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REGIONAL SEISMIC NETWORKS IN CALIFORNIA

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Regional Seismic Networks in California

Introduction

Short period seismic networks in California have a long history. They have been developed by different institutions with different objectives. Equipment for recording and analyzing earthquakes has undergone several revolutions. What can be done easily and routinely today could hardly have been imagined by the planners of the first extended networks in the decades following the great 1906 San Francisco earthquake. Moreover, the conceptual framework of plate tectonics and the needs of the earthquake hazard reduction program lead to far more detailed and sophisticated questions for the modern network to answer than those addressed by the early networks.

The plan of this paper is to trace the history of the development of seismic networks in California, with emphasis on size, density, instrumentation, and analysis procedures as well as on the purposes that the networks served. The paper is offered to help resolve the impasse that has frozen the networks, prematurely, in their 1982 configuation for nearly 10 years and to encourage a renewed effort to bring the networks to a state of completion that will permit them to fulfill their essential role in earthquake research and hazard reduction.

I. History of network development

A. Original local earthquake networks at UC Berkeley and Caltech

The frequent occurrence of earthquakes in California and the need for coordinated networks of seismographs to study them have been recognized since the time of Holden at the dawn of instrumental seismology in the U. S. 100 years ago (Louderback, 1942). The seismic networks that have evolved in northern and southern California over the last century have pressed the limits of available technology; but for many decades the lack of adequate instruments for detecting, recording, and timing earthquake waves and for collecting and analyzing their records placed crippling restraints on the size and effectiveness of seismic networks. From 1887 to the late 1920's, the UC Berkeley stations at Mt Hamilton and Berkeley were the only stations with accurate timing in the state. They operated mechanical seismographs with magnifications of about 100. Even after the development of the Wood-Anderson and Benioff seismographs in the late 1920's and early 1930's, the California networks remained primarily reconnaisance in nature. In 1952 the California networks consisted of only 10 northern (UC Berkeley) and 15 southern (Caltech) widely scattered self-contained seismograph stations, with relatively poor time control, that wrote "paper" records of moderate dynamic range. Collection and hand processing of the records was labor intensive and slow; and the resulting earthquake solutions were generally poorly constrained, especially as regards focal depth.

Significant upgrading of the UC Berkeley northern California network was carried out by Don Tocher in 1959-1961 (Bolt, 1989) with the installation of 8 telemetered short-period stations that were recorded together on a 16 mm film recorder (Develocorder). That equipment had been developed to serve the U S nuclear test detection program. Seismic network telemetry was introduced to southern California in 1966-1972, when most of the Caltech stations were equipped for telemetering to Pasadena for recording. Both networks remained very sparse and provided essentially reconnaisance coverage of earthquakes of magnitude 3 and larger. In 1968 the northern California network contained about 15 stations and the southern California network contained about 20 stations.

B. Early microearthquake network experiments in California

When the USGS began to develop a program of earthquake research in California in 1966 in response to the challenge posed by the Press Panel report on earthquake prediction (Press, et al., 1965), it brought different experiences with seismic instrumentation and with level-of-detail in local earthquake studies than those underlying the existing California networks. Its study of microearthquakes at Kilauea volcano in Hawaii in the late 1950's and early 1960's, by means of a dense high-gain short-period seismic net that included a small telemetered subnet at its center, had shown the importance of matching seismometer response to the recording environment and the character of the earthquakes studied (Klein and Koyanagi, 1980; Eaton, 1986a, 1986b). Its study of earthquakes produced by injection of waste-water into basement rocks beneath the Rocky Mountain Arsenal in Colorado in the early 1960's, by means of improvised seismic arrays employing truck-mounted, low-frequency seismic systems designed for long-range refraction profiling, had demonstrated the precision of hypocenter determinations that could be obtained with a suitable network (Healy, et al., 1968).

The primary instruments for earthquake studies brought to California by the USGS in 1966 were the 20 portable 3-component seismic systems that recorded on low-power, "10-day", fm tape recorders (Criley and Eaton, 1978). With internal chronometers and WWVB radio time signals recorded on tape along with high- and low-gain tracks for seismic data, these systems provided reliable timing and moderate dynamic range (60+ db). The electronic response was flat from dc to about 17 hz; and with the 1-hz moving coil seimometers employed (EV-17's), the overall system response was flat, for constant peak ground velocity, from 1 hz to 17 hz. The shape of the response curve, coupled with the very high electronic amplification available, made these instruments very well suited for recording microearthquakes in the California environment. Earthquake signals that exceeded natural background noise levels in the frequency range 1 hz to 20 hz could be detected at virtually any site in the region.

During the next two years these systems were used with great success in exploratory microearthquake studies along the San Andreas fault. The 10-day portable stations were laid out in a dense cluster (5 to 10 km spacing) over the region studied, and refraction profiles were run through the cluster with truck-mounted refraction systems to determine the local crustal structure for interpreting records of earthquakes recorded by the cluster. This work was in response to the Press Panel recommendaton for the development of network clusters along major faults for earthquake prediction.

The first experiment was carried out on aftershocks of the 1966 Parkfield-Cholame earthquake (fig 1). An 8-station, 20-km diameter network of 10-day recorders was deployed around the southern end of the 1966 rupture zone and operated for about 10 weeks. The hypocenters of the hundreds of aftershocks recorded by the net were sufficiently precise (estimated errors less than 1 km) that they mapped out the slip surface of the main shock in great detail (Eaton et al., 1970a). In the second experiment, in 1967, an 18-station portable network about 50 km in diameter was laid out around Bear Valley, south of Hollister, to study microearthquakes on that creeping section of the San Andreas fault (fig 2). That network, which was operated for about 6 weeks, unexpectedly recorded a shallow M4 earthquake along with hundreds of aftershocks near the center of the network. In addition, it recorded an ongoing background of small earthquakes on the San Andreas fault where it crossed the network. This study demonstrated the detail that such a network can achieve in resolving complex distributions of earthquakes in close proximity to one another (Eaton et al., 1970b).

Concurrent with the portable network experiments, the parameters for a telemetered network were being explored. Because such nets are limited by availability and cost of telemetry, careful thought was given to the selection of a data multiplexing system. A constant bandwidth, IRIG standard, 8-channel audio frequency fm system that operates over a 300 hz to 3000 hz voice-grade phone line was selected (Wayne Jackson, written communication; Eaton, 1976). It provides the same frequency response in each channel, dc to about 30 hz, and can yield 40+ db dynamic range on all channels if carefully implemented. Data recording was initially on film strip recorders (Develocorders) that permitted about 0.05 sec timing resolution and recorded 16 stations with a dynamic range of 30 to 40 db. The overall system response was about the same as the 10-day recorder system: flat, to constant peak ground velocity, from about 2 hz to about 15 hz.

Small experimental telemetered clusters were set up on the San Andeas fault near Palo Alto (9 stations) in 1966 and near San Juan Bautista (8 stations) in 1967. In 1967 and 1968 an additional 11 stations were set up between the Palo Alto and San Juan Bautista clusters and a small 4 station cluster was set up at Parkfield. All stations were recorded on Develocorders in Menlo Park. Analysis of 14 months' data (March 1968-May 1969) from the 30+ station telemetered network between Hollister and Palo Alto produced exciting results (fig 3) (Eaton et al., 1970b). Some sections of the major faults (probably creeping at depth) were marked by dense, narrow zones of microearthquakes between the surface and 10 to 12 km depth, while other sections (probably locked at depth) had virtually no microearthquakes along them. The three-dimensional mapping of microearthquakes made possible by the telemetered network provided new details on the subsurface relationships between faults that were mapped in close proximity at the surface.

C. Growth of a full scale microearthquake network in central California

Lessons drawn from the three experiments described above were: 1) dense microearthquake networks can map faults in three dimensions on the basis of aftershocks of large quakes or ongoing microearthquake activity associated with creeping sections of the faults; 2) the portable nets attain good resolution and are very flexible, but they require considerable effort and time to record, collate, and analyze the data; 3) the telmetered network, with somewhat sparser station spacing, attained results comparable to those of the portable nets, was far simpler to operate and analyze, and could be operated continuously rather than sporadically; 4) a telemetered strip network along the major faults would permit mapping of locked and creeping sections as well as provide a long term record of variations of activity along the faults.

These lessons provided impetus for considerable expansion of the use of telemetered networks over the next decade. The expansion took two forms: gradual expansion of the central California network to cover the Coast Ranges from Cholame to Clear Lake, and deployment of a large number of detached, special-purpose environmental networks that were analyzed separately from the central California network and from each other. Some of the detached networks eventually became important extensions of the central or southern California networks. When the first broad plans for a California prediction network were developed in 1971, the overall network was conceived as a group of strip networks along the major faults with large blank areas between them (Eaton, 1971).

From 1966 through 1979 the central California network was viewed as an experiment to develop a dense network covering the most active part of the San Andreas fault system in central California and to evaluate what role such a net should play in an earthquake research/hazard reduction program. All stations were recorded on Develocorders (and magnetic tape after the mid-1970's). Events that were detected by scanning the Develocorder films were timed by hand on the viewer screen or on a tabletop digitizer onto which an image of the film was projected. Events that originated significantly outside the network were not processed. Summary results from the network for the years 1970 through 1977 (Eaton, 1985) are as follows (fig 4):
1) yearly plots of M1.5 and larger shocks show dense continuous lines of epicenters along creeping sections of the major faults; 2) locked sections of major faults, including the sections of the San Andreas fault that broke in 1906 and 1857, are virtually aseismic; 3) earthquakes scattered across the Coast Ranges are somewhat concentrated in bands along both flanks of the Coast

Ranges; 4) focal depths were generally well determined along the major faults near the center of the network but were poorly determined along the flanks of the Coast Ranges where the network was sparse.

D. Emergence of the northern and southern California regional networks

In early 1980 the procedures for analyzing stations telemetered to Menlo Park were revised (Eaton, et al., 1981). All of the northern California environmental networks were added to the central Coast Range network to form a combined northern California network. All stations were recorded on Develocorders, which were scanned to identify events for further processing. The scan lists were supplemented by events from an improved computer-based, real-time processor (RTP) (Allen, 1978, 1982), which detected and located many events in dense parts of the network that fell below the threshold for hand processing. Events continued to be timed by hand from film projected onto a tabletop digitizer. Earthquake phase lists were supplemented selectively by RTP data. With these changes, the northern California network took on the character of a true regional network; and by 1982 the number of stations telmetered to Menlo Park exceeded 300.

In southern California, early special-purpose telemetered environmental networks were installed as follows: 1969 - Santa Barbara Channel; 1971 - Los Angeles Basin; 1973 - Oxnard/Ventura Basin and Imperial Valley; 1974 - eastern Mojave Desert. An agreement between the USGS and Caltech for cooperation in the operation and analysis of the southern California nets led to integration and further expansion of the network from 1975 onward. A computer-based system for recording and analyzing the network data was developed at Caltech by Carl Johnson during the late 1970's (Johnson, 1979). By 1982 the number of southern California stations recorded and analyzed at Pasadena exceeded 200.

In an attempt to present a broader picture of

California/Nevada seismicity than was possible from the isolated regional networks, summary seismic results for the years 1978-1981 were combined from the four contiguous networks in northern California (USGS,Menlo), southern California (Caltech/USGS, Pasadena), central Nevada (UNR, Reno), and southern Nevada (USGS, Denver). The catalogs were combined to provide best coverage, without overlap and duplication of events, of the four subnet regions; and yearly seismicity maps for the California/Nevada region were prepared. The maps for 1980 and 1981 (fig 5), when the networks were most extensive, were most interesting. These maps showed the seismicity associated with the entire San Andreas fault system in some detail - from Mexico to Cape Mendocino and from the Pacific Ocean to western Nevada, and they helped to put seismicity of individual parts of the region in better perspective with that of the region as a whole (Eaton, 1982). They also showed that the network was too sparse in the Great Valley and southern Sierra Nevada to delineate the seismicity in those regions.

The most significant change in the networks after 1982 was the application of the CUSP computer-based recording and analysis system to the northern California network in 1984. That system, which is an outgrowth of the earlier system (CEDAR) developed by Carl Johnson at Caltech for the southern California network, greatly simplifies the collection and analysis of network data. The entire network is digitized and screened by computer for the occurrence of earthquakes in real time. Only the portions of the record corresponding to detected earthquakes are preserved; so the CUSP system requires better network configuration and performance to avoid loss of earthquakes than did the older procedure based on hand analysis. Although the analog fm signals of the entire network are still recorded on magnetic tape so that missed events can be recovered, the tape recorders and associated playback equipment are obsolete and expensive to maintain and use; so that backup facility must be updated, or it will be lost eventually.

Since 1982, network expansion has been limited mostly to small environmental networks that reduce the size of holes in the net or extend it a little farther into seismically active regions around its margins. The largest addition was the network in the Long Valley region to monitor seismicity in Long Valley caldera and the surrounding region.

E. Impact of network results versus network coverage

The examples of results from the network at successive stages in its development summarized above show that the scope of problems addressed by the network expanded rapidly as the network grew and its analysis became more comprehensive. The limited portable network studies at Parkfield (1966) (fig 1) and Bear Valley (1967) (fig 2) demonstrated the resolution of a dense network and showed details of earthquake processes on small sections of individual faults. The prototype telemetered network between Palo Alto and Hollister (1968-1969) (fig 3) resolved activity on individual faults at the junction of the San Andreas, Sargent, and Calaveras faults. The telemetered strip network between Clear Lake and Parkfield (1976-1977) (fig 4) documented the very different seismic behavior of locked and creeping sections of the San Andreas Fault and placed them in the context of seismicity in adjacent parts of the Coast Ranges. Even though the network was 500 km long and 100 km wide at that time, it covered only a fraction of the greater San Andreas fault system; and it offered limited insight into the broader relationships among the tectonic elements composing that system.

A much more comprehensive picture of seismicity and the associated crustal deformation emerged when the results of the contiguous California and Nevada networks were combined and plotted together for 1980 and 1981 (fig 5). Contrasting tectonic styles across the region were matched by contrasting patterns of seismicity. The slipping sections of the major faults were outlined clearly on the annual seimicity maps, but patterns of seismicity in less active regions were not, however.

By the end of 1986, the northern and southern California networks had operated with few changes in station configuration for seven years. Combined maps of earthquakes from the California and Nevada networks for 1980-1986 resolved patterns of seimicity that were not clear on the annual plots. The 1980-1986 seismicity maps and supporting catalog were analyzed and compared with the principal tectonic features of northern California by Eaton (1989) (fig 6) and of all of California by Hill, Eaton, and Jones (1990) (fig 7). These two papers deal primarily with aspects of the catalog that document the seismicity (and, by inference, the deformation) of the entire San Andreas fault system and its major tectonic subdivisions. Analyses at such a scale are required to place sections of the faults that generate M7+ earthquakes in context with the complex system of which they are parts.

The networks serve interests with a broad range of spatial and temporal scales. The comprehensive regional coverage coupled with the timely, systematic analysis of their data place the microearthquake networks first among our tools for detecting and interpreting significant events and trends within the fault system as well as for preserving a detailed historical record of them. The seismic and strain networks fulfill a statewide observatory function by capturing and preserving the earthquake and strain histories associated with the ongoing movement between the Pacific and North American plates and the inexorabe preparation for future major earthquakes. The single thing that we can do today that our successors will not be able to do better is to record and preserve those histories. The cost of failing to do so could be years, perhaps decades, of unnecessary delay in developing a sufficient understanding of the San Andreas fault system to permit prediction of major events within it.

II. Factors underlying the design and implementation of the northern and southern California short-period seismic networks.

For more than 20 years the U.S. Geological Survey has been a leader in the development and application of modern microearthquake networks for detailed studies of geologic processes in the earth's crust. Although this work had important beginnings at HVO in Hawaii and in the Crustal Studies Branch in Denver, it has been pursued most vigorously under the earthquake prediction research program within the Office of Earthquake Studies in Menlo Park. Selection of the seismic systems and network configuration employed has been driven by a combination of factors, including:

1) The USGS mission to monitor and elucidate active geologic processes in the crust, such as volcanic activity and active faulting, at a scale commensurate with that of regional geologic framework mapping and analysis,
2) the amplitude and spectral characteristics of seismic signals from small earthquakes ($1< M <3$) in relation to background microseisms and cultural noise in the regions studied,
3) the number, quality, and distribution of observations required to obtain the needed precision in epicenter location and focal depth of shallow earthquakes ($0< h <15$) in the heterogeneous earth's crust,
4) the intrinsic limitations of the instrumental components and communications systems available for use in the system (cost and complexity have been important considerations in determining what was "available"),
5) the experience and skills of the staff available to install and maintain the network,
6) the level of funding available to install the network and to support its ongoing operations.

Regional networks like those in California and Hawaii could not have been developed without the advances in electronics and telemetry that have occurred over the last 25 years. The early telemetered networks, such as LASA, that were employed in nuclear test detection and the sophisticated multichannel seismic systems developed for petroleum exploration were particularly stimulating and helpful. The defining characteristics of the regional networks, however, (seismic response and number and spacing of the stations) have evolved in response to the tasks to which the developing regional networks were applied.

