:56	27.53	32.9870	-115.8237	0.88	A	3.7	M_L	0.13	29	736419	
1987 NOV 26	16:55	17.78	32.9898	-115.8351	0.58	A	3.1	M_{CA}	0.19	36	736597	
1987 NOV 26	17:39	1.99	33.0286	-115.8879	1.77	A	4.3	M_L	0.12	39	736607	
1987 NOV 26	23:18	29.04	33.0049	-115.8462	0.82	A	3.1	M_{CA}	0.20	32	736684	
1987 NOV 27	1:10	10.53	32.9956	-115.8162	6.00	B	4.7	M_L	0.13	34	134937	
1987 NOV 27	9:22	57.59	33.0022	-115.8038	2.32	A	3.6	M_{CA}	0.14	58	736798	
1987 NOV 27	10:05	49.36	33.1017	-115.7523	2.25	A	3.4	M_{CA}	0.13	33	736801	
1987 NOV 27	11:33	14.96	33.0181	-115.8583	0.76	A	3.1	M_{CA}	0.20	26	736812	

APPENDIX A. (continued)

DATE	TIME	SEC	LAT	LON	Z	Q	M	TYP	RMS	NPH	CUSPID	FM
1987 NOV 27	15:15	2.33	32.9856	-115.8358	0.62	A	3.1	M_{CA}	0.19	32	736843	
1987 NOV 28	0:39	10.94	32.9802	-115.8091	0.84	A	4.2	M_L	0.14	54	736919	
1987 NOV 29	17:19	48.07	33.0075	-115.8591	2.13	A	3.0	M_{CA}	0.14	35	737215	
1987 NOV 29	23:55	0.38	33.9696	-118.7536	14.64	A	3.0	M_{CA}	0.15	42	737262	
1987 NOV 30	19:54	48.89	32.9804	-115.8105	0.55	A	3.0	M_{CA}	0.15	27	137451	
1987 DEC 1	7:03	47.75	33.6571	-117.8643	11.78	A	3.1	M_L	0.10	29	737450	
1987 DEC 1	11:13	19.64	34.2934	-116.9229	7.11	A	3.4	M_{CA}	0.11	79	737466	
1987 DEC 1	11:14	8.69	34.2804	-116.9166	3.16	A	3.0	M_{CA}	0.16	31	134946	
1987 DEC 1	15:49	33.54	35.8539	-116.9028	6.00	C	3.0	M_{CA}	0.18	20	737500	
1987 DEC 2	4:03	6.19	32.9950	-115.8134	1.72	A	4.0	M_{CA}	0.15	54	737585	
1987 DEC 3	8:25	42.87	32.9457	-115.7991	2.09	A	3.0	M_{CA}	0.13	27	629691	
1987 DEC 3	13:45	57.97	33.0025	-115.7899	4.45	A	3.1	M_{CA}	0.12	45	629713	
1987 DEC 3	19:04	36.60	33.0060	-115.8735	1.66	A	3.8	M_{CA}	0.20	53	737804	
1987 DEC 4	5:23	54.03	32.9865	-115.8056	3.38	A	3.1	M_{CA}	0.14	46	629789	
1987 DEC 4	8:56	59.69	33.0080	-115.8677	1.59	A	3.1	M_{CA}	0.21	39	629805	
1987 DEC 4	20:18	10.22	32.9841	-115.8263	3.54	A	3.1	M_{CA}	0.16	21	737942	
1987 DEC 5	20:36	29.33	35.4888	-118.2882	8.96	A	3.1	M_{CA}	0.09	56	629955	
1987 DEC 8	6:36	5.83	33.0029	-115.8322	1.72	A	3.1	M_{CA}	0.14	31	630141	
1987 DEC 8	18:45	33.23	32.9960	-115.8551	1.92	A	3.4	M_{CA}	0.20	44	630186	
1987 DEC 12	18:20	48.99	33.0003	-115.8028	3.34	A	3.0	M_{CA}	0.11	37	738731	
1987 DEC 13	15:02	39.04	32.9059	-115.7008	4.10	A	3.2	M_{CA}	0.13	33	738805	
1987 DEC 14	2:30	5.57	34.8884	-119.0463	13.66	A	3.2	M_{CA}	0.18	55	630556	
1987 DEC 15	18:23	46.10	35.3724	-118.7743	3.20	A	4.1	M_L	0.14	111	630677	14
1987 DEC 17	1:51	58.89	33.0299	-117.7638	6.00	C	3.5	M_L	0.19	44	630763	15
1987 DEC 17	7:26	25.65	33.9806	-116.6840	8.64	A	3.1	M_{CA}	0.10	57	630775	
1987 DEC 19	7:20	59.79	32.9385	-117.7309	6.00	C	3.0	M_{CA}	0.27	29	630929	
1987 DEC 19	8:06	45.85	32.9421	-117.7346	6.00	C	3.3	M_{CA}	0.29	48	630932	
1987 DEC 24	16:12	2.34	35.4777	-118.3571	5.39	A	3.1	M_{CA}	0.10	60	631273	
1987 DEC 25	1:00	46.97	34.1807	-116.4088	2.60	A	3.1	M_{CA}	0.10	60	631310	
1987 DEC 25	18:15	48.85	33.1248	-115.7411	2.64	A	3.5	M_{CA}	0.15	38	631350	
1987 DEC 28	3:04	36.32	32.6085	-115.7962	6.00	A	3.0	M_{CA}	0.11	40	739700	16
1987 DEC 29	10:17	18.24	33.5471	-117.2013	5.51	C	3.1	M_{CA}	0.19	59	631594	17
1987 DEC 31	21:08	14.93	34.1751	-116.4001	6.00	C	3.0	M_H	0.06	9	135424	
1987 DEC 31	21:34	1.33	34.1758	-116.4163	2.22	A	3.9	M_L	0.12	92	740044	18

