G100990

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SEMIANNUAL TECHNICAL REPORT

February 1979

PERIOD COVERED 1 May 1978 - 20 October 1978

CONTRACT NUMBER:	14-08-0001-16741
NAME OF CONTRACTOR:	University of Nevada
PRINCIPAL INVESTIGATORS:	J. D. VanWormer and Alan Ryall
GOVERNMENT TECHNICAL OFFICER:	J. F. Evernden
SHORT TITLE OF WORK:	Seismic Hazard Evaluation of Large Known and Suspected Active Faults in Western Nevada
EFFECTIVE DATE OF CONTRACT:	20 October 1977
CONTRACT EXPIRATION DATE:	19 October 1978
AMOUNT OF CONTRACT:	$90,171
REPORT PREPARED BY:	J. D. VanWormer, A. Ryall, A. Mohler, and F. Ryall

Sponsored by the

U. S. Geological Survey

Contract No. 14-08-0001-16741

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A. RESEARCH PROGRAM

Investigate the seismic potential and state of activity of large known or suspected faults in western Nevada; continue to monitor seismic activity in the Mina region at a reduced level of effort; search for changes in regional seismicity that may indicate an impending major earthquake; analyze the distribution, magnitude, and mechanisms of earthquakes in the area of interest; and continue analysis of earthquakes in Nevada recorded by the Statewide network.

B. TECHNICAL DISCUSSION

I. SUMMARY OF OPERATIONS AND ANALYSIS

Instrumentation

The extensive Mina network was reduced to seven stations in July, 1977, and the equipment was reinstalled in the Reno-Carson City-Pyramid Lake region to provide better coverage of known and suspected faults in the most populated area of northern Nevada. The configuration of the Statewide network remained unchanged, and it still lacks coverage over much of southern and eastern Nevada.

Under an NSF grant we have begun design of a digital telemetering