The development of the network and refinement of its characteristics went hand in hand with the development of the seismological research based on its records. Attributes of the regional networks that have been found to be vital for detailed seismicity studies include:

1) the system frequency response and gain permit the recording of background earth noise (and everything larger) in the frequency range of about 1 hz to 20 hz where small earthquakes (M <3±) have the best signal to earth noise ratio. The shape of the response curve approximates the inverse of the quiet site earth noise amplitude spectrum at frequencies above about 0.2 hz, so the limited dynamic range of the system is utilized effectively.

2) the spacing of stations in the network is dense enough so that earthquakes above the network threshold (about M 1.5) are recorded at 6 or more stations to insure enough redundancy to avoid gross location errors. The small station separation is also extremely important for determing reliable focal depths for shallow earthquakes.

3) earthquake detection and location thresholds are low enough that the relatively frequent small events in the network can be used to delineate seismogenic structures in a reasonably short time.

4) the networks cover large regions with relatively uniform density, so major seismogenic structures such as the San Andreas fault system from Mexico to Cape Mendocino can be studied in their entirety.

Earthquake focal depth plays a special role in the design of regional networks. Focal depth is the most difficult hypocentral parameter to determine reliably; and it depends most critically on network geometry (particularly the distance to the nearest station) and crustal model. Experience has shown that at least one station at an epicentral distance of one focal depth or less is required for a reliable depth determination. Because California earthquakes rarely exceed 15 km in depth and most are less than 10 km deep, station separations of 10 km or so are needed. It appears that a regional network adequate to monitor the San Andreas fault system should cover virtually all of California. If such a network had a station spacing of only 10 km, more than 4000 stations would be required. Because so many stations appears to be an impractical goal, we must seek a distribution of stations that provides adequate coverage in critical regions, and relaxed coverage elsewhere, with a smaller number of stations. Such a modified network derived by selective augmentation of the present northern and southern California networks would have about 800 stations. If uniformly distributed, an 800 station network covering all of California would have an average station separation of about 23 km.

Another critical issue is the choice of seismic system for the network. That choice must depend on the primary uses the data will serve, on the spectral characteristics of the earthquakes studied and of the background noise, and on the limits on wave propagation imposed by the earth's crust. The frequency response and sensitivity of the standard system employed in the USGS networks have been shown to be well suited to recording M1 to M5 earthquakes in California (Eaton, 1977, 1989). The limited dynamic range of the telemetry system (40 to 46 db) is a problem that has been offset, in part, by operating a sparse subset of dual-gain stations in the network.

Another issue is the complement of instruments in the stations. Ideally, we would like to record all three components of ground motion at each station, but the number of components in the network would be unmanageably large if we were to do so. The reasons for recording the horizontal components are 1) to improve the resolution of S waves, 2) to obtain horizontal component amplitudes for computing local magnitudes, and 3) to obtain all three components of ground motion to support further analysis of the recorded waves. These purposes do not require the density of stations that is needed to determine reliable focal depths, however.

Clear S wave arrivals at one or more relatively near-in stations are extremely helpful in determining origin time; and for events outside the network, S wave arrival times are essential for determining accurate epicenters as well. Because S waves stand out most clearly on the seismograms in the distance range of direct arrivals (epicenter to 50 km or so), it is desirable to have one or more stations with horizontal components within that range. Detecting S waves on the records also depends on having sufficient dynamic range so that the record is not "clipped", which makes secondary phases virtually impossible to pick.

The subset of NCSN stations with horizontal component systems operating at 42db attenuation has proved to be very effective in providing readable S wave arrivals for M2- to M3+ earthquakes. These systems also provide on-scale amplitude measurements for M2- to M5+ events (the larger ones are on-scale only at larger recording distances). Still lower gain (or higher dynamic range) systems are needed to obtain S wave arrivals at short distances for earthquakes larger than M3.5 or so.

Yet another important issue is the telemetry system employed by the network. Digital telemetry would provide much better dynamic range (96db or more) than the fm analog system currently used (40 to 46db). The lower cost and greater flexibility of the fm system made it ideal for the early network that was recorded on Develocorders (<40db dynamic range) or analog magnetic tape (about 50db dynamic range). When computer based recording and analysis was introduced, however, the fm telemetry system was found to limit the overall dynamic range of the system unnecessarily.

Digital telemetry has several practical drawbacks compared with fm telemetry of the analog signals, however. Combining digital signals from several sources in the field is complicated and expensive, and each digital channel requires greater bandwidth in the communications system than does each fm channel. The advantage of fm telemetry is greatest with single component stations: signals from 8 stations can be combined in the field for transmission via one microwave or telephone channel to the central recording facility by means of simple summing amplifiers. For the multi-component stations used in NCSC that generate four analog signals the advantage of fm over digital telemetry is much reduced. One microwave channel can carry the signals from one 3-component digital station (16 bits at 100 sps per channel) or from two 3-component analog stations (8 channels at 40 to 46db dynamic range).

The foregoing analysis suggests the use of a hybrid network that employs analog fm telemetry for the many simple vertical component stations required to insure reliable focal depths and digital telemetry for a subset of 3-component stations, operating at slightly lower sensitivities, that will insure recording of readable S waves and on-scale maximum amplitudes for quakes in the M2+ to M5+ range.

The general structure of our telemetry communications system will readily support such a hybrid network. USGS and cooperating agency microwave systems form the backbone of the system, and VHF (and UHF) radios bring signals from field sites to the microwave towers. The microwave system carries a sufficient number of channels that a modest number of channels (40 +/-) in both northern and southern California could be devoted to digital stations whose data would be telemetered continuously to the recording site for time stamping and recording.

III. Current status of the northern and southern California regional networks

Both NCSN and SCSN have remained incomplete since their development was arrested in 1982. At that time several factors combined to stop network development: 1) the cost of maintenance, telemetry, and analysis reached the limit that could be sustained by available funding; 2) the analysis systems were saturated by records from stations already operating; 3) the impact of network results had not been felt fully because papers describing those results were slow to appear; 4) there was general concern over signal quality, dynamic range, bandwidth, etc., as well as the lack of reliable magnitudes computed from network records. Unfortunately, both networks had been deployed somewhat opportunistically as region-specific or topic-specific funds were available; and the final states in which both networks were frozen in 1982 were somewhat illogical and unbalanced with regard to coverage, density, and distribution of components.

Many improvements in network equipment and analysis have been made over the last 10 years;

1) increased use of microwave telemetry and vhf/uhf radio links has greatly expanded network telemetry range and capacity while reducing its cost,

2) improved field units with solar power supplies have improved dynamic range and reduced maintenance visits to field sites,

3) pre-recording digitization of network seismic events has largely eliminated the delay, work, and expense of dubbing events from 5 analog tape recorders onto a single library tape for eventual digitization and analysis,

4) analysis of digitized events in CUSP is much faster, more accurate, and more comprehensive than the hand reading and analysis previously carried out.

5) methods for computing amplitude and duration magnitudes, MX and MF, have been developed and evaluated (Eaton, 1992); and they have been implemented in HYPOINVERSE (Klein, written communication) for routine use,

6) the effectiveness of the RTP for providing near-real-time monitoring of events in an aftershock sequence has been proven resoundingly. The ability of the network, through RTP analysis, to provide such monitoring is of vital importance for crisis management after a major earthquake,

7) many papers documenting network results have now been published; and those papers have established NCSN and SCSN as the primary sources of information on the seismicity and current tectonics of California (Oppenheimer, et al., 1992).

The problems that halted network deployment in 1982 have been mostly overcome. Moreover, the earthquake catalog and research papers based on network results, as well as the development of the equipment and analytical procedures required to record and interpret the network data, rank among the very best accomplishments of the earthquake program. It is, therefore, appropriate to identify deficiencies of the present networks and to discuss how those deficiencies might be remedied.

STATUS OF NCSN

For a variety of reasons the distribution of stations in NCSN is very uneven. The original "prediction" network built up between 1969 and 1974 consisted of 30-km-wide strips of stations along the San Andreas, Calaveras, and Hayward faults between Clear Lake and Cholame. This network was designed to "map" earthquakes that occurred on or very close to these faults, and average separation of stations was only about 10 to 15 km.

Further development of NCSN was far less orderly than that of the core network described above. It proceeded along two rather different lines that reflected sources of funding. First, funding from non-prediction sources became available to install and operate small special purpose monitoring networks, some of which were near enough to the core network to be treated as part of NCSN. Such networks included NTS (discontinued), Santa Barbara Channel (transferred to SCSN), Coso (transferred to SCSN), Geysers, Warm Springs Dam, Melones Dam, Auburn Dam, Berryessa Reservoir, Lassen Volcano, Shasta Reservoir, Shasta

Volcano, and Long Valley Caldera. Second, as the catalog of earthquakes recorded by the core network and special networks took shape, it became clear that important seismicity extended well beyond the limits of the core network; so prediction funds were used to extend the core network laterally to cover the width of the Coast Ranges, southward to include the 1857 break, and northward to include the Cape Mendocino region (the latter using COE microwave telemetry). A cluster network was installed around Oroville Reservoir following the 1975 Oroville earthquake, the Coso network was extended westward across the southern Sierra Nevada (Walker Pass net, transferred to SCSN), and a sparse Central Valley/Sierra Foothills net (discontinued because of high telemetry costs) was set up between Modesto and Merced. Station separation in the fill-in networks funded from both sources was commonly more than double that in the core network. When the network deployment moratorium took effect in 1982, there remained several large holes in NCSN station coverage as well as the need to increase station density in parts of the network where computed focal depths were unreliable.

Signals from 27 stations operated by other institutions (LLL, DWR, UCB,and UNR) are also telemetered to Menlo Park and processed with the USGS stations. The number of stations in the combined NCSN now recorded in Menlo Park is about 370. In addition, 33 stations from the north edge of SCSN are recorded and processed with NCSN, bringing the total number of stations recorded in Menlo Park up to about 400.

STATUS OF SCSN

The development of SCSN began in 1969 as a piecemeal augmentation of the broad 20-station telemetered Caltech network that had grown over the previous 40 years or so.
From the first, however, SCSN took on a character rather different from NCSN. Well defined, narrow linear zones of seismicity were not nearly as apparent in southern California as in northern California; so stations were spread more uniformly over broader areas than in the core of NCSN. Specialized

networks were installed approximately as follows:

1969 6 stations around the Santa Barbara Channel
1971 7 stations around the Los Angeles Basin (Caltech)
1973 15 stations in Imperial Valley
8 stations in the Ventura/Oxnard region
1974 17 stations in the eastern Mojave Desert

Beginning in 1975, the USGS/CIT joint effort to complete the network systematically was undertaken.

1975 17 stations San Bernardino Mountains
9 stations Coso Range
1976 4 stations Elsinore fault region
8 stations Carrizo Plains
13 stations San Bernardino Mountains
1979 12 stations Southern Sierra Nevada (Walker Pass)
5 stations Mojave Desert
1981 6 stations Elsinore fault region
10 stations Mojave Desert
10 stations Imperial Valley
13 stations San Bernardino Mountains
7 stations Transverse Ranges
5 stations Walker/Coso nets (China Lake)
1982-1987 12 stations

Twenty four stations of the Caltech network as well as 11 stations of the USC Los Angeles Basin network (primarily downhole) are also telemeterd to Pasadena and analyzed with the USGS stations. Over the years about 30 southern California stations have been discontinued because of the high costs of telemetry and maintenance. The number of stations in the combined SCSN now recorded at Pasadena is about 200. Moreover, 14 stations along the south edge of NCSN are recorded and processed in Pasadena.

Although station coverage appears to be more uniform in SCSN than in NCSN, it is also much sparser, on average. The most glaring deficiency of coverage in SCSN is the absence of telmetered stations in Owens Valley. Other regions with seriously inadequate coverage are the Elsinore fault to Pacific shore belt and the eastern Mojave/Basin-and-Range boundary region. Moreover, station density over large areas is too low to support reliable focal depth determinations or focal mechanism determinations.

IV. Principal functions of the regional networks, and dependence of their performance on network configuration

A. Network purposes

Although the short-period seismic networks in California support a wide range of monitoring and research objectives, their primary purposes are:

1) long-term monitoring of local earthquakes throughout the broad zone of seismicity associated with the San Andreas and related fault systems:

   a) to construct a uniform, long-term earthquake catalog (with supporting phase data and seismograms) to document seismicity of the region,

   b) to map seismogenic zones and to identify the geologic structures and styles of deformation with which these zones are associated,

   c) to provide a basis for monitoring spatial and temporal variations in seismicity that might presage major earthquakes in the region,

2) detailed monitoring and determination of precise hypocentral, magnitude, and focal mechanism parameters of earthquakes along sections of major faults that are expected to produce damaging earthquakes within a decade or so,

3) real-time monitoring and analysis of earthquakes to provide timely, reliable information on their locations and magnitudes for crisis management after large earthquakes and to fill the need for general public information on "felt" earthquakes at any time.

Important additional research based on regional network records include:

1) determination of improved velocity structures of the lower crust and upper mantle to refine the analysis of local earthquakes,
2) tomographic studies of the crust and mantle beneath the network to clarify the relationship of current and past plate tectonic regimes to major structures and seismic zones of the region,
3) array analysis of teleseismic body waves to refine our understanding of the velocity structure of the deep interior of the earth.

B. Dependence of network performance on configuration

Network design requirements for fulfilling its primary purposes differ principally in the allowable distance between contiguous stations. This parameter plays a critical role in the calculation of focal depths and in establishing magnitude thresholds for event detection and focal mechanism determinations.

Focal depths

The need for accurate focal depths of events less than 10 km deep sets the most stringent requirement on station spacing. To map out locked patches on a fault surface like the one filled in by the Loma Prieta quake or the one expected to be filled in by the next Parkfield quake, station separation along the fault should be 10 km or less. For station spacing of 20 km, which insures that no event will be farther than about 10 km from the nearest station, we should be able to determine whether earthquakes are in the lower crust (>10 km), middle crust (5 km to 10 km), or upper crust (<5 km); but likely errors in depth for events shallower than 10 km will be quite large. For station spacing of 40 km we should be able to distinguish between quakes in the lower crust or upper mantle and those at mid- or upper-crustal depths. The greater the spacing of stations, however, the stronger will be the dependence of calculated focal depth on the crustal model.

Event detection

Network requirements to insure detection of small events depend on the manner in which the events are detected. An analyst scanning appropriate seismograms can identify an earthquake (or blast) if it is recorded by a single station. Computer detection of events from the network requires that some simple algorithm (e.g. variation in the short-term/long-term ratio of average trace amplitude) be able to detect an "event" more or less simultaneously at a minimum number of stations in the same region. Commonly, that number is set at about 6 to suppress false triggers due to local noise at individual stations.

The number of stations triggered by a small event depends on event magnitude, station spacing, and background noise at the individual stations. As a practical approach, examination of a suite of earthquakes analyzed on CUSP shows that an earthquake of magnitude M1.5 can be read out to different distances in different regions: about 40 km in the central Coast Ranges, about 30 km in the Geysers region, about 50 km in the Cape Mendocino region, and about 60 km in the Lassen/Sierra region. For a square grid of node spacing L, a circle of radius 1.5xL encloses between 4 and 9 nodes; and the probability that it will enclose between 6 and 8 nodes is very high (the area of a circle of radius 1.5xL is $7.07xL^2$). Thus, to assure a high probability of recording an M1.5 event at 6 or more stations of a network laid out as a square grid, the station spacing for the regions enumerated above should be 27 km in the central Coast Ranges, 20 km in the Geysers region, 33 km in the Cape Mendocino region, and 40 km in the Lassen/Sierra region. The foregoing logic applies to the detection and capture of an event by both the CUSP and RTP systems, but it does not promise that all captured events can be assigned reliable focal depths. For a region of high cultural noise such as the S.F. Bay area, the L. A. Basin, and the Great Valley, station spacing should be decreased to about 20 km to insure detection of M1.5 events.

Focal mechanisms

Determination of focal mechanisms sets somewhat different network requirements. For earthquakes of magnitude M3.5 and larger, arrivals in the Pn range (beyond 100 km to 120 km in the Coast Ranges) can be used; so rather distant parts of the network come into play. For smaller events, only arrivals within 100 km (perhaps 50 km for M2 events) are sharp enough to provide useful first motion data. To insure that observations adequately cover the focal sphere, a moderate number of stations (15 to 20) that are well distributed in azimuth and distance are required. For a square grid network with 25 km station spacing, a 75-km-radius circle centered on a station includes 29 stations within it; and a 50-km-radius circle on the same grid includes 13 stations. Thus, it appears that a homogeneous network with 25 km station spacing would support routine focal mechanism determinations of M2 to M2.5 and larger earthquakes. The quality of focal mechanism solutions depends on focal depth, velocity model, and other factors in addition to the number of observations, however.