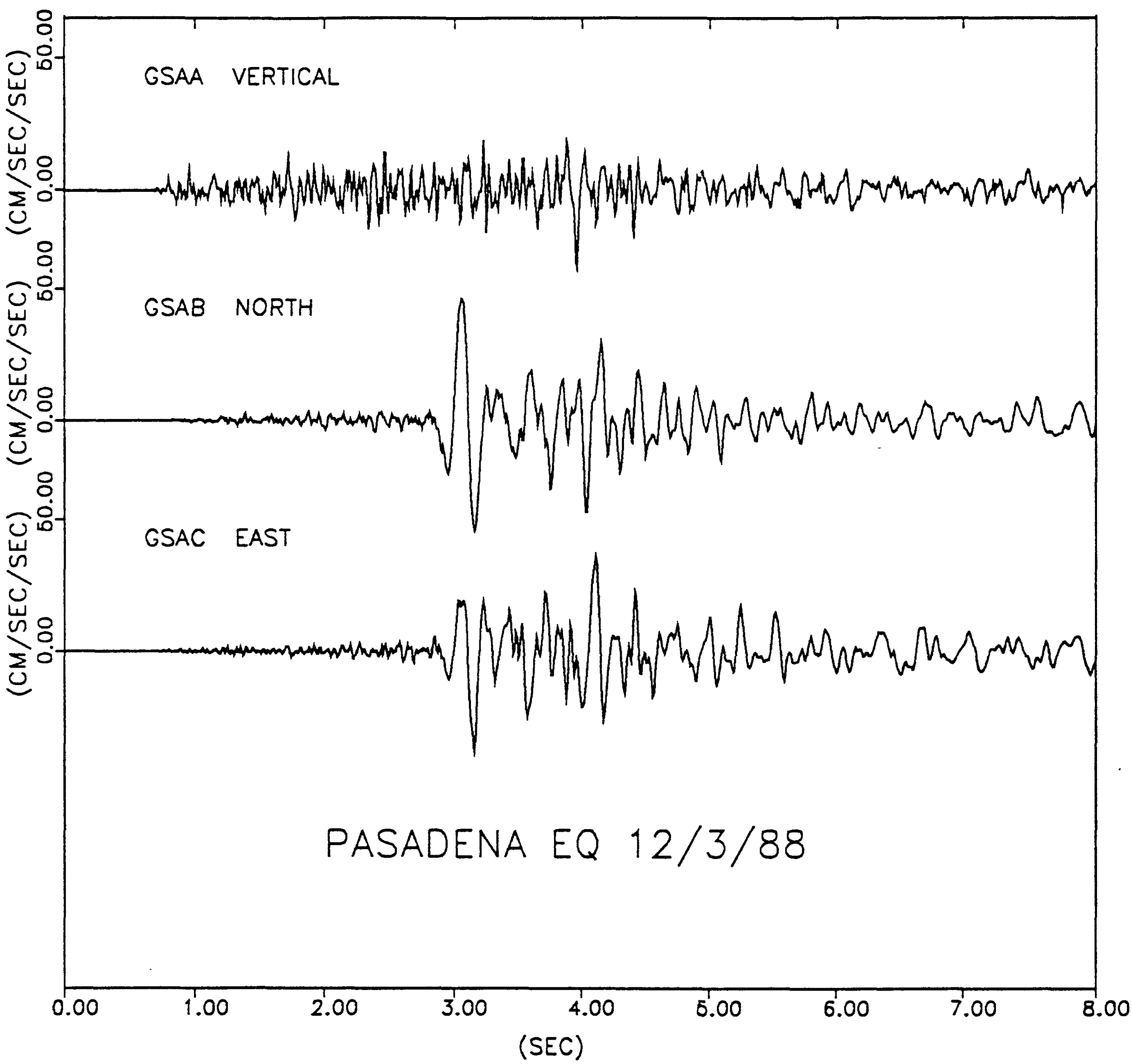

Figure 1. A sample record from the GSA low gain force balance accelerometer for the Pasadena earthquake of December 3, 1988 (M_L 4.9).

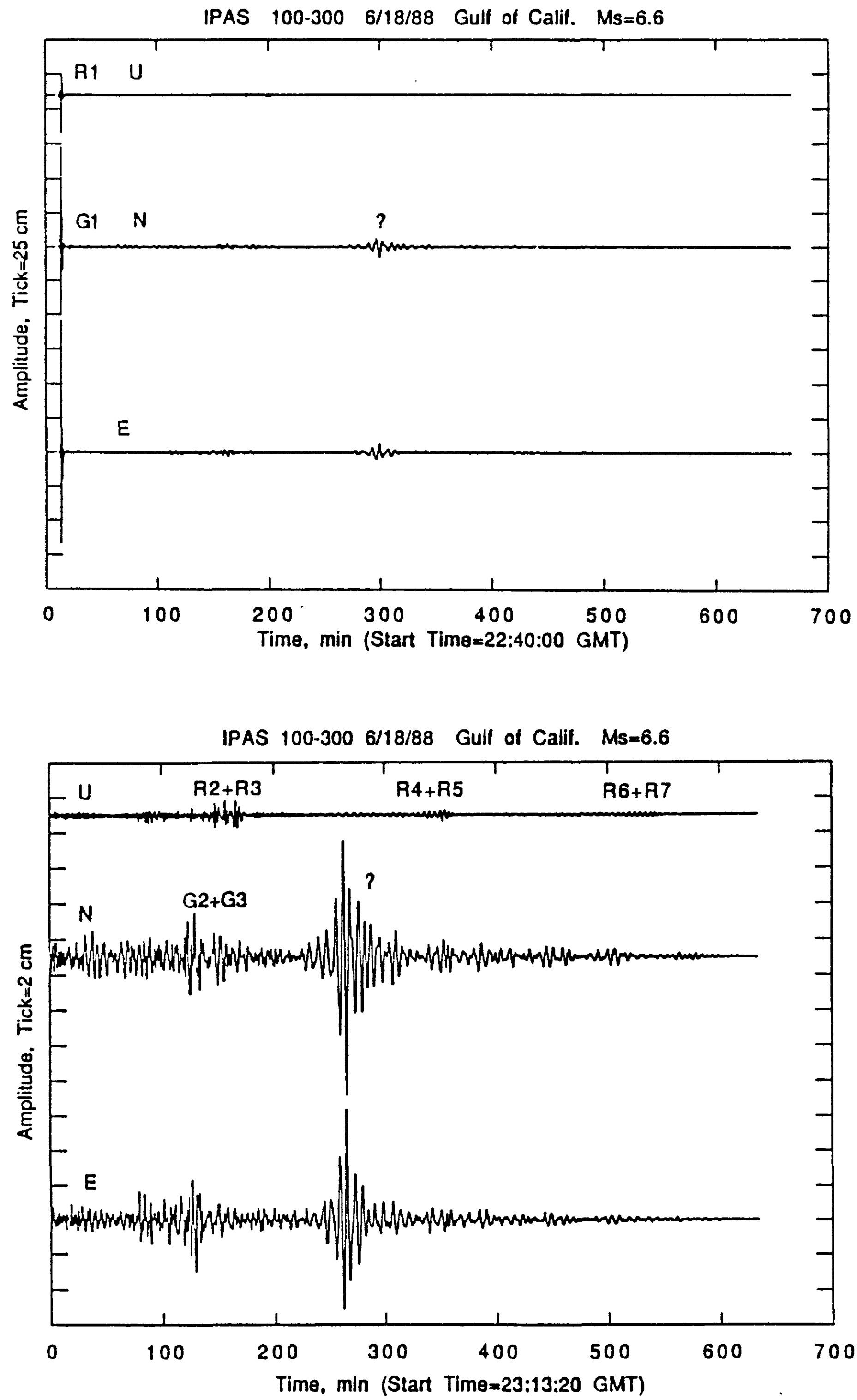

Figure 2. The 100–300 (ultra-long period) seismogram from the PAS site for the Gulf of California earthquake. a) The pulse in the beginning is the surface-wave train, and the question mark indicates the unknown phase. b) Same record with the first surface wave trains removed and the amplitude blown up by a factor of eight.

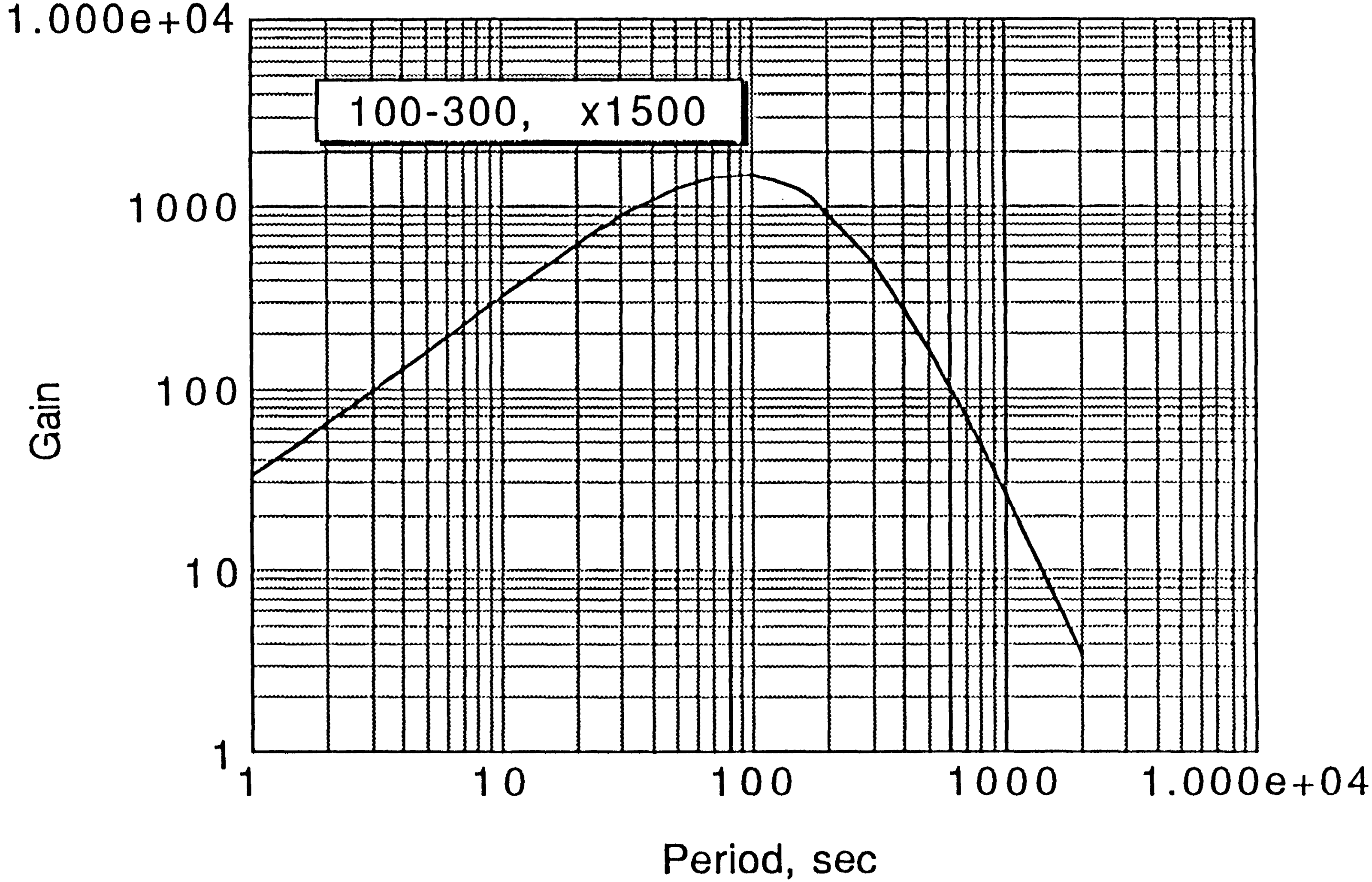

Figure 3. Response curve of the 100–300, x1500 (ultra-long period) system.

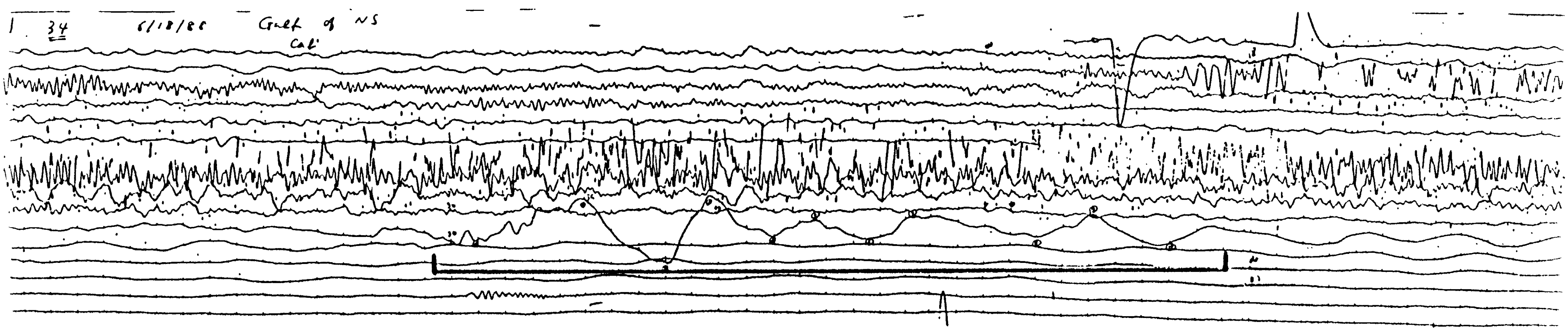

Figure 4. The Press-Ewing seismogram of the same phase shown in Figure 2.