C. Comparison of regions of dense network coverage with regions expected to produce damaging earthquakes

The regions in the networks that have a station spacing of the order of 10 to 15 km required for the detailed mapping of the distribution of earthquakes at 5 km depth or less on seismogenic structures in the crust are: 1) a narrow 60-km-long strip along the San Andreas fault centered at Parkfield, 2) a 150-km-long strip along the San Andreas fault from San Benito to Los Gatos, 3) a 20 km by 50 km band of stations from the Geysers to Warm Springs Dam, 4) an 80-km-long cluster of stations from Mammoth Lakes to the north end of Owens Valley, 5) a small cluster of stations at the Coso Range, 6) a small cluster of stations on the San Andreas fault near Palmdale, and 7) a small cluster of stations in the Brawley seismic zone at the southeast end of the Salton Sea. In some of these cases, the network density falls off so rapidly away from the dense zones that the networks do not provide adequate coverage for focal mechanism determinations of M2 to M2.5 earthquakes.

Next, consider the regions that have been identified as having high probabilities of producing M6.5 and larger earthquakes in the next 30 years or so: S. F. Peninsula section of the San Andreas fault, both the southern and northern halves of the Hayward fault, Healdsburg fault, southern section of the San Andreas fault, San Jacinto fault, and the Los Angeles Basin (fig 11). For the detailed monitoring that these regions require, the network should be augmented so that earthquakes can be mapped on the fault surfaces that are the presumed sources of the impending large quakes. The discussion of network capabilities versus station spacing developed above suggests the need for strip networks with station spacing of about 10 km along the faults flanked by broad areas in which station spacing is not greater than 25 km.

Outside of these immediate high-risk areas the network should be upgraded for more adequate long-term monitoring of earthquakes throughout the San Andreas and related fault systems. Specific targets should include sections of major faults that will produce future large quakes: San Andreas fault north of San Francisco and in the region of the 1857 Fort Tejon break, Sierra Frontal fault in Owens Valley, White Wolf fault, etc. The targets should also include regions of potential large earthquakes where the causative faults are not so obvious: west flank of the Coast Ranges southeast of San Francisco, Great Valley/Coast Ranges boundary at least from Winters to Lost Hills, zone of crustal convergence in the Santa Maria/Santa Barbara/Ventura/San Fernando region, Mendocino Fracture Zone and adjacent subduction zone north of Cape Mendocino, etc.

An overall objective of the broad regional network should be to refine and complete the picture of San Andreas seismicity presented in USGS PP 1515 (fig 7). An accurate analysis of seismicity, tectonics, and crustal structure on that scale is needed for correlation with the rapidly accumulating information from VLBI and other space-based geodetic techniques on the nature and distribution of deformation in the Pacific Plate/North American Plate boundary zone. Joint analysis of long-term seismicity and deformation of the plate boundary zone is needed to document the accumulation of elastic strain in the source regions of future large earthquakes.

D. Network augmentation to improve coverage of the San Andreas Fault system

On the basis of the map of existing stations, the 1980-1986 seismicity map, the historic record of large earthquakes, and the considerations discussed above, proposed new stations were "added" to the short period seismic networks in California so that they might better meet the needs of the Earthquake Hazards Reduction Program. The needs of the northern and southern networks will be listed separately.

NCSN

Network subregions, number of proposed new stations, and approximate maximum station separations within these subregions are as follows:

Network Subregion	Number of new Stations	Maximum stn Separation
Central Coast Ranges	25	20-25 km
S. F. Bay Area: South	24	10-15 km
S. F. Bay Area: North	24	15 km
Northern Coast Ranges	15	20-30 km
Mendocino Region	14	30-40 km
Shasta/Lassen Region	11	20-30 km
Northern Great Valley	18	25-35 km
Southern Great Valley	21	35-40 km
Northern Sierra	10	30-40 km
Central Sierra	17	30-40 km
TOTAL	179	

In addition to the proposed new sites, all of which should have high-gain vertical seismometers, low-gain horizontal and vertical instruments should be scattered throughout the network to obtain better data for S arrivals and magnitudes. About 40 new low-gain (or high dynamic range) 3-component installations, some replacing single-component low-gain vertical or horizontal components will be needed.

SCSN

Network subregion, number of proposed new stations, and maximum station separation within each subregion are as follows:

Network Subregion	Number of new Stations	Maximum stn Separation
Santa Barbara/Santa Maria	18	20-25 km
White Wolf	13	20-30 km
So. Sierra/Owens Valley	25	20-40 km
Garlock	9	15-30 km
Basin and Range Borderland	15	40-60 km
Eastern Mojave	17	20-40 km
So. San Andreas/San Jacinto	35	15 km
Ventura	10	15 km
Los Angeles Basin	14	15-20 km
Elsinor/San Diego	13	20-30 km
Offshore	5	20-60 km
TOTAL	174	

In addition to the proposed new sites with high-gain verticals, 40 low-gain (or high dynamic range) 3-component installations should be scattered throughout the network.

V. Analysis of coverage provided by the current and proposed short-period seismic networks

To evaluate the ability of the regional network to meet the various requirements placed upon it, a computer program was written to examine the network as viewed from points on a grid that blanket the network. The specific parameters evaluated at each grid point and the network performance features they characterize are as follows:

1) distance to the 6th nearest station, D6 - automatic event detection. For stations deployed in a square grid with spacing L, $1.2 < D6/L < 1.5$. For values of D6=40 km and D6=60 km, respectively, we expect effective automatic detection of earthquakes of magnitudes 1.5 and 1.8, respectively.

2) distance to the 3rd nearest station, D3 - focal depth determination. For stations deployed in a square grid with spacing L, av $D3/L=0.95$; and the distance to the nearest station, D1, is less than L/4 for 22% of random events and less than L/2 for 72% of random events. Thus, for D3<20 km (D1 < 11 km for 72% of events) and D3<40 km (D1 < 21 km for 72% of events), respectively, we expect focal depths to be adequately determined for events deeper than about 5 km or about 10 km, respectively,

3) number of stations within 75 km, N75 - focal mechanisms of M2 to M2.5 events.

4) maximum azimuthal gap between stations within 75 km, G75 - focal mechanisms of M2 to M2.5 events. Parameters N75 and G75, together, characterize the number and distribution of stations available for focal mechanism determinations of small earthquakes. For N75>20 and G75<90°, we should be able to construct usable first motion plots for M2 to M2.5 earthquakes. These parameters also provide a measure of the network's ability to determine reliable earthquake locations.

These four parameters for the current network (NCSN plus SCSN), shown in fig 8, and the proposed augmented network, shown in fig 10, are plotted in figures 12 through 15. The coverage indicated by figures 12 - 15 for the two versions of the network should be examined in the context of the principal faults and geologic features of the region (fig 11) as well as the seismicity of the region for the interval 1980-1986 (fig 7) as determined from the current network.

For the proposed network, the contours enclosing regions with D6<40 km (fig 12b), N75>20 (fig 14b), and G75<90° (fig 15b) are very similar; and the region they enclose is about 1100 km long by 200 km to 400 km (av 250 km) wide. Except for a zone along the east side of the Sierra Nevada northwest of Mono Lake, which should be covered by the UNR net, this region covers virtually all of onshore California with significant seismicity. Within it we should expect effective auto-detection of M1.5 and larger events as well as sufficient coverage to provide good locations for those events and adequate first motion fault mechanism solutions of M2.5 and larger events.

The plot of D3 (fig 13b) shows that the region with D3<40 km (focal depths adequate for depths of 10 km or more) coincides approximately with that for D6<60 km (auto-detection of M1.8 events). The contour for D3<20 km (focal depths adequate for depths of 5 km or more) encloses a more restricted region: most of seismically active onshore southern California, southern Sierra Nevada/Owens Valley/Long Valley region, Transverse Ranges, central and northern Coast Ranges, and western foothill belt of the northern Sierra Nevada. It does not include the central Sierra Nevada, Great Valley, and Mendocino to Shasta region of northernmost California.

The principal deficiencies of the current network are revealed by a parameter by parameter comparison of the current network with the proposed network, i.e., fig 12a with 12b, etc. From fig 12a it is apparent that auto-detection at the M1.5 level fails in a number of important regions: a large region around San Diego, a large section of the western Transverse Ranges, most of California north of 41°N, most of the Great Valley, and the entire south-central Sierra Nevada and Owens Valley region. Adequate auto-detection is an indispensable network requirement.

If an event is not detected it is lost, except, possibly, from tape backup.

Figure 13a indicates that focal depth determinations for shallow events are now possible along the axis of the central and southern Coast Ranges, in the Imperial Valley region, in a zone from the Los Angeles Basin to the southeastern Sierra Nevada, in the Long Valley region, and in the foothills of the northern Sierra Nevada. Absent from the list are the western Transverse Ranges, the San Diego/Elsinor fault region, most of California north of 39°N, the Great Valley, and the south-central Sierra Nevada/Owens Valley region. In the last two regions, focal depths cannot be determined adequately even for events deeper than 10 to 15 km.

The contours enclosing regions with 20+ stations within 75 km (Fig 14a) show how the existing California network is composed of three practically distinct patches - northern California, southern California, and Long Valley. The vital region of the Transverse Ranges where the 1857 San Andreas break passes between the northern and southern sections of the network is very poorly covered. Even worse coverage is found in the south-central Sierra Nevada/Owens Valley region.

The contour enclosing the region with G75<180° in fig 15a shows the effective edge of the network Events outside that region require special care to obtain adequate locations; at least a few S wave arrival times are needed to constrain the origin time. On the same figure, the region with G75<90° is very similar to the region within which we expect effective auto-detection at the M1.5 level (fig 12a).

VI. Further development of NCSN and SCSN

The major regional networks have attained a "footprint" that nearly covers the entire zone of seismicity associated with the San Andreas and related fault systems that mark the tectonically active boundary between the Pacific and North American plates in California. The quality of network coverage within that broad region varies considerably, and in some places it is clearly inadequate to fulfill the principal objectives of the network. The statewide map of seismicity in figure 7 can even be said to be misleading. It suggests a degree of completeness that simply cannot be attained with the present networks. Because of the dominant role that we (USGS) have played in the development and operation of the California regional microearthquake networks, it is clearly our responsibility to address the inadequacies of the present networks and to make every reasonable effort to correct them. In decades to come our seismology program will be judged more rigorously on the quality and completeness of the record of California earthquakes that we pass on to our successors than on any other issue.

The strengths and weaknesses of the network have been described above on a region by region basis; and a general plan to add stations to attain the level of coverage appropriate for each region has been outlined. The overall network augmentation needed is quite large, about 350 additional high-gain short-period vertical-component analog stations plus about 80 three-component short-period digital stations, split about equally between NCSN and SCSN.

Experience over the last 20 years has shown that the task of upgrading the network is closely linked to the ongoing work of maintaining and operating the existing network. The knowledge, skills, and facilities required for both are the same; and changes to improve the network must be integrated into the operation and analysis of the network as they are made.

To assess the impact of network expansion on the overall network enterprise, it is helpful to identify the primary activities that sustain the network and its operation.

1) telemetry - operation and maintenance of the microwave trunks and VHF/UHF radio feeder links,

2) seismic systems - operation and maintenance of the seismometers and preamp/VCO's in the field and the discriminators and signal distribution system in the

recording center,

3) recording and analysis

a) backup recording of incoming network signals,

b) real-time detection and preliminary location of earthquakes to permit timely response during earthquake emergencies,

c) online computer detection of earthquakes and spooling of digitized seismograms,

d) offline interactive analysis of earthquakes,

4) archiving of seismograms and products of analysis to preserve these materials and to make them available to the seismology community for further exloitation and analysis.

Next, we shall eximine how the proposed network augmentation depends upon and impacts these activities.

Recording and analysis

When the network was young, we were far more successful installing stations and gathering data than analyzing the data. This problem grew more acute as the network approached its present size in the early 1980's. Heavy committment to the development of improved digital data acquisition and analysis systems during the last 10 years has now tipped the balance in favor of analysis. The CUSP systems now operating in Menlo Park and Pasadena both have the potential capacity (depending on the A/D convertors) to record substantially more stations than they now are. Moreover, these systems are based on modern microcomputer "workstation" equipment that is much less expensive and more reliable than the equipment used to record and analyze the early networks. In the near future even the backup network recording will be carried out digitally on inexpensive equipment, retiring the bank of half-a-dozen cumbersome, costly, high maintenance analog recorders that have performed that function for the last 20 years. Most impressive, however, is the relative efficiency of data processing in CUSP compared to that of earlier methods: the improvement approaches a full order of magnitude. Thus, the several hundred additional analog stations needed to fill out NCSC and SCSN could be recorded and analyzed on existing equipment with a minimum of additional effort and expense.

Seismic systems

The analog seismic systems employed in the network have been refined over the years to meet the most critical network requirements: simplicity, low cost, low maintenance, reliability, and good data quality (within the bandwidth and dynamic range permitted by analog fm telemetry). Augmentation of the network with this equipment would have a minimum impact on the cost of maintaining the network. One field maintenance technician can take care of at least 100 stations. A fifty percent increase in the number of stations would require no increase in the manpower required to operate and maintain the discriminators and signal distribution systems in the recording centers.

The limited dynamic range of the analog fm telemetry system has been offset by the operation of a subnet of low-gain stations, many with three-component seismic systems, with the same frequency response as the high-gain systems. Development of a simple three-component, 100 sps, 16-bit digital system to replace the low-gain analog systems is nearly complete. That system utilizes a standard 4800 baud communications channel that can be provided by our current microwave and VHF/UHF telemetry system. Time stamping and recording is carried out in a PC-based system, developed by the USGS, that should accomodate up to 48 independent 3-component stations. The data collected by this system will be combined with the CUSP digital network data so that all stations (digitized high-gain analog stations plus low-gain 3-component digital stations) can be analyzed in the CUSP system.

Telemetry

The networks were set up originally to operate over commercial telphone circuits. We were forced to change to a microwave and VHF/UHF radio based system because of excessive cost, inadequate areal coverage, and inadequate data quality of the commercial systems. The remaining long-distance phone circuits that we use will be replaced as soon as microwave facilities can be developed.

Fourteen microwave sites in the Coast Ranges between Eureka and San Luis Obispo constitute the communications backbone of NCSC, and 4 microwave sites in the L. A. Basin and Mojave Desert provide the core of the SCSN communications system. The northern Coast Range sites belong to COE, and the USGS maintains them on a reimbursable basis. The microwave system currently operated by the USGS spans about 1000 km and includes 18 sites. Our access to this system was developed by negotiation with COE, purchase and installation of key USGS links, and considerable self-education in the areas of microwave electronics and transmission paths over the last decade. A large fraction of the network is now served by this system, but other parts of the network have been beyond its reach.

We have recently gained access to additional microwave facilities, by agreement with COE and FAA, that will provide improved, inexpensive telemetry for much of the rest of the network. The new system covers the Great Valley/Sierra foothills region and the Pasadena to Imperial Valley to southeastern Mojave Desert region. It will also provide a limited number of circuits between Menlo Park and Pasadena and between Menlo Park and Reno, which will repace some of our most expensive phone lines as well as facilitate better exchange of data among these recording and analysis centers. Addition of these new facilities virtually doubles the length of microwave trunk line and number of microwave sites in the overall system that serves the networks.

Although the microwave trunks do not reach the very ends of the networks, they have been "extended" effectively by means of broad-band VHF radio links that can carry four voice-grade channels. Such a system is now bringing stations in northeastern California into the Coast Range microwave system. Similar equipment could extend the southern California microwave system into Owens Valley and into the San Diego region.

In addition to microwave trunks, the network communications system employs several hundred 100-mw VHF and UHF transmitters and corresponding receivers. The low power of the transmitters and the relatively long transmission paths employed in the network, combined with the need for uninterrupted signal transmission, require great skill in the use of these radios.

The impact of our network telemetry system on network coverage, data quality, and efficiency of data analysis cannot be overemphasized. In an important sense the telemetry system _is_ the network, supplmented by seismic systems in the field and recording and analysis systems at the recording centers. Degraded telemetry leads not only to a serious loss of data but also to a huge increase in the time and effort required to process the noisy events that can be recovered. Assuring adequate maintenance for the telemetry system should have very high priority.

Archiving of seismograms and results of analysis

In the late 1960's when the USGS commenced network seismology in California, methods of preserving seismic data were those that had been used for 100 years: original paper or film seismograms were saved, lists of hypocenters and magnitudes were published in network bulletins, and records of phase arrival times, etc., were filed away for possible future use.

When the regional networks expanded from 15 or 20 stations to several hundred stations and paper or film seismograms were replaced by magnetic tape records, the old methods of preserving the data were completely inadequate. By the mid-1970's the results of analysis, both summary lists of hypocenters and the phase picks on which they were based, were preserved as ascii computer files on digital magnetic tape. The seismograms were preserve both on 16mm film (Develocorders) and on analog magnetic tape. Recovery of seismograms from the analog tape can be carried out by equipment, now largely obsolete, that is available only in Menlo Park; and it is very time consuming. Moreover, there is considerable apprehension over the stability of the tape records.