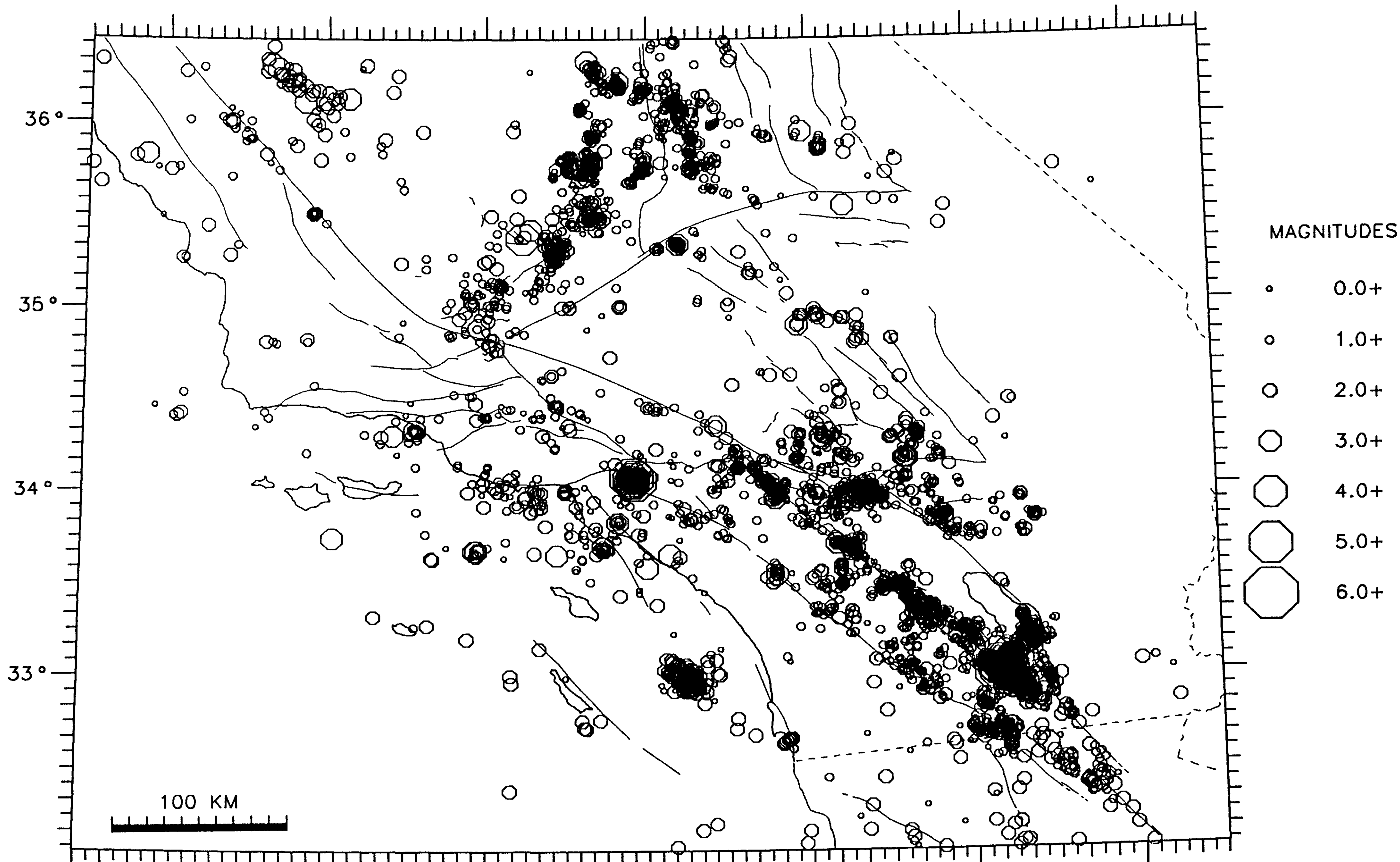

Figure 5. Map of all located earthquakes in southern California for the period of July through December 1987.