From the mid 1980's, for NCSN (and the late 1970's, for SCSN), the primary records of both the results of analysis and the seismograms themselves have been saved on 9-track digital magnetic tape written by the CUSP system. Because the CUSP format is both unique and intractable, recovery of CUSP data has been carried out in a functioning CUSP environment. Although CUSP is used in several networks, standardization is not complete, and reading tapes from one installation at another requires considerable knowledge of both systems.

Flexibility in analysis of network phase data has been achieved by constructing event phase files, in HYPOINVERSE or HYPO71 format, from CUSP "MEM" files. Summary files of hypocenters as well as the phase files are then preserved in monthly "directories" that are written to 9-track magnetic tape.

Recovery of the seismograms, however, still requires use of the CUSP system, which requires matching "GRM" and "MEM" files for each event recovered. The procedure is so cumbersome and slow that it has been used only on a limited basis. Alan Walter is currently working on a program to read the CUSP "MEM" and "GRM" files directly on the SUN computer. This program will facilitate access to network data for SUN and other non-CUSP users.

The lack of a uniform, "complete" catalog and supporting phase data has impeded setting up a routine procedure for filling data reqests; so such requests have been filled on an ad hoc basis. This situation will improve markedly in the near future when Dave Oppenheimer and Fred Klein complete the massive reprocessing of the NCSC data set that has been underway for several years.

Long-term solutions to the data distribution problem currently are being pursued through cooperation with other institutions: Caltech, UC Berkeley, and IRIS (Seattle). NCSC and SCSN data in the form of hypocenter summary lists, phase lists, and seismograms will be loaded onto mass-storage devices (eg. optical juke-boxes) and accessed via computer network or magnetic tape.

What next?

I propose that the moratorium on network development be lifted and that we proceed to complete the network in an orderly fashion at whatever pace funding will allow. The augmentation plan sketched above was primarily to show the scale of the problem. We must now set priorities and develop specific plans to get on with the work. The brief summaries of network activities given above suggest an approach that would bring a high return for the effort and funding devoted to network augmentation.

Two specific needs are apparent: 1) filling large holes in the network that will become accessible with the expanded microwave system, with at least a sparse network of standard analog stations, and 2) upgrading and extending the subnet of low-gain multi-component stations with 3-component digital instruments. Owens Valley, the southern Sierra/Great Valley, and the western Transverse Ranges are regions that should have high priority for additional analog stations. Digital stations can be installed most easily at microwave sites, which are well distributed in northern and central California. The smaller number of microwave sites in southern California will require the use of VHF (or UHF) radios to develop the southern part of the digital net.

These suggestions do not constitute the needed plan for augmenting the network, which will not be presented here. Such a plan should be worked out jointly between operators of NCSN and SCSN. The plan should address the need to produce a unified catalog for all of California. It should also develop procedures for joint analysis of events that occur between the nets, where each records only half of the stations required for locating the events.

It took more than a decade to build the network to its present state. It took another decade to develop recording, analysis, and archiving systems that can cope with the data from the existing network; and those systems could handle a 50% increase in the network without significant problems. If we begin an orderly upgrading of the network at this time, the work could be completed before the end of the next decade. If we fail to complete the network, we shall pass an incomplete historical record of earthquakes to our successors and impair their ability to identify and quantify seismic hazards in a California that is even more populous and developed than now.

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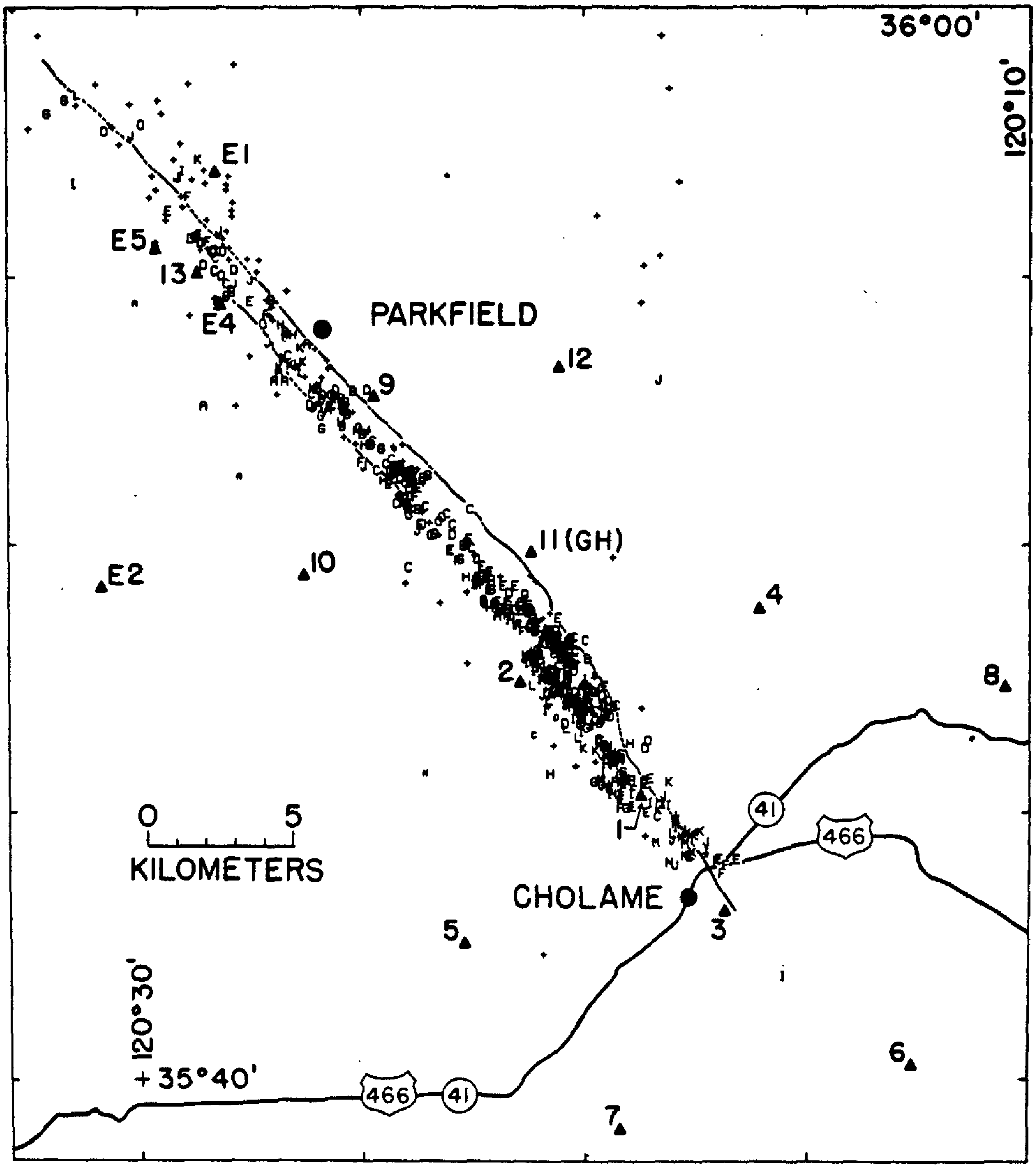

Fig.11. Aftershocks of the 1966 Parkfield–Cholame, California, earthquake. Stations of the portable network are indicated by triangles. Stations *E1* through *E5* were operated by the Earthquake Mechanism Laboratory of E.S.S.A.; the others by N.C.E.R. Zones of surface fracturing that accompanied the main shock and the aftershock sequence are shown as heavy solid and broken lines extending from the upper left to station *3*. The letter symbol that shows the epicenter of an aftershock also indicates its focal depth: 0–1 km = *A*, 1–2 km = *B*, and so on. Aftershocks for which focal depths could not be determined are plotted as crosses.

Figure 1

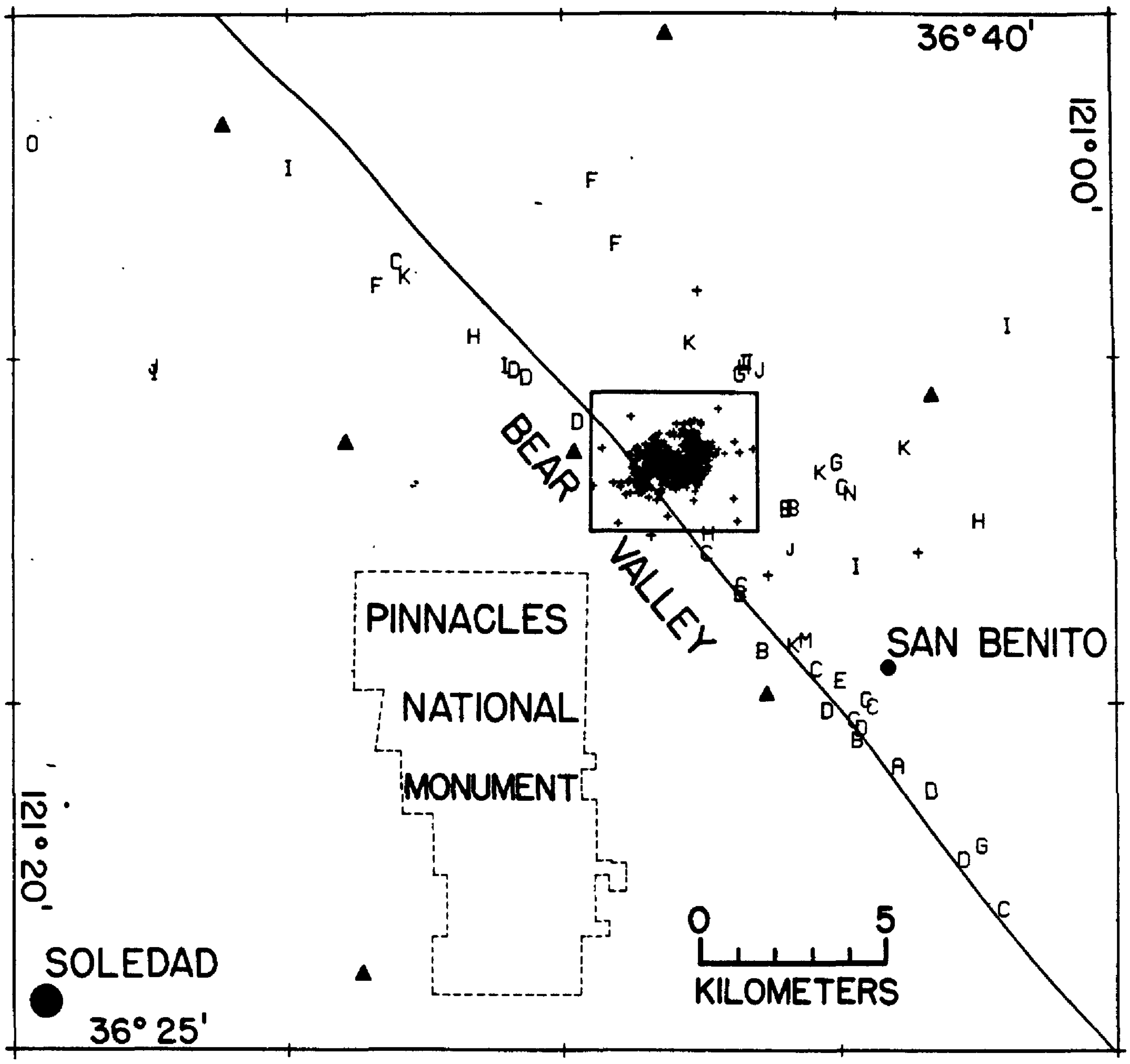

Fig.9. Aftershocks of the July 23, 1967, Bear Valley earthquake. The actively creeping trace of the San Andreas fault is shown by the solid line; but the rift zone is several km wide at Bear Valley and extends from about 1 km southwest of the active trace to about 3 km northeast of it. Portable seismograph stations are shown as solid triangles. Outside of the central rectangle, the letter symbol showing the epicenter of an earthquake also indicates its focal depth: 0–1 km = *A*, 1–2 km = *B*, and so on; a large cross indicates a shallow event for which a reliable depth could not be calculated. Inside the central rectangle hypocenters were very closely spaced (more than 300 of them), and they are plotted as small crosses.

Figure 2

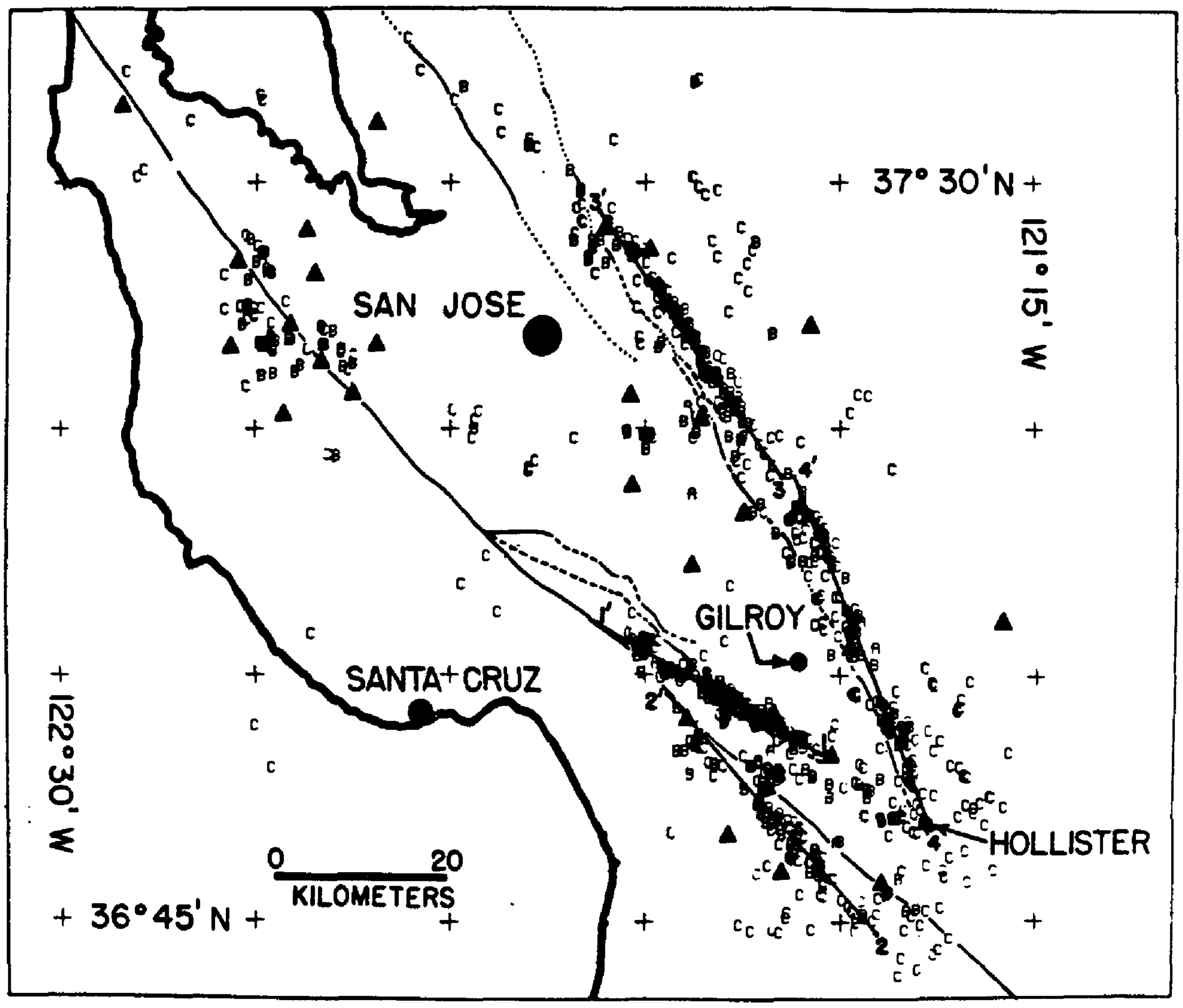

Fig.5. Epicenters of well recorded events within the telemetered network from March 1968 through April 1969. Plotted symbols indicate the reliability of hypocenter determinations: *A*, well determined epicenter (± 1 km) and focal depth (± 2 km); *B*, fairly well determined epicenter (± 2.5 km) and focal depth (± 5 km); and *C*, moderately well determined epicenter (± 5 km) but undetermined focal depth. Zones of hypocenter concentrations marked off by the numbered lines are as follows: *1–1'*, Sargent fault; *2–2'*, San Andreas fault west of Hollister; *3–3'*, Calaveras fault, northern section; *4–4'*, Calaveras fault, southern section.