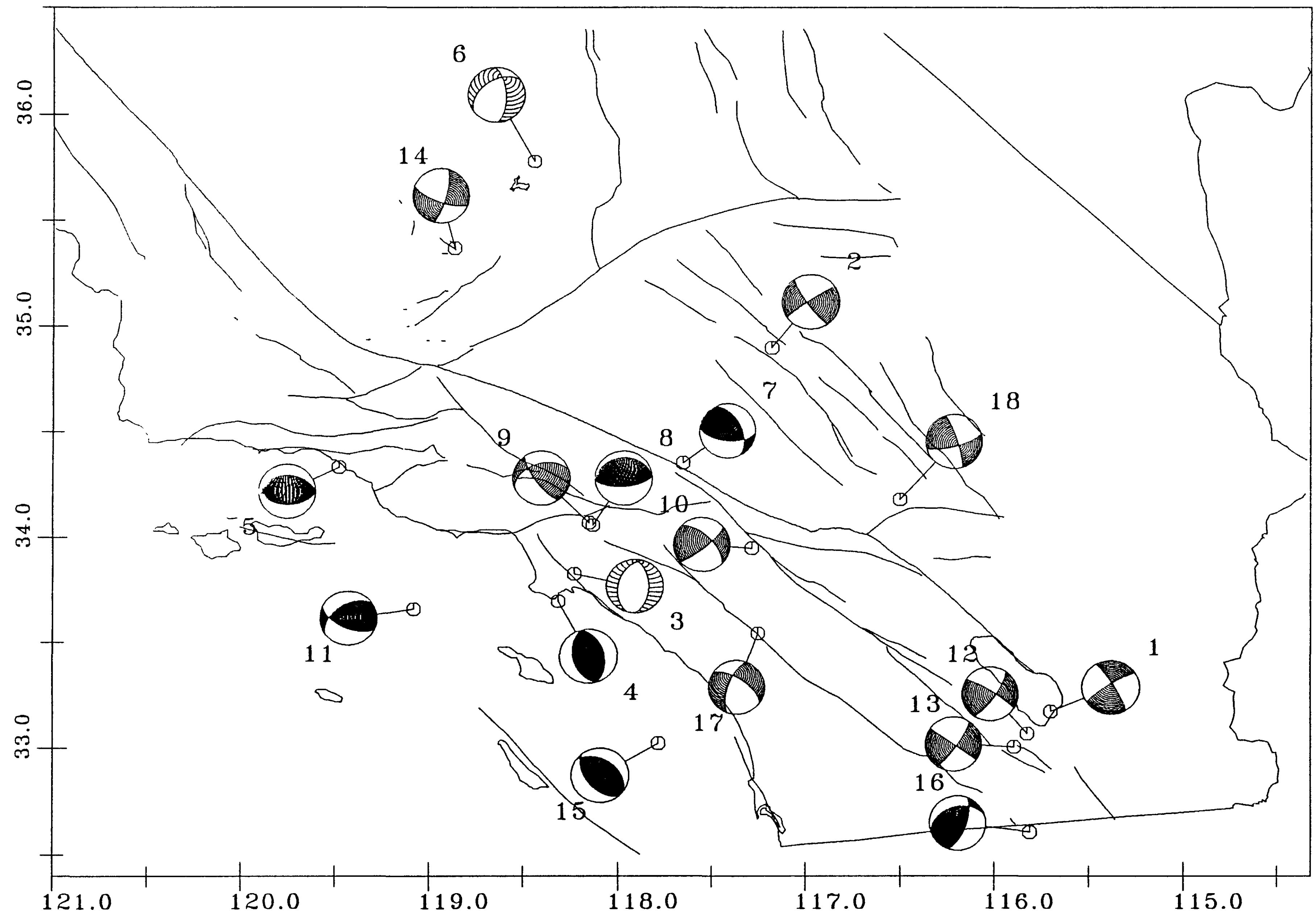

Figure 6. Lower hemisphere focal mechanisms for selected events for the period July through December 1987.
Event numbers corrispond to numbers in FM column of Appendix A.

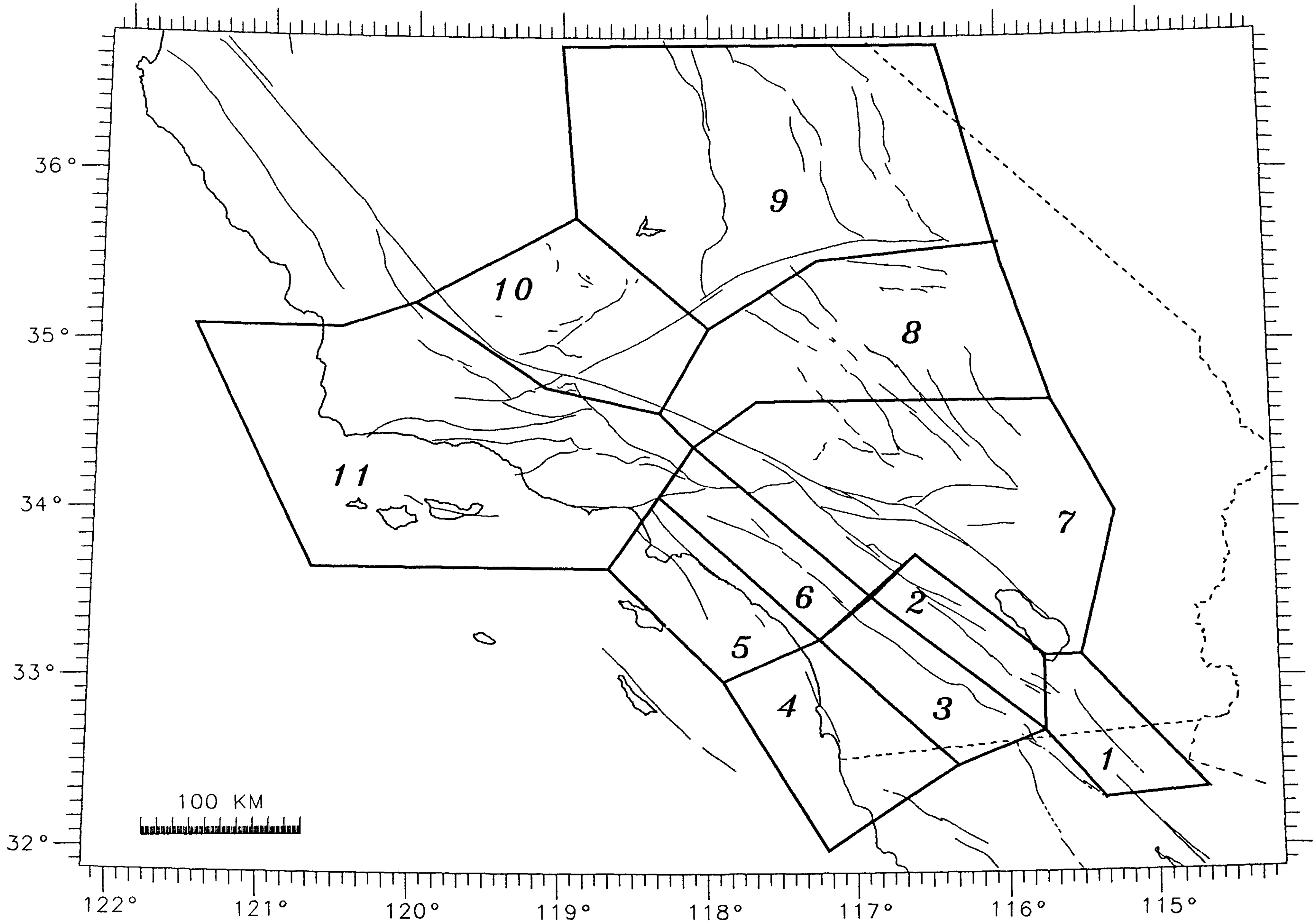

Figure 7. **Map** of sub-regions used in Figures 8a and 8b. The geographic name of each sub-region, as used in the text, can be found in the headings of Figures 8a and 8b.

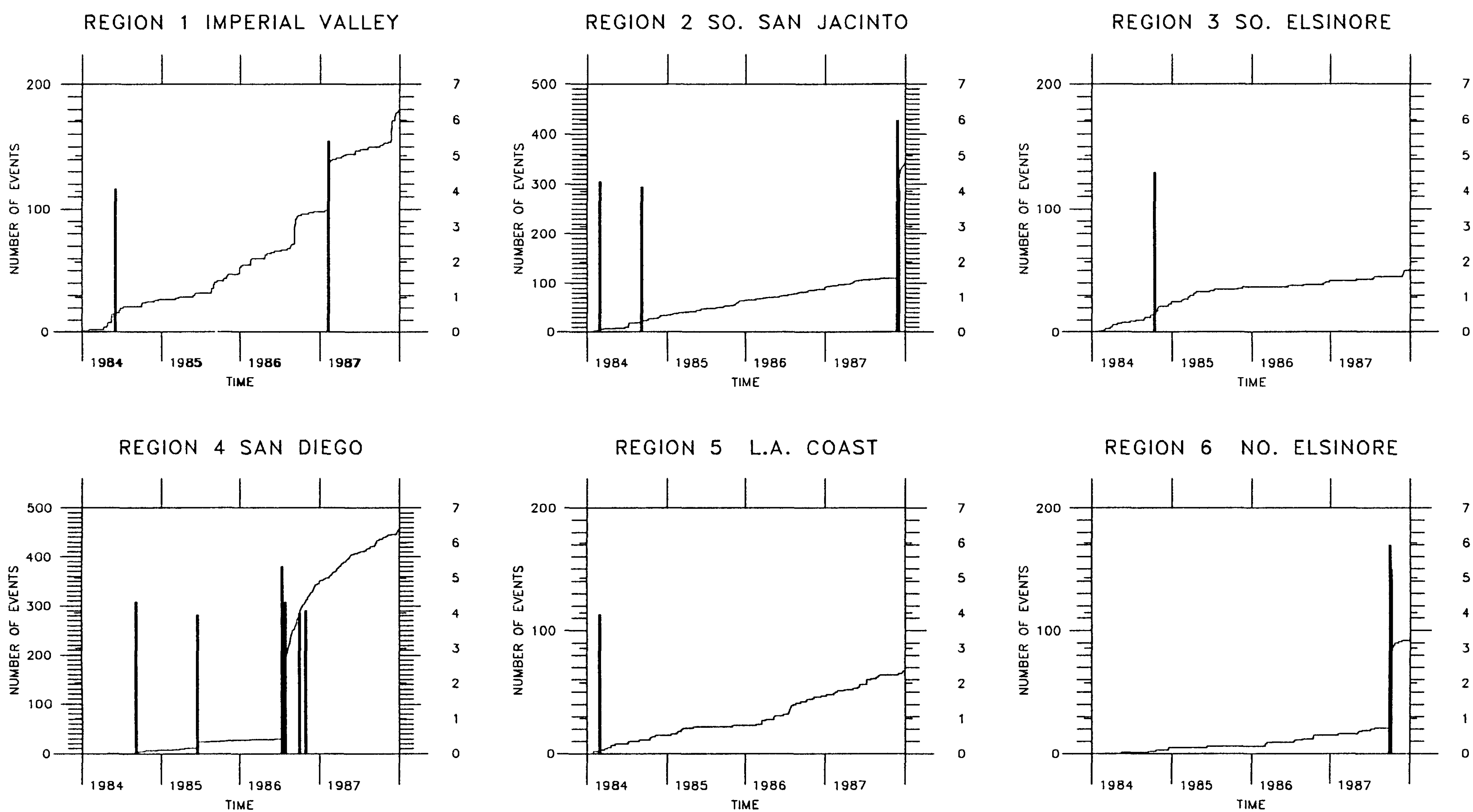

Figure 8a. Cumulative number of events ($M_L \geq 2.5$) in sub-regions 1 through 6 over the four year period December 1987. The boundaries of the sub-regions are shown in Figure 7. Vertical bars represent time and magnitude (scale on right) of large events ($M_L \geq 4.0$). Note that the vertical scales of the plots may not be the same.

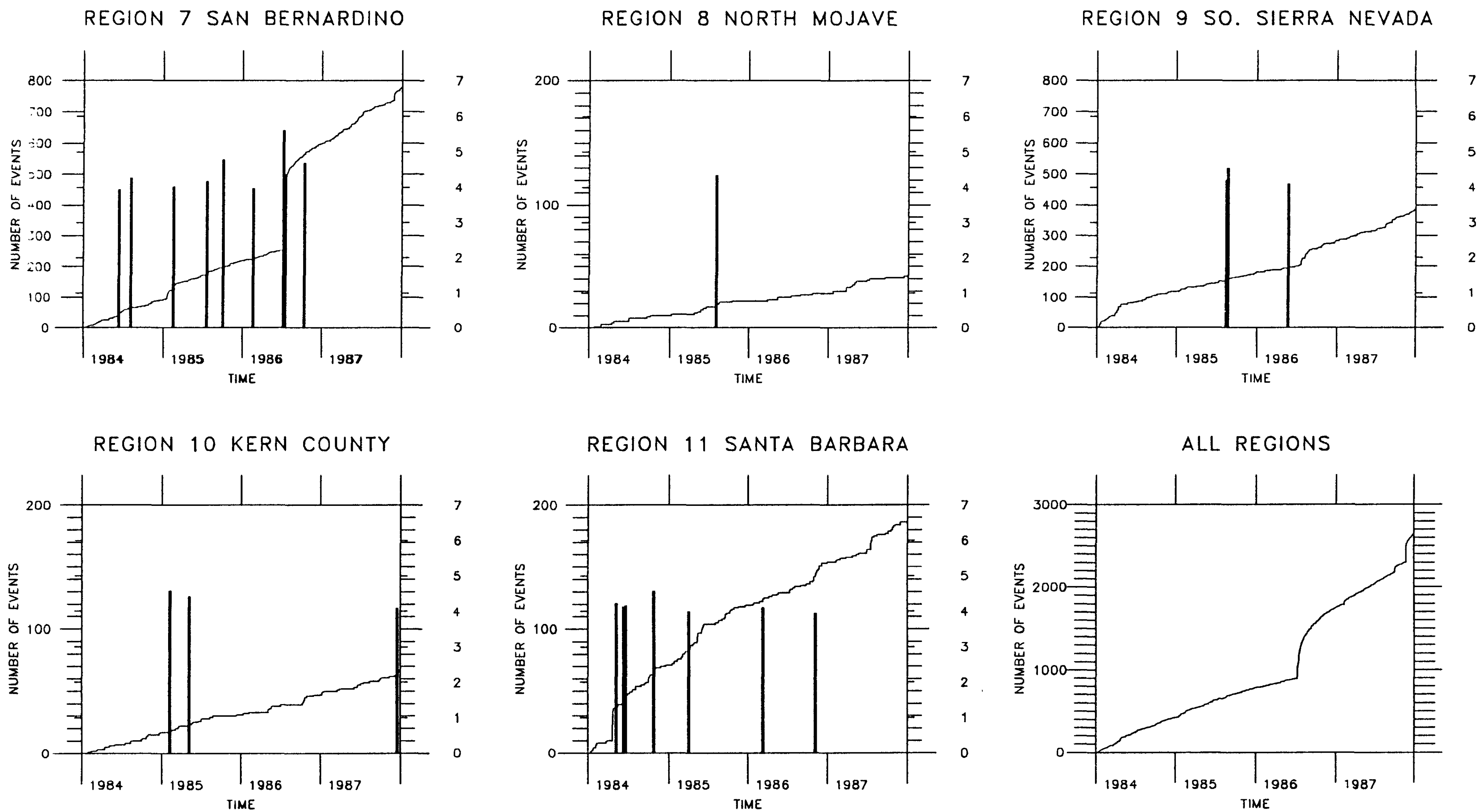

Figure 8b. Cumulative number of events ($M_L \geq 2.5$) in sub-regions 7 through 11 and for all sub-regions over the four year period ending December 1987. The boundaries of the sub-regions are shown in Figure 7. Vertical bars represent time and magnitude (scale on right) of large events ($M_L \geq 4.0$). Note that the vertical scales of the plots may not be the same.