Figure 3

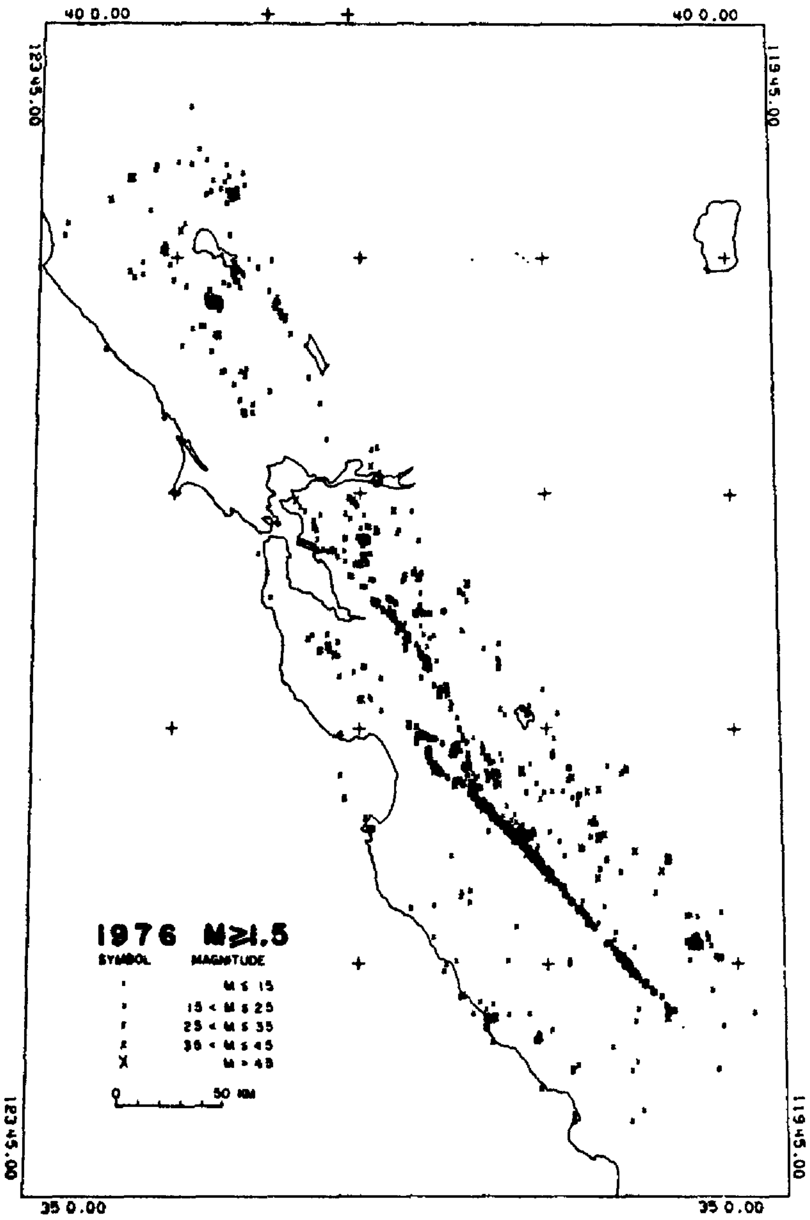

Fig. 9. Epicentres of earthquakes in central California with $M \geq 1.5$ during 1976.

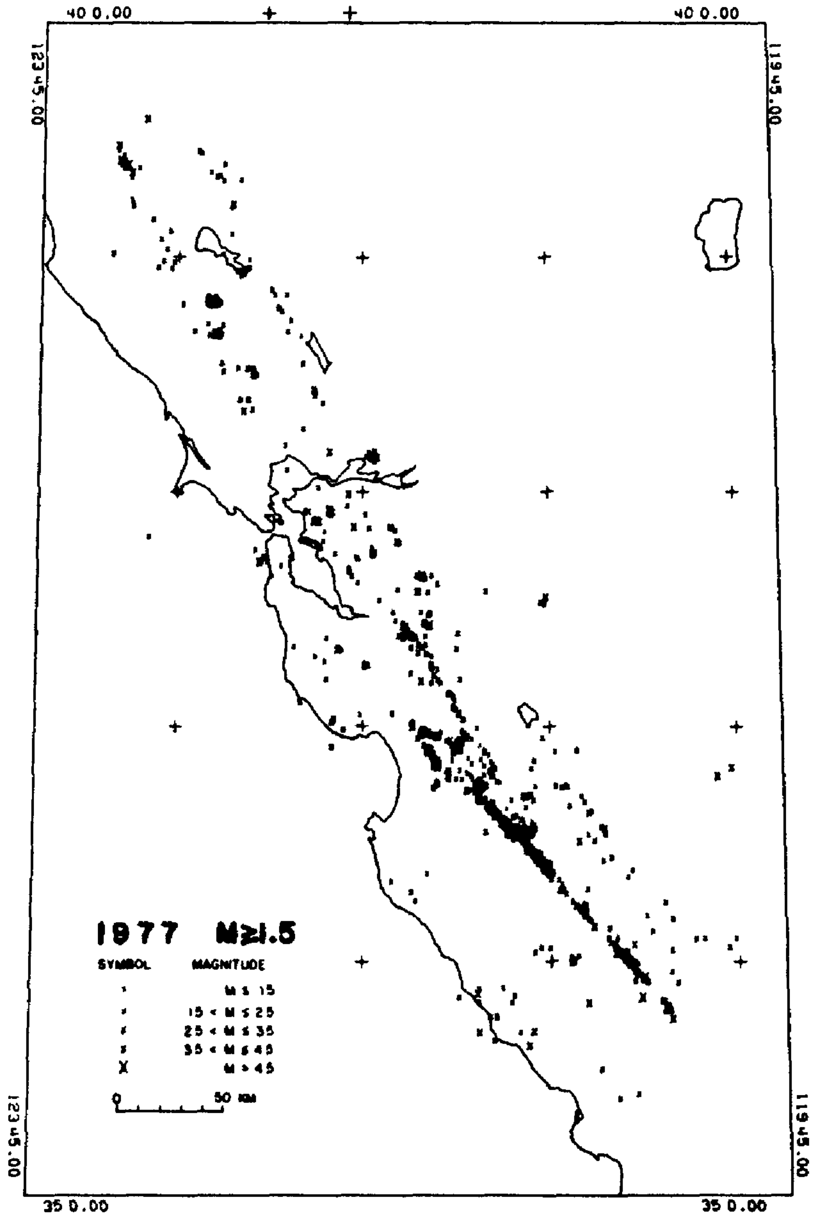

Fig. 10. Epicentres of earthquakes in central California with $M \geq 1.5$ during 1977.

Figure 4

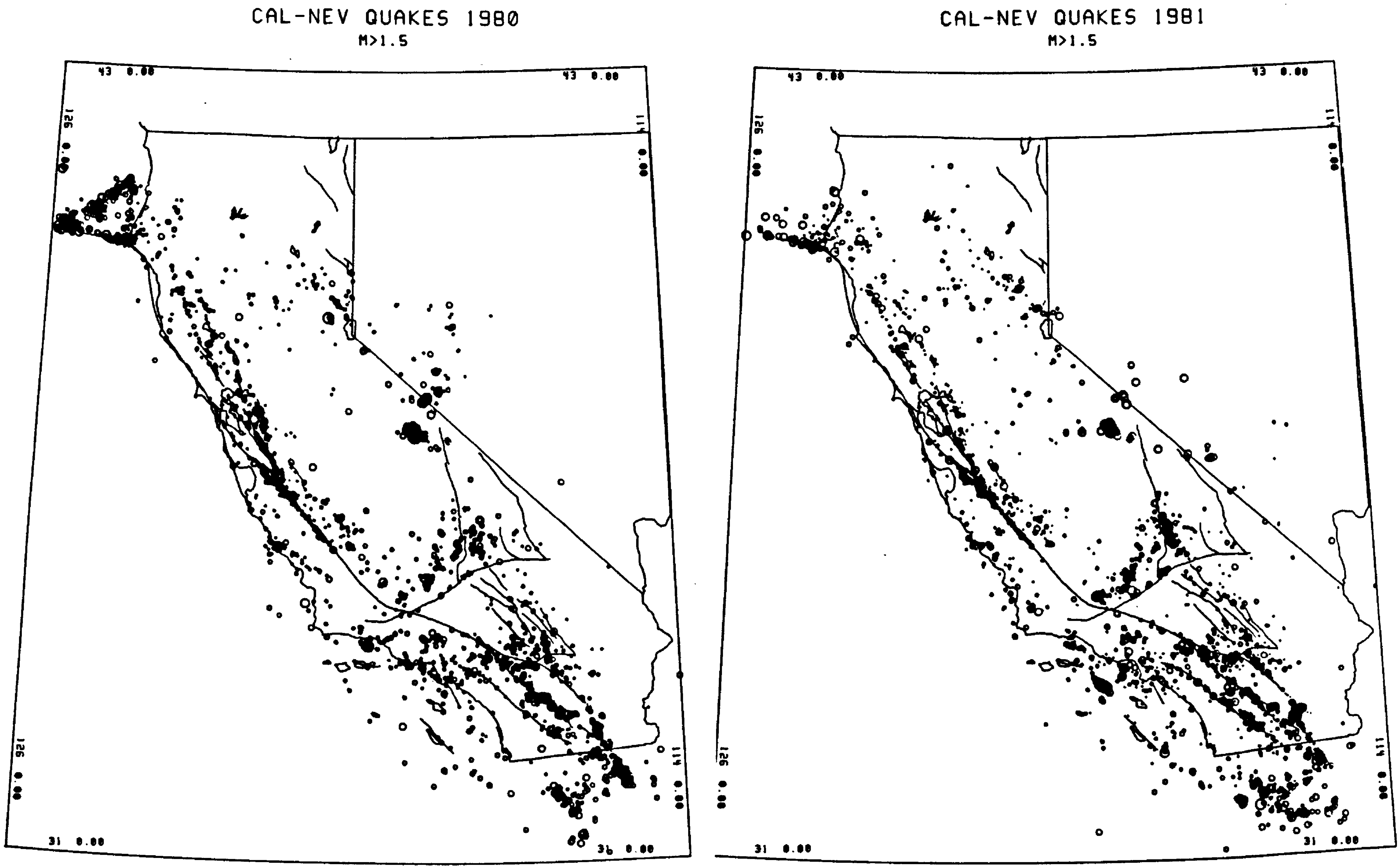
CAL-NEV QUAKES 1980
M>1.5
43 0.00
43 0.00
126 0.00
114 0.00
126 0.00
114 0.00
31 0.00
31 0.00
CAL-NEV QUAKES 1981
M>1.5
43 0.00
43 0.00
126 0.00
114 0.00
126 0.00
114 0.00
31 0.00
31 0.00

Figure 5

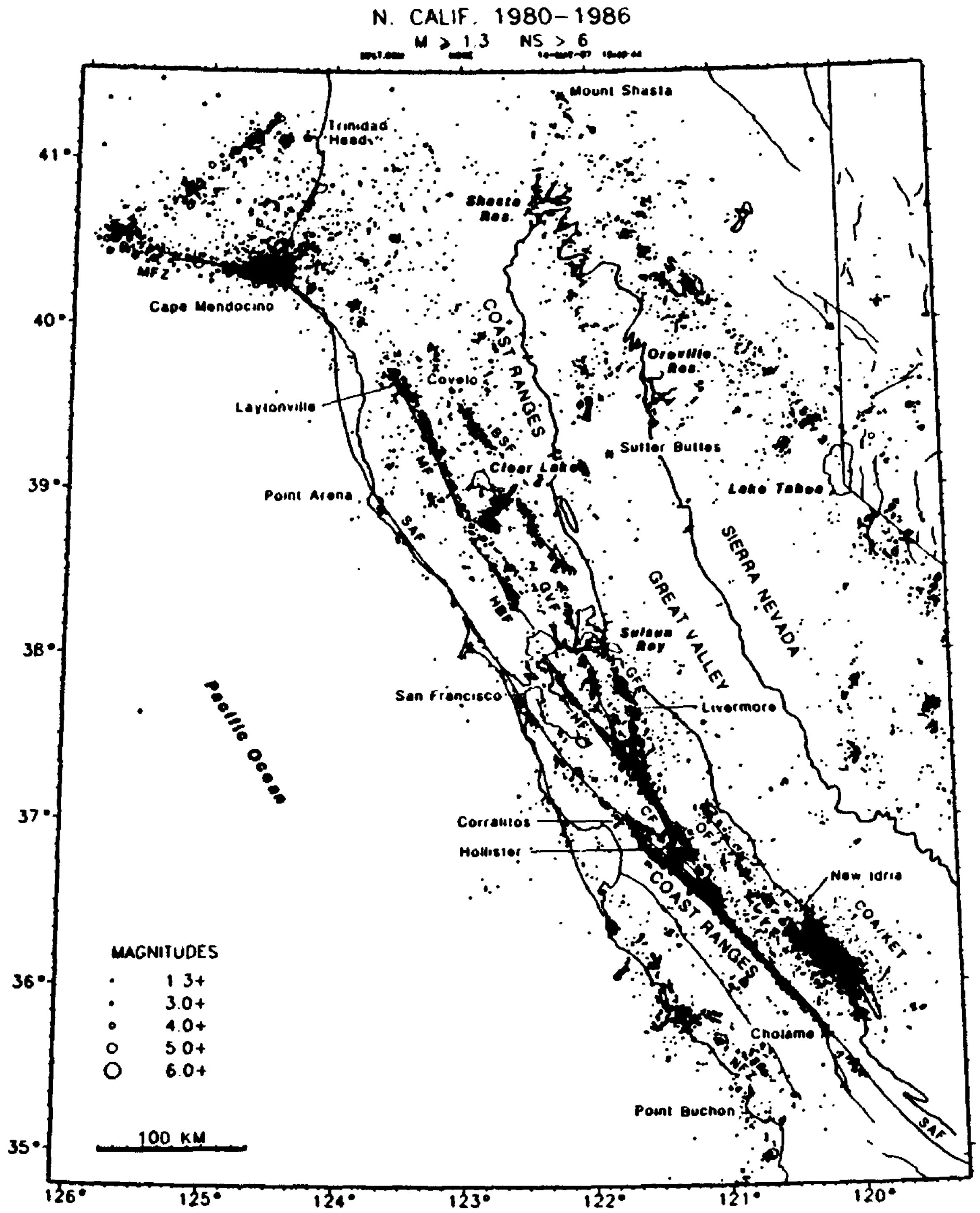

Figure 5. Northern California seismicity: 1980–1986. Symbol sizes are scaled according to magitudes. Only events with magnitudes greater than or equal to 1.3 and with seven or more stations in the hypocentral solution were included in the plot. Abbreviations: SAF = San Andreas fault, NFZ = Nacimiento fault zone, OF = Ortigalita fault, CF = Calaveras fault, HF = Hayward fault, GF = Greenville fault, GVF = Green Valley fault, BSF = Bartlett Springs fault, HBF = Healdsburg fault, MF = Maacama fault, MFZ = Mendocino fracture zone, COA/KET = Coalinga/Kettleman aftershocks region.

Figure 6

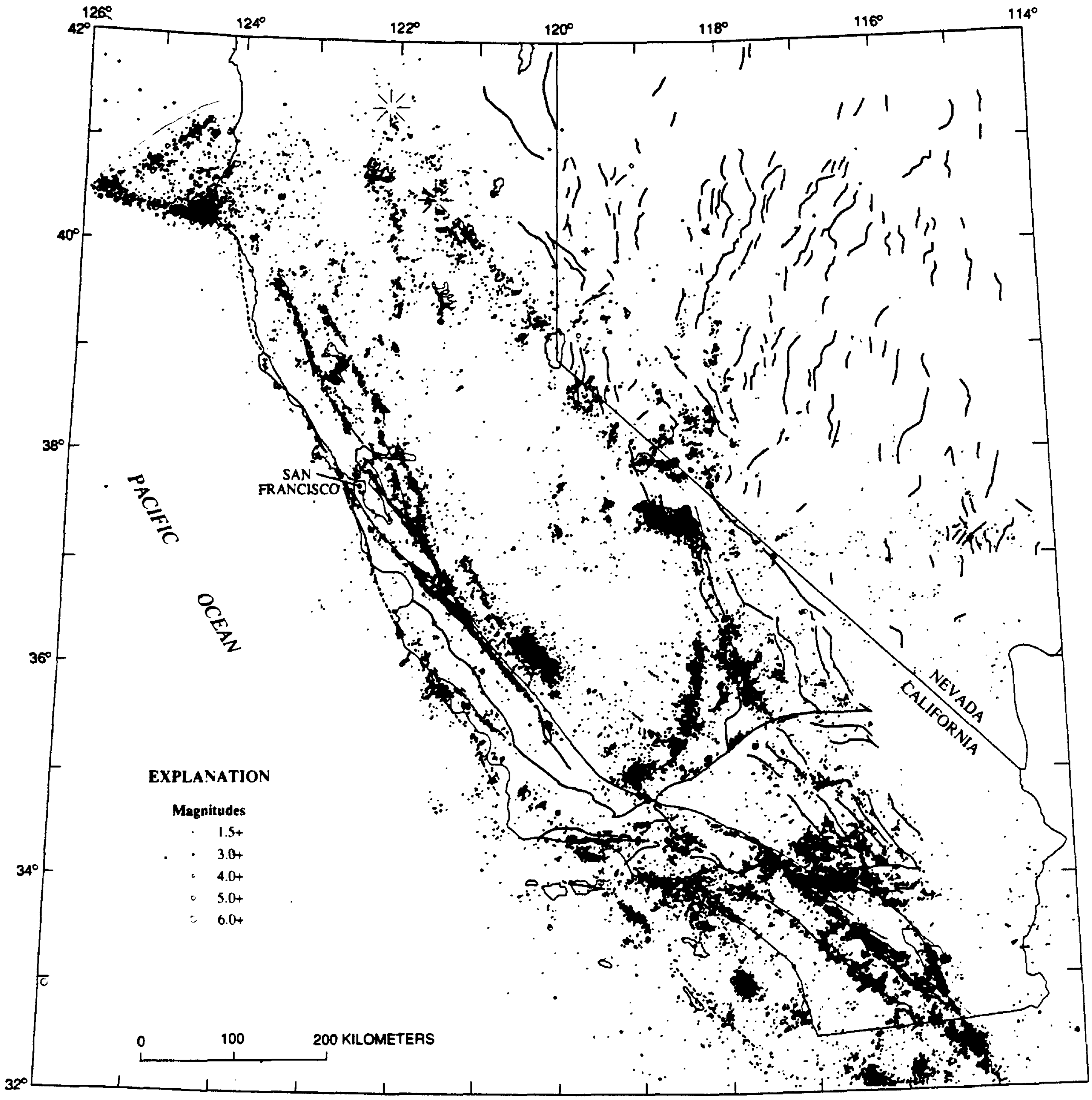

FIGURE 5.4.—Locations of 64,000 $M \geq 1.5$ earthquakes in California and western Nevada during 1980–86 and mapped Holocene faults (dotted where concealed; major branches of the San Andreas fault system marked in red).