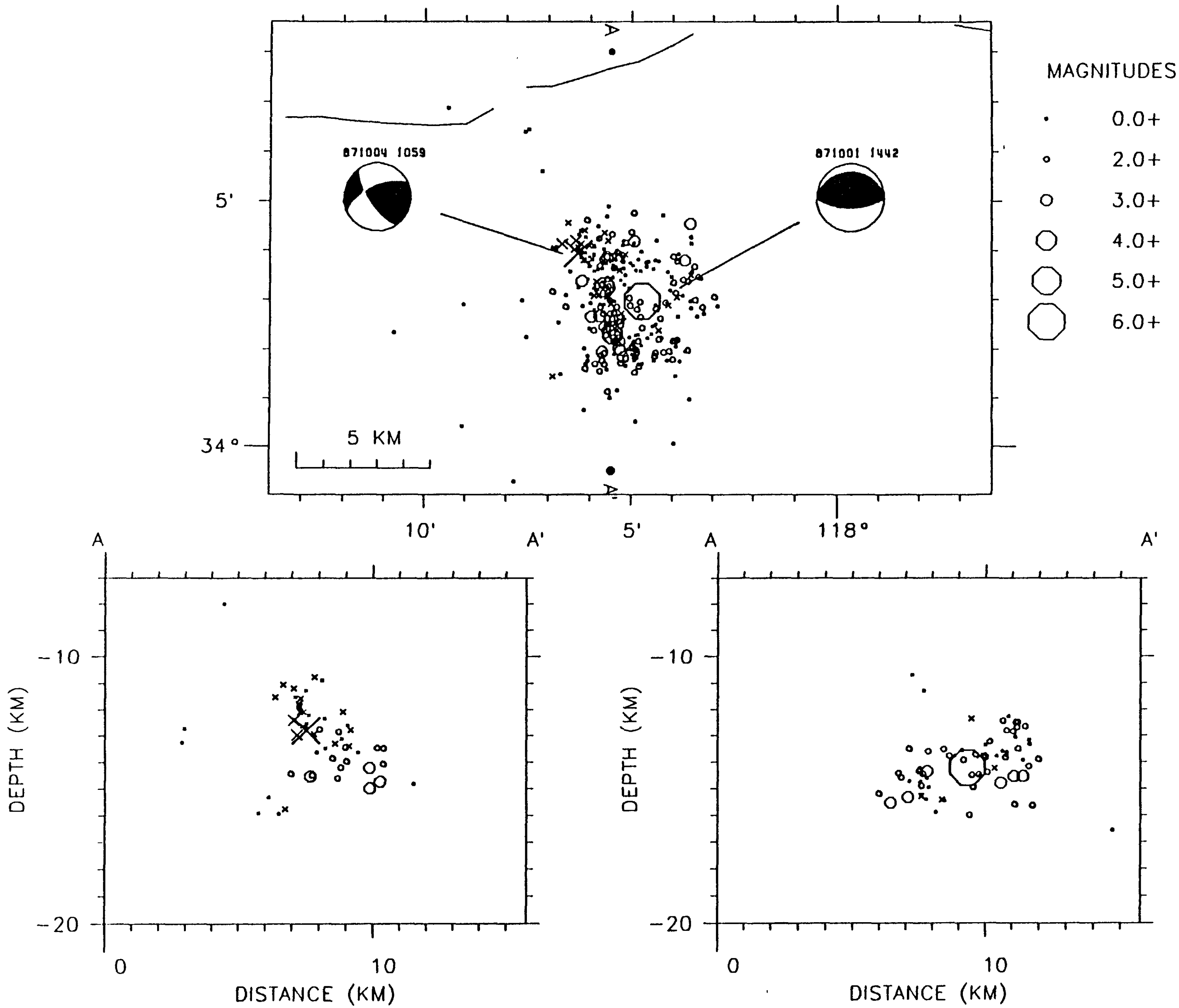

Figure 9. a) Map view of the Whittier Narrows earthquake sequence. Events are represented by cirles for the period before the M_L 5.3 aftershock and as x's for the period after. Focal mechanisms are lower hemisphere projections. b) Cross section of events west of the line A–A′. c) Cross section of events east of the line A–A′.