Figure 7

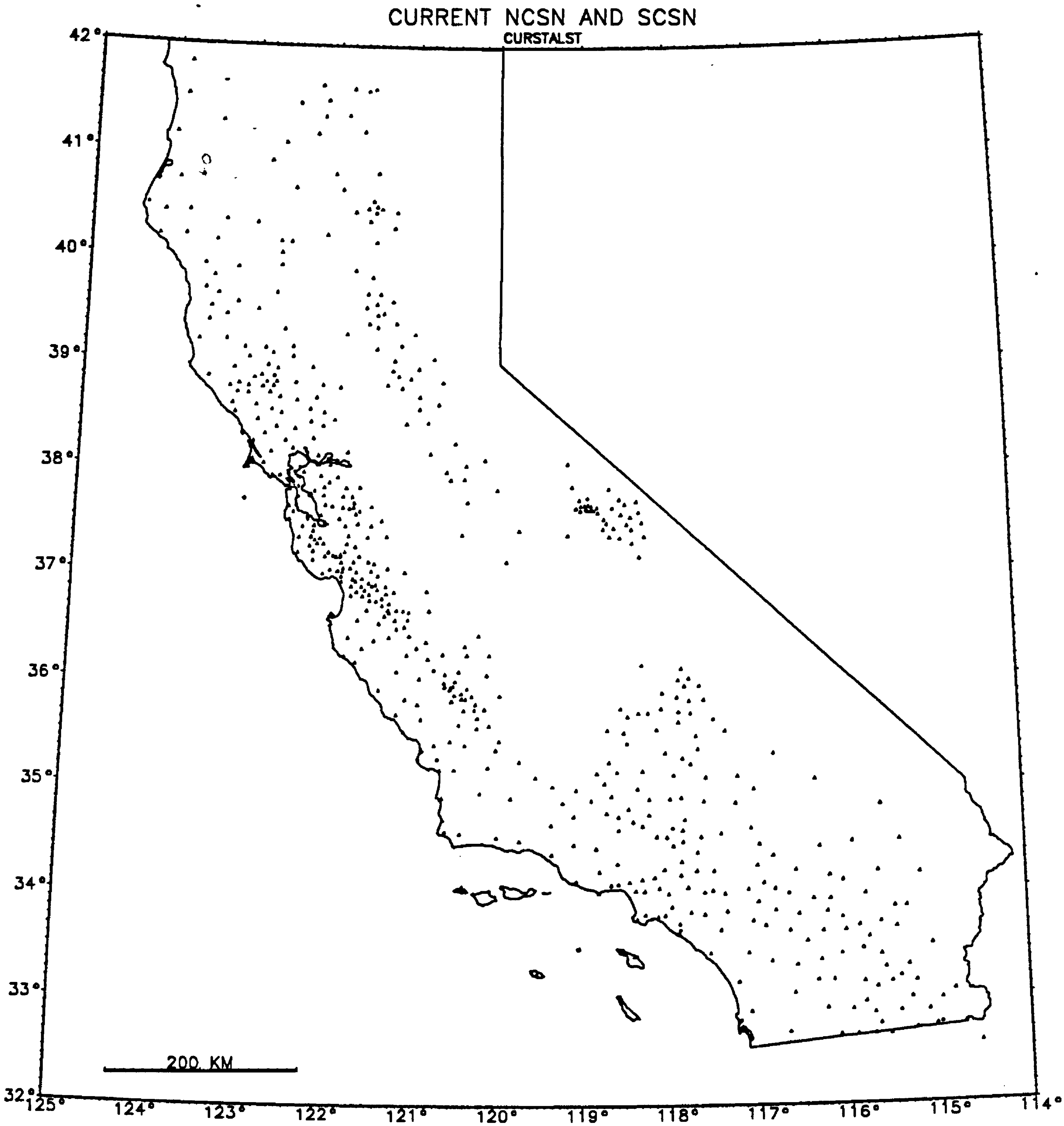
CURRENT NCSN AND SCSN
CURSTALST
42°
41°
40°
39°
38°
37°
36°
35°
34°
33°
32°
125°
124°
123°
122°
121°
120°
119°
118°
117°
116°
115°
114°
200 KM

Figure 8

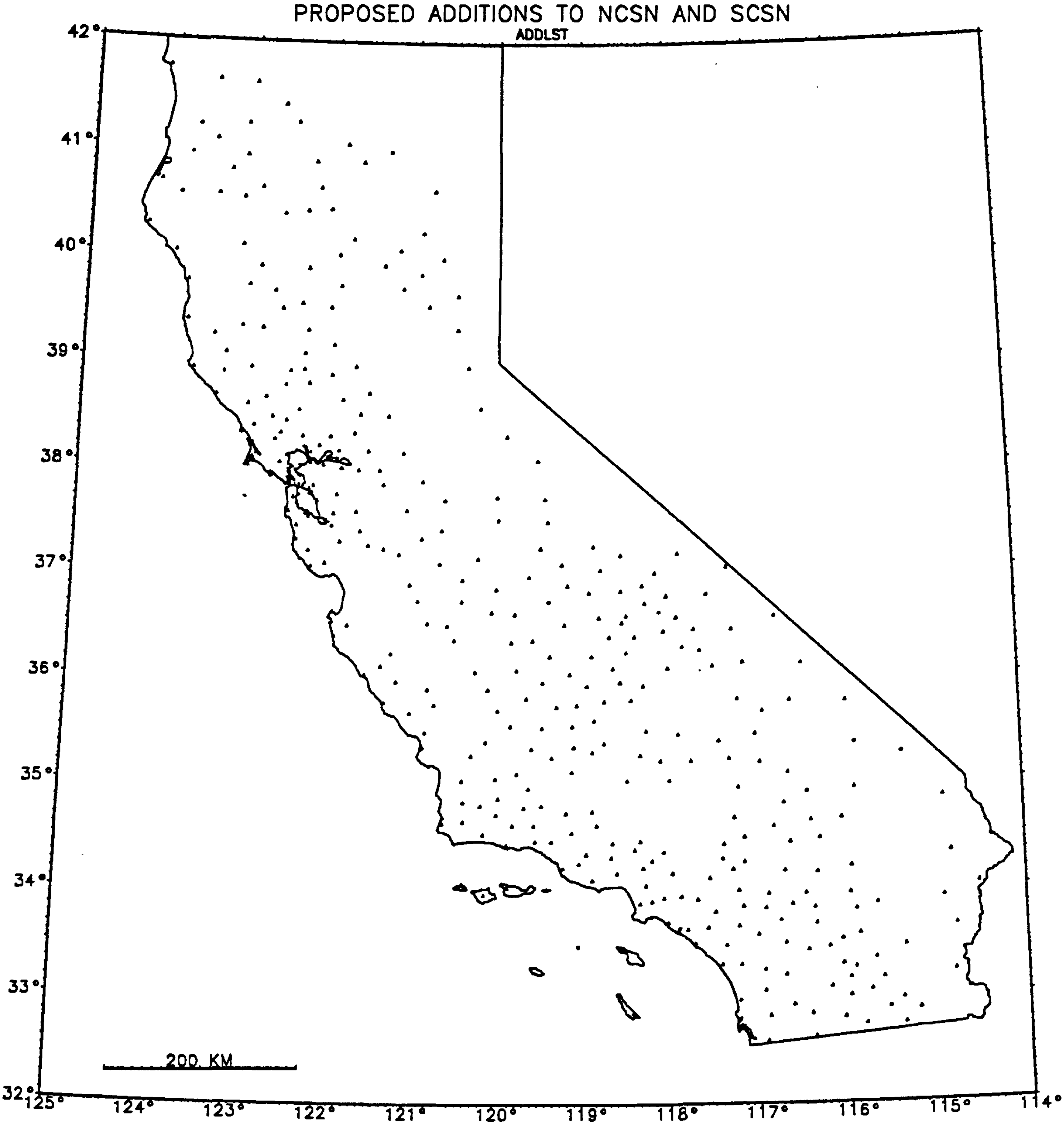
PROPOSED ADDITIONS TO NCSN AND SCSN
ADDLST
42°
41°
40°
39°
38°
37°
36°
35°
34°
33°
32°
125°
124°
123°
122°
121°
120°
119°
118°
117°
116°
115°
114°
200 KM

Figure 9

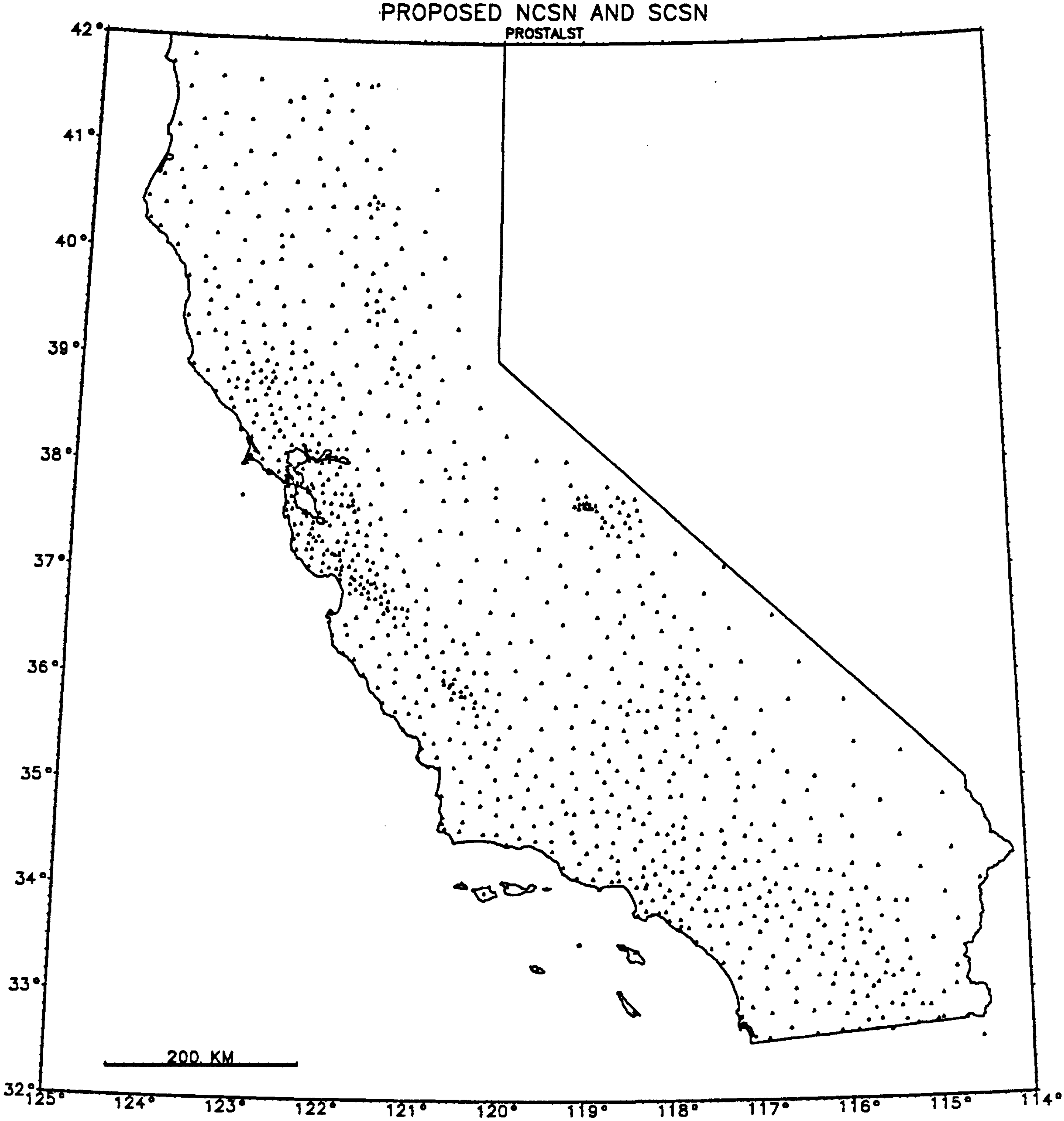
PROPOSED NCSN AND SCSN
PROSTALST
42°
41°
40°
39°
38°
37°
36°
35°
34°
33°
32°
125°
124°
123°
122°
121°
120°
119°
118°
117°
116°
115°
114°
200 KM

Figure 10

record of earthquake occurrence in California (see chap. 6; Ellsworth and others, 1981; Hill and others, in press; Hutton and others, in press).

In outline, the seismicity pattern for California and western Nevada forms a hollow ellipse with its long axis nearly coincident with the transform boundary. This

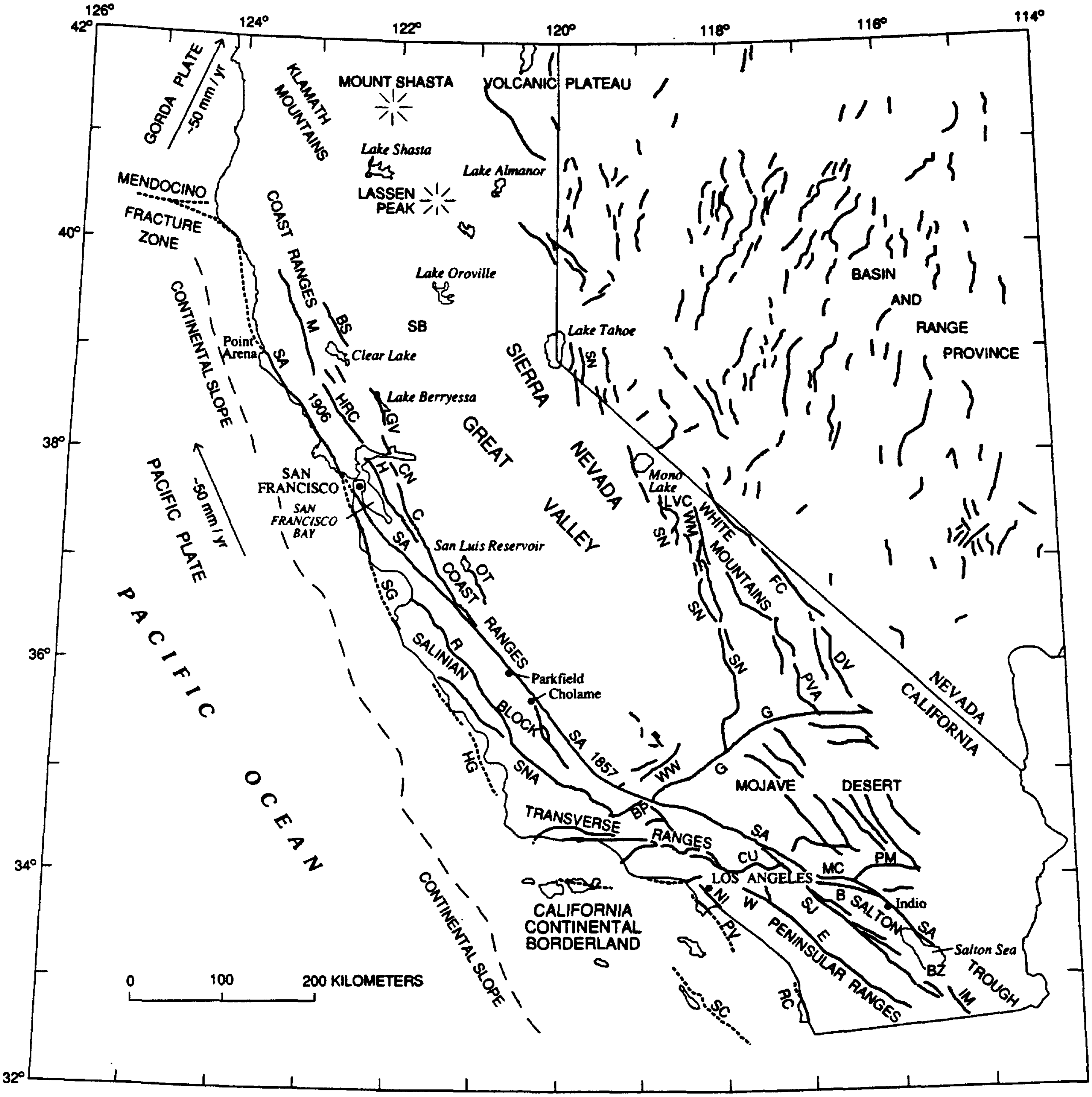

FIGURE 5.3.—Place names and faults most commonly used in text (see front of book for more complete maps of place names and faults). Faults (dotted where concealed): B, Banning; BP, Big Pine; BS, Bartlett Springs; BZ, Brawley seismic zone; C, Calaveras; CN, Concord; CU, Cucamonga; DV, Death Valley; E, Elsinore; FC, Furnace Creek; G, Garlock; GV, Green Valley; H, Hayward; HG, Hosgri; HRC, Healdsburg-Rodgers Creek; IM, Imperial; LVC, Long Valley caldera; M, Maacama; MC, Mission Creek; NI, Newport-Inglewood; OT, Ortigalita; PM, Pinto Mountain; PV, Palos Verdes; PVA, Panamint Valley; R, Rinconada; RC, Rose Canyon; SA, San Andreas; SC, San Clemente Island; SG, San Gregorio; SJ, San Jacinto; SN, Sierra Nevada; SNA, Sur-Nacimiento; W, Whittier; WM, White Mountains; WW, White Wolf. Arrows and numbers indicate direction and amount of motion, respectively, of Pacific and Gorda plates with respect to North American plate to the east; red lines indicate 1857 and 1906 ruptures of San Andreas fault.

Figure 11

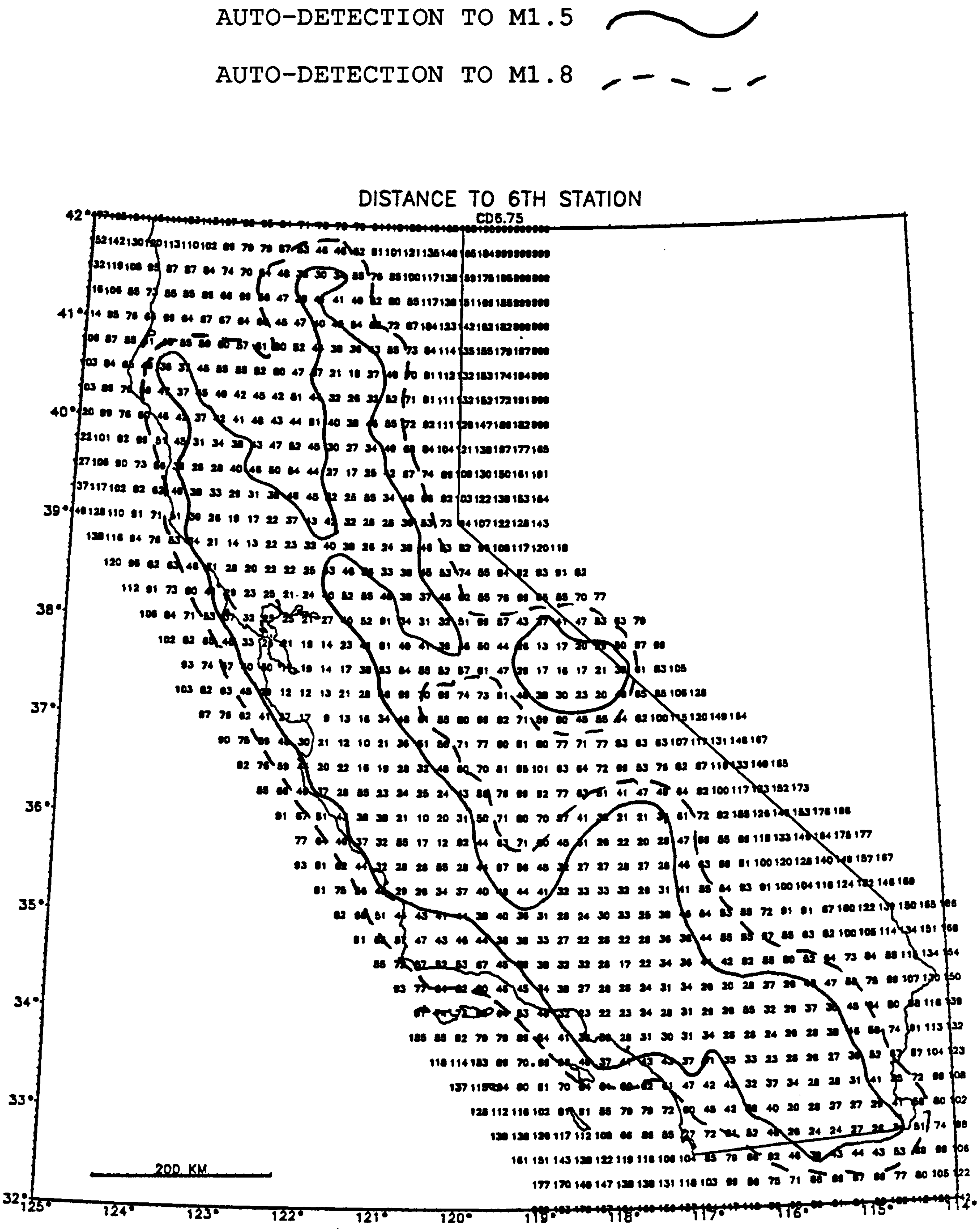

Figure 12a

CURRENT NET

AUTO-DETECTION TO M1.5

AUTO-DETECTION TO M1.8

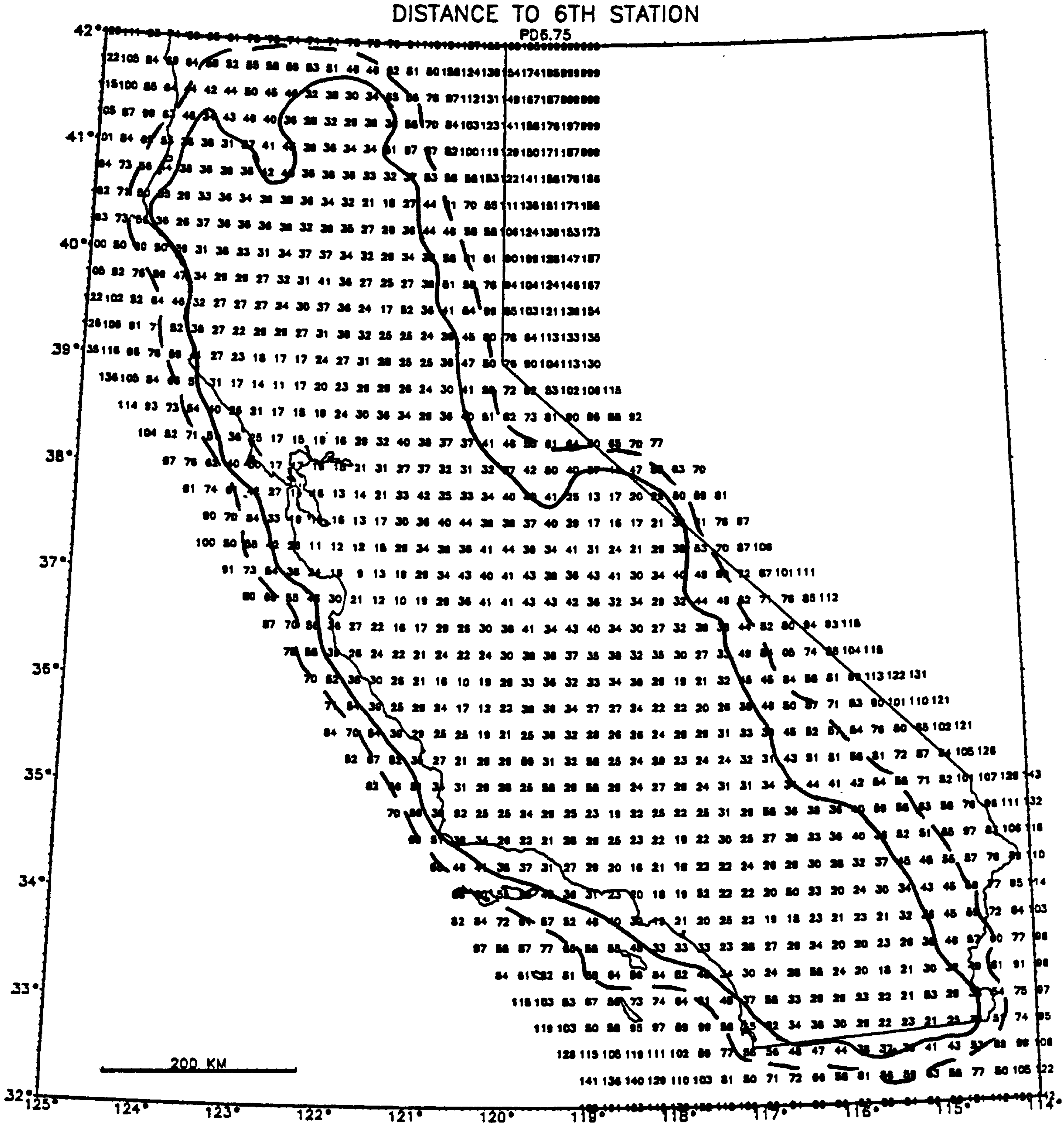

Figure 12b PROPOSED NET

FOCAL DEPTHS ADEQUATE FOR H > 5 KM

FOCAL DEPTHS ADEQUATE FOR H > 10 KM

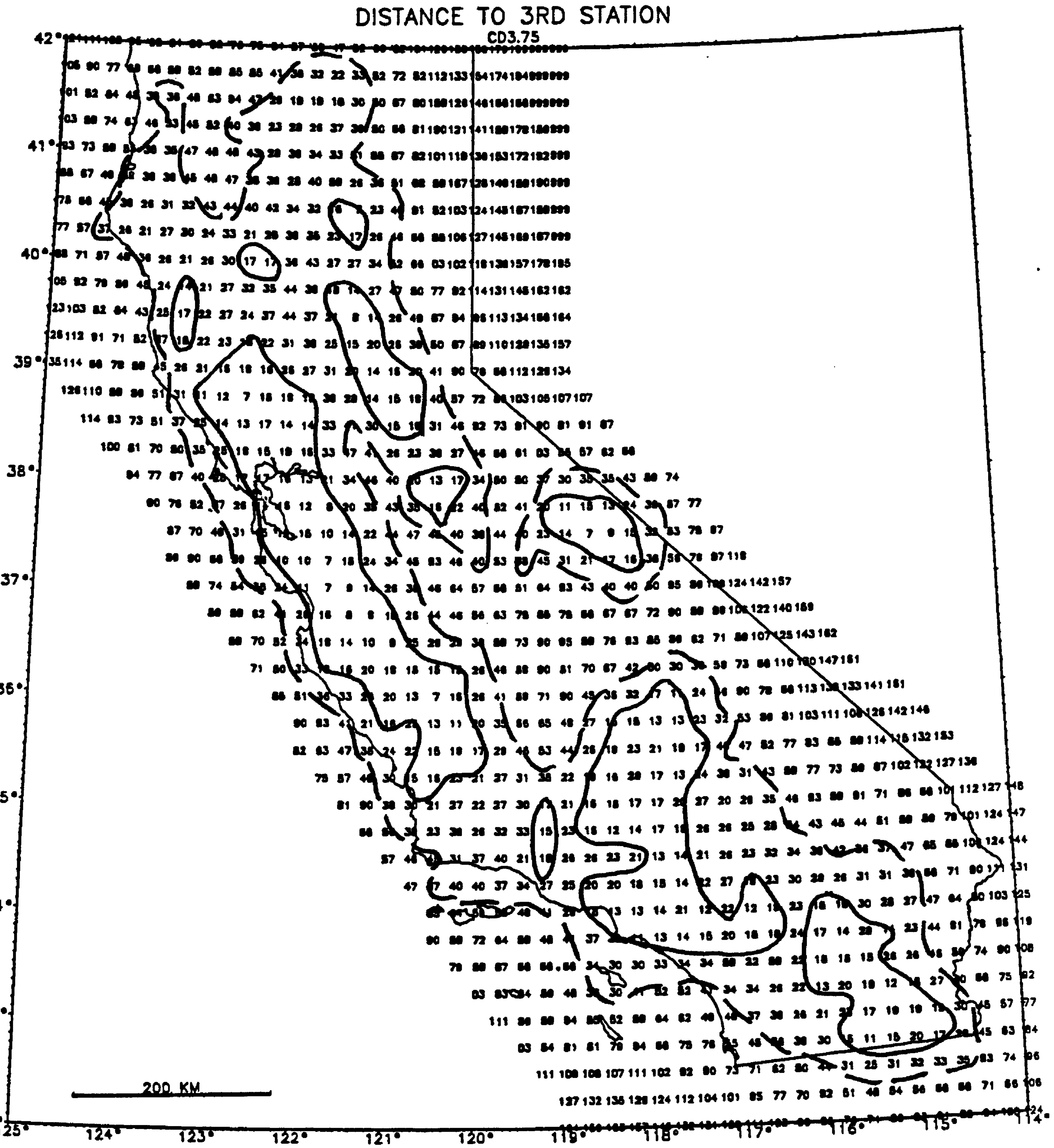

Figure 13a

CURRENT NET

FOCAL DEPTHS ADEQUATE FOR H > 5 KM

FOCAL DEPTHS ADEQUATE FOR H > 10 KM

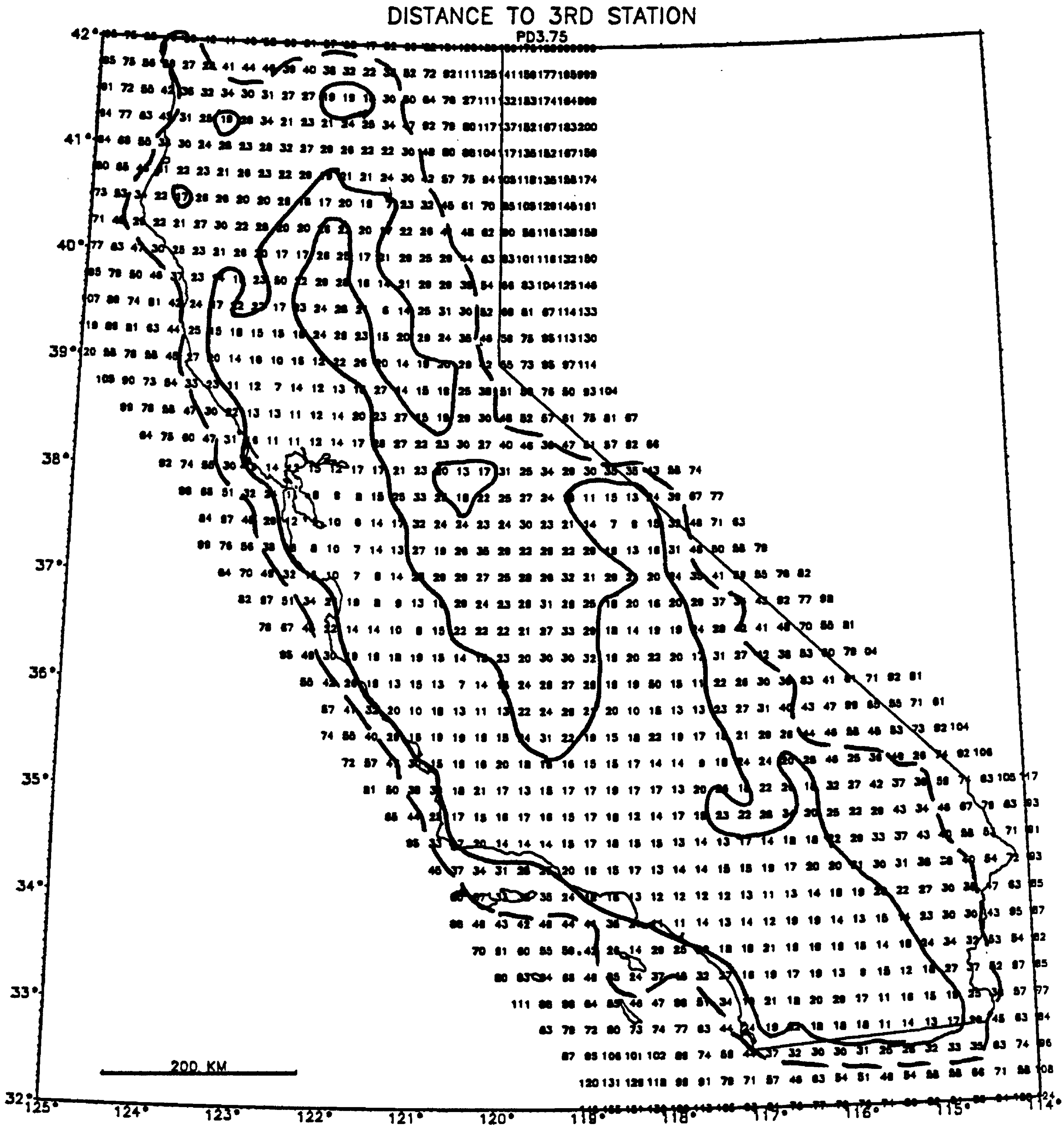

Figure 13b PROPOSED NET

20 STATIONS WITHIN 75 KM

10 STATIONS WITHIN 75 KM