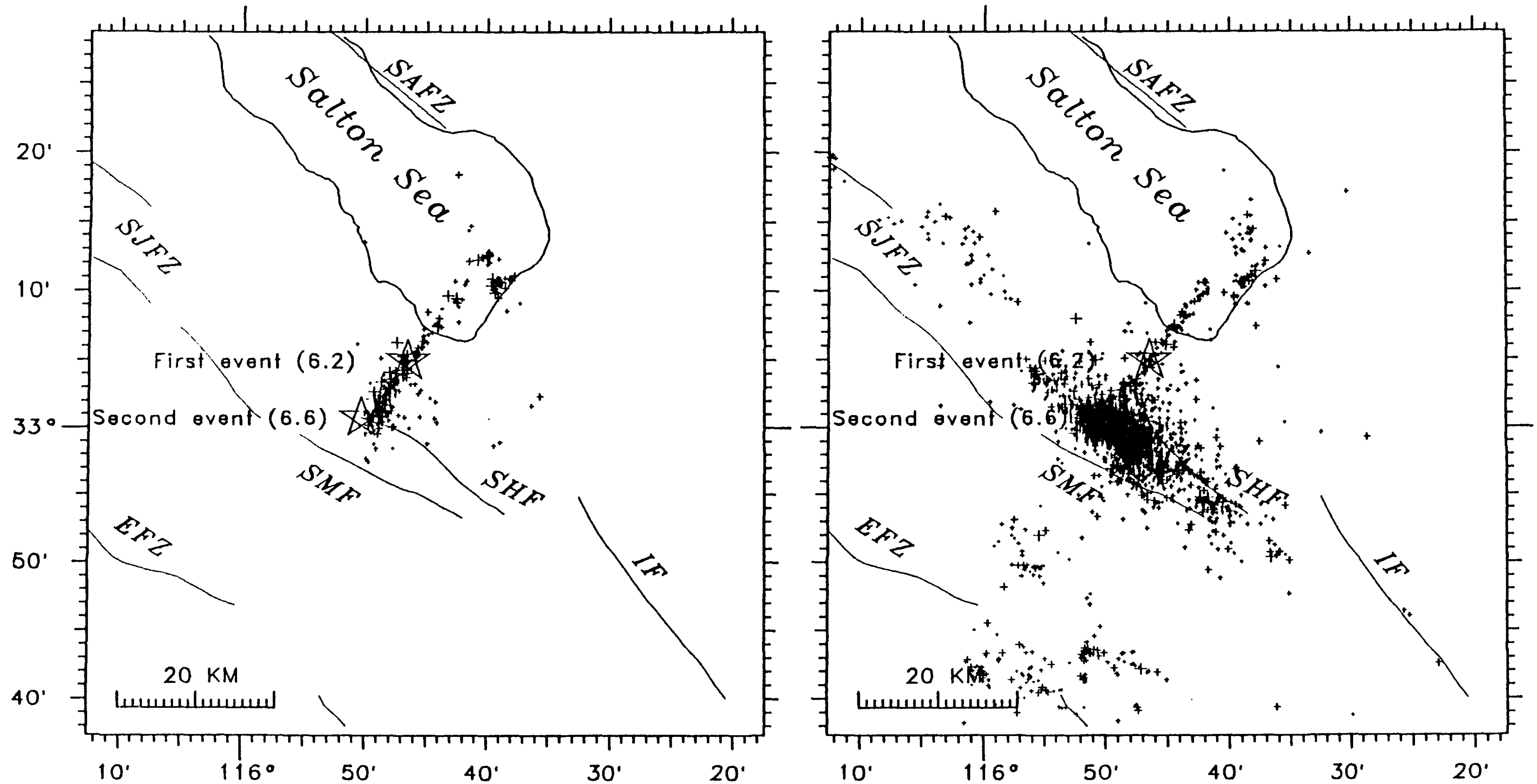

Figure 10. The Superstition Hill earthquake sequence. a) The first mainshock and its aftershocks delineate the Elmore Ranch fault trend in the 11.4 hours before the second mainshock. b) Aftershocks following the second mainshock through December, 1987. EFZ = Elsinore fault zone, IF = Imperial fault, SAFZ =

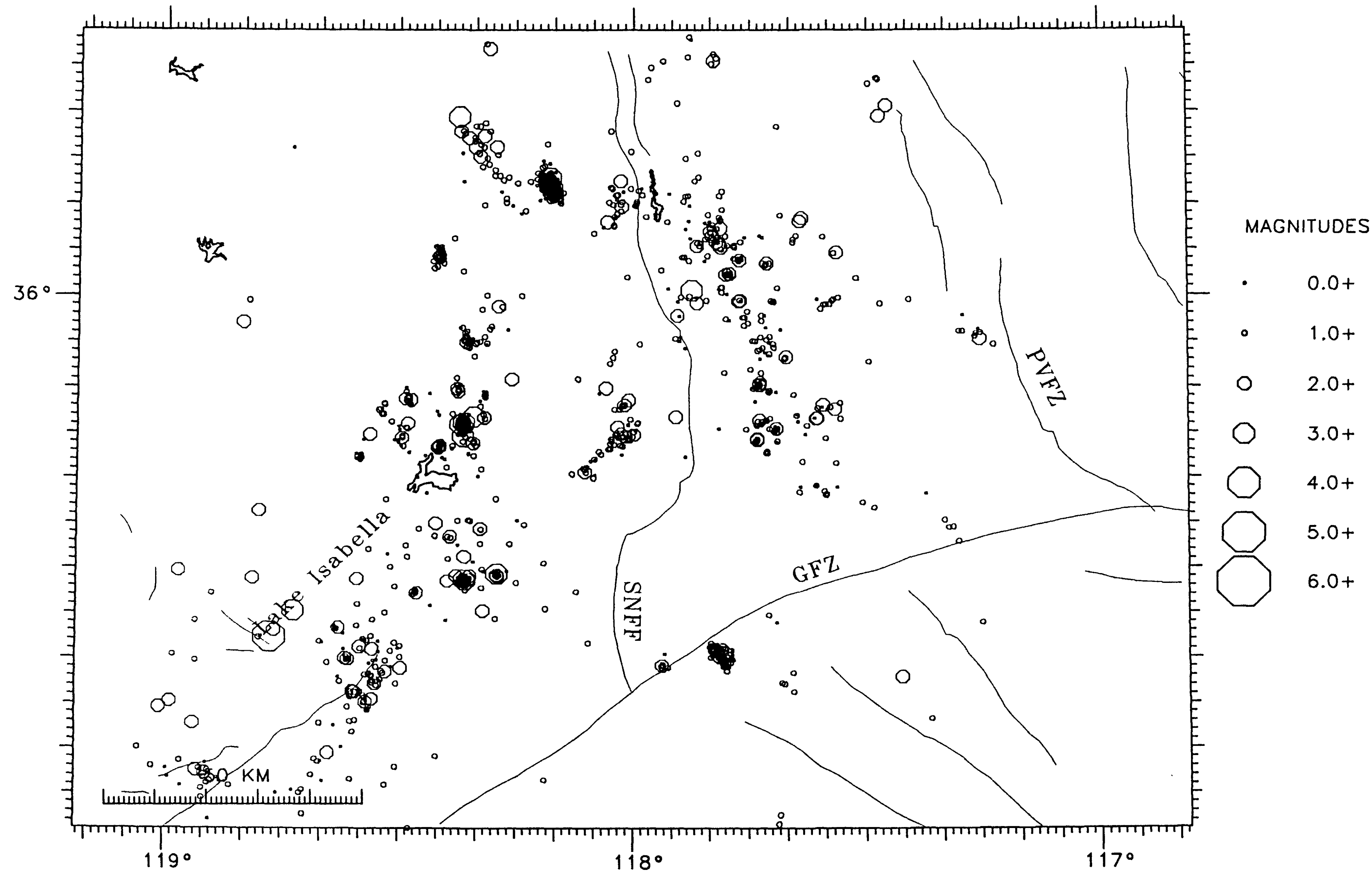

Figure 11. Earthquake activity in the Southern Sierra and Coso areas. Many clusters of activity are evident, several are discussed in the text. GFZ = Garlock fault zone, PVFZ = Panamint Valley fault zone, and SNFF = Sierra Nevada frontal fault.