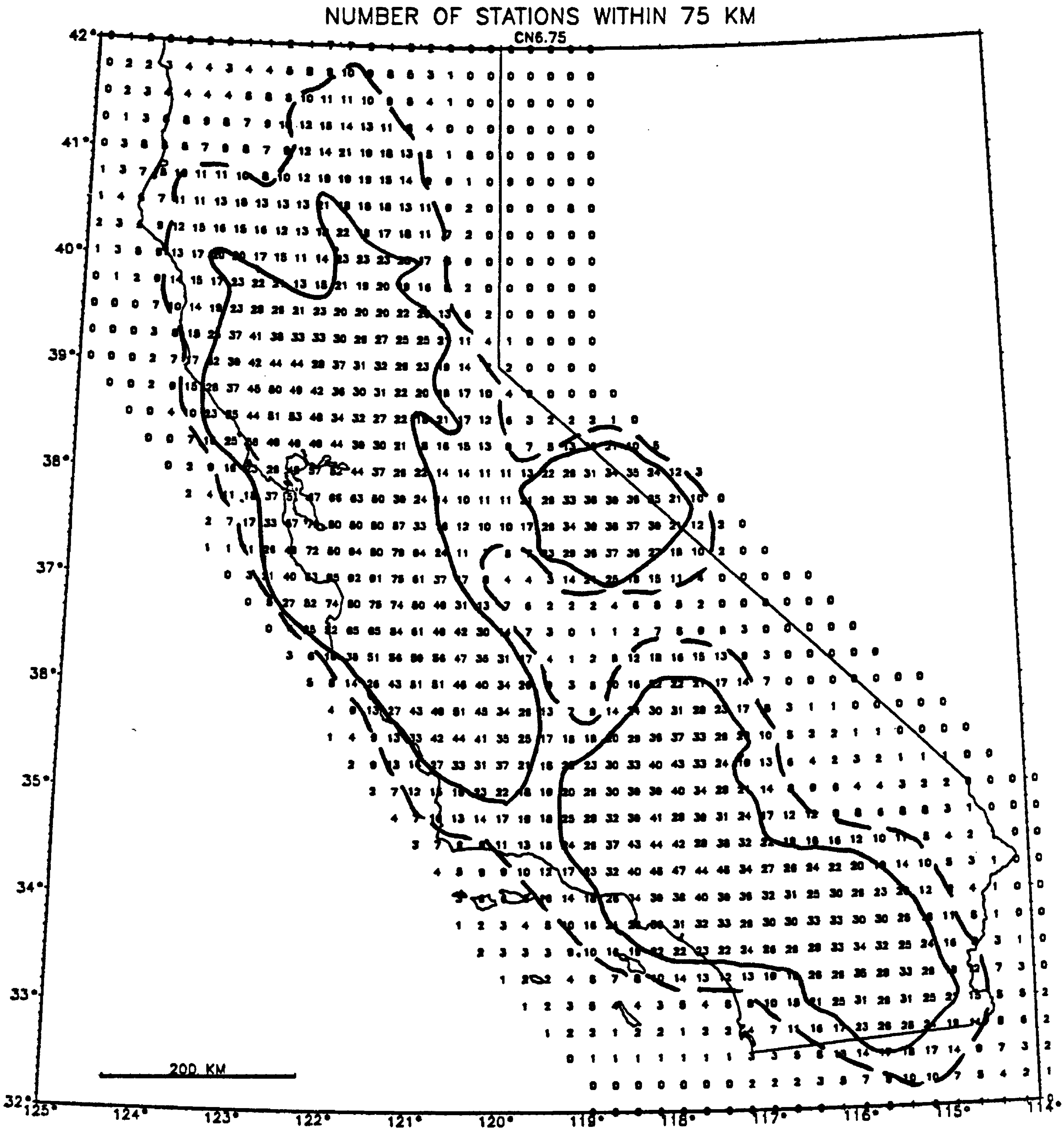

Figure 14a CURRENT NET

20 STATIONS WITHIN 75 KM

10 STATIONS WITHIN 75 KM

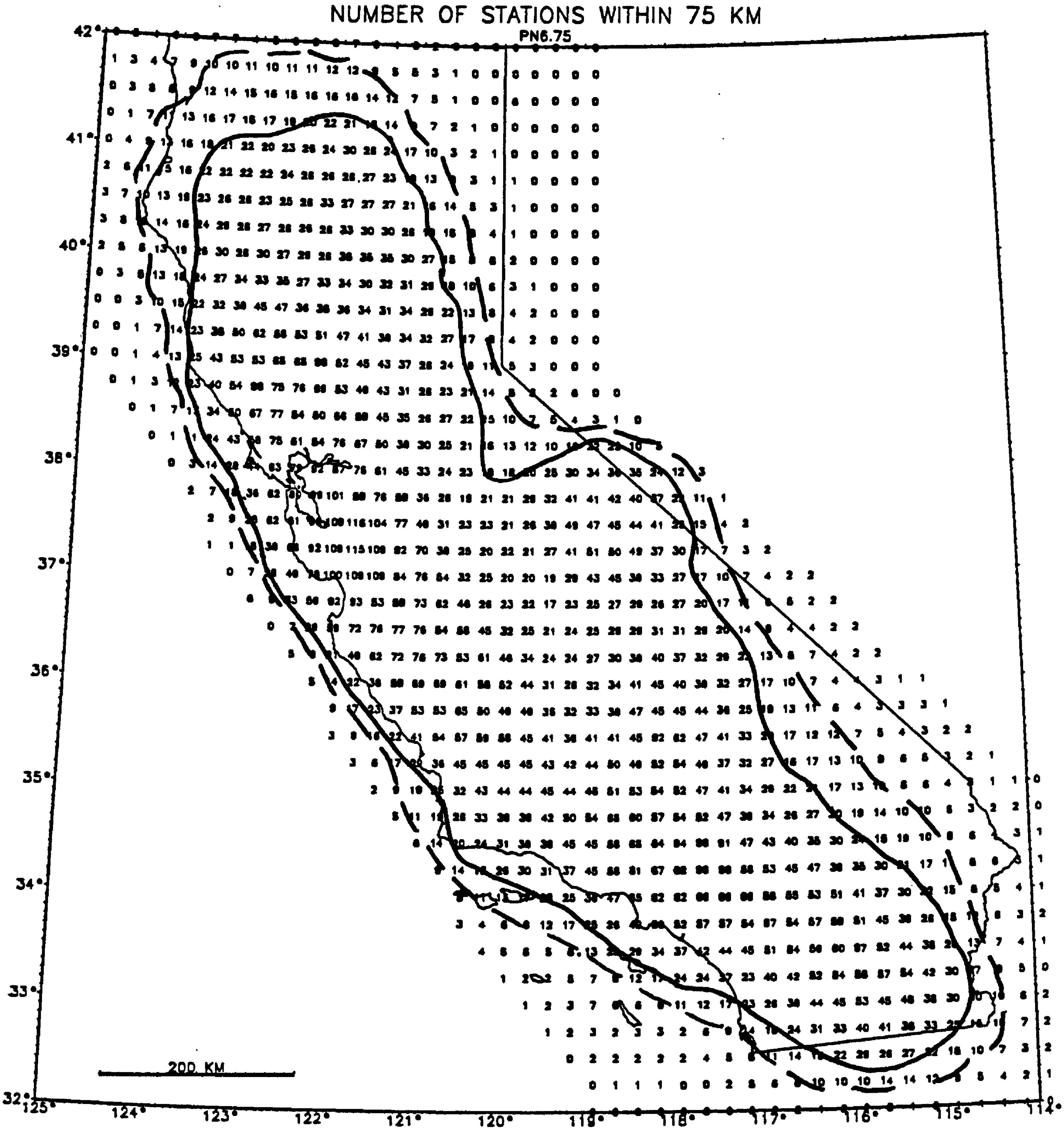

Figure 14b PROPOSED NET

MAX AZIM GAP < 90 DEG FOR STATIONS WITHIN 75 KM

MAX AZIM GAP < 180 DEG FOR STATIONS WITHIN 75 KM

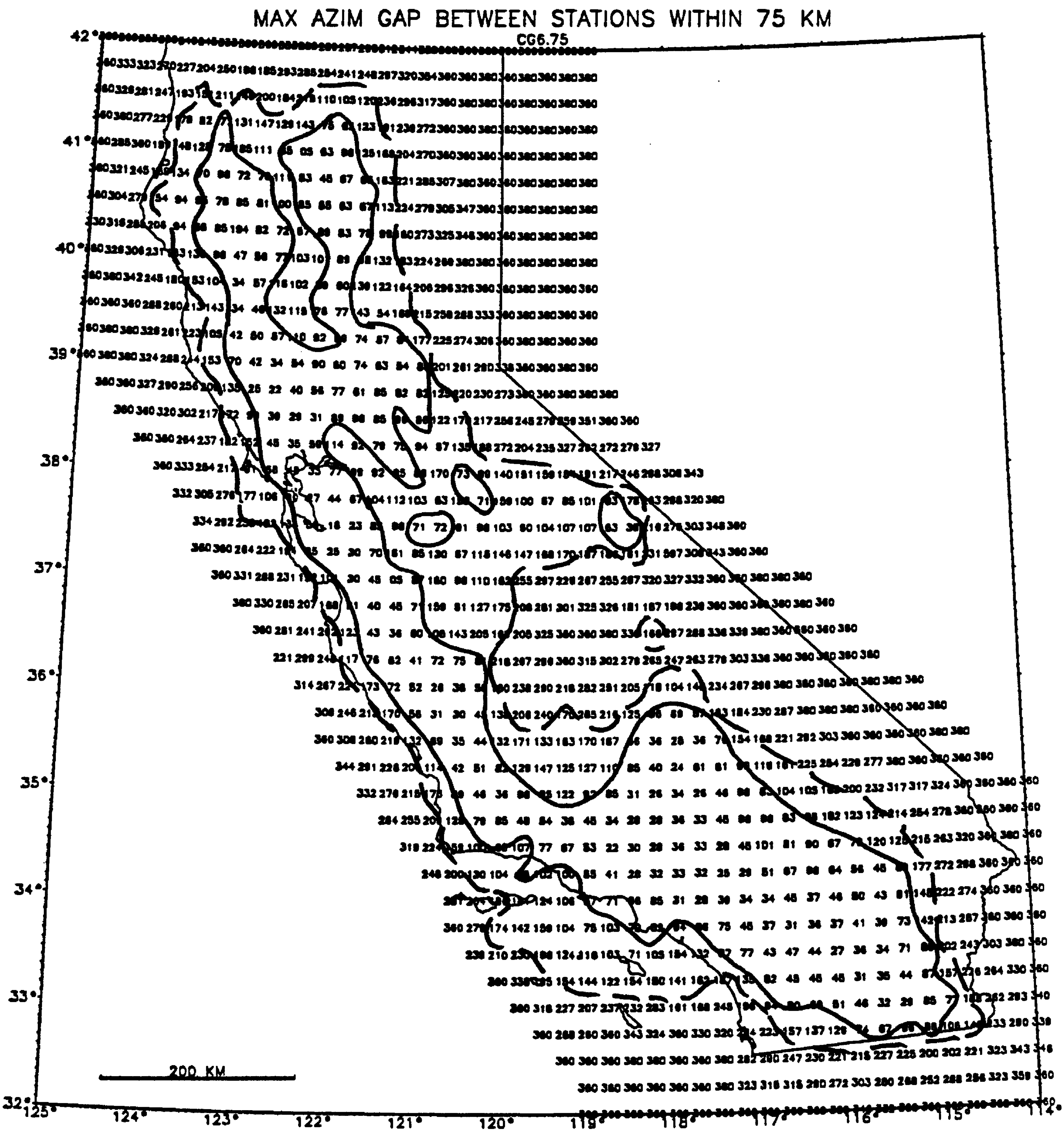

Figure 15a CURRENT NET

MAX AZIM GAP < 90 DEG FOR STATIONS WITHIN 75 KM

MAX AZIM GAP < 180 DEG FOR STATIONS WITHIN 75 KM

MAX AZIM GAP BETWEEN STATIONS WITHIN 75 KM

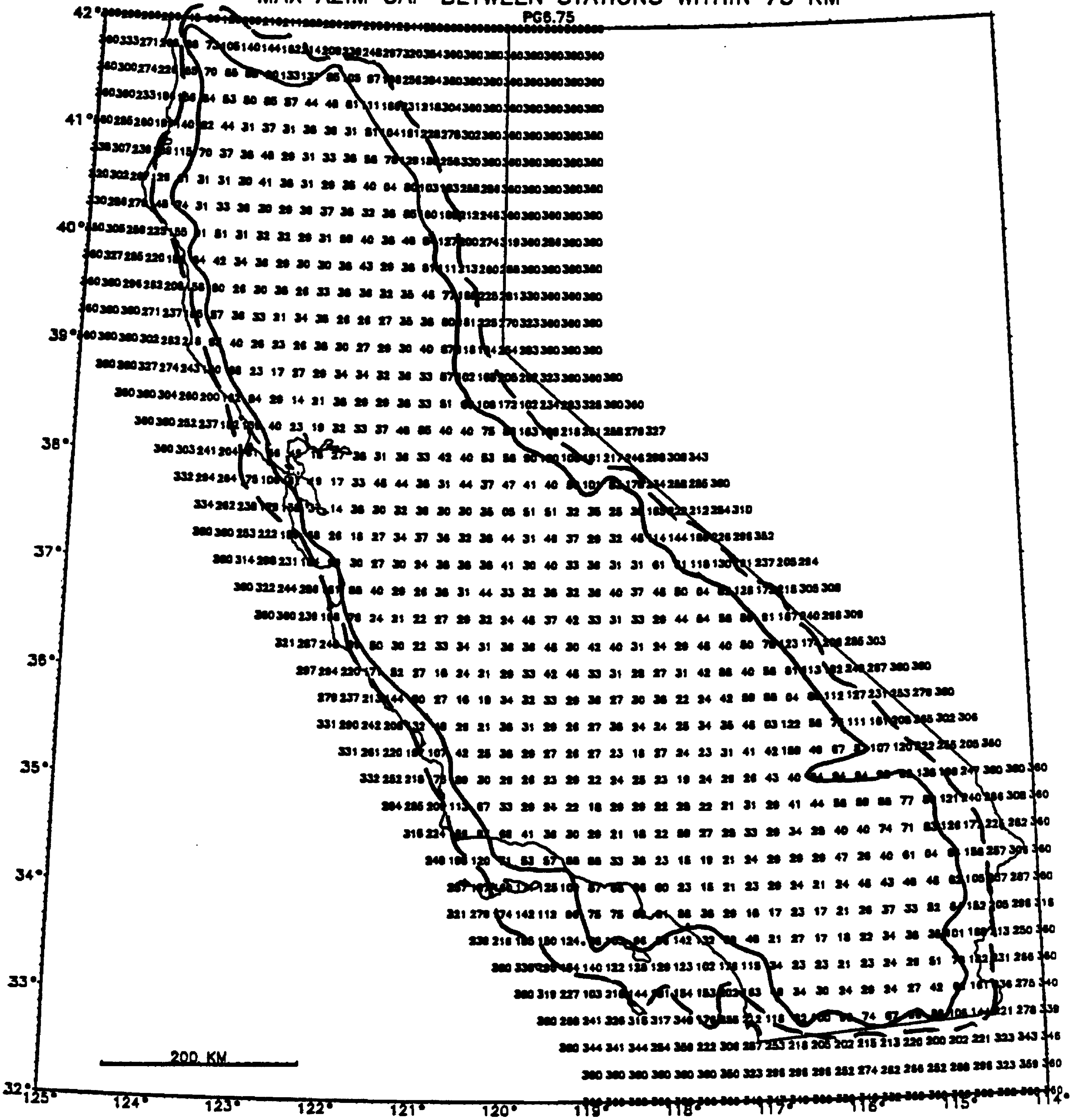

Figure 15b PROPOSED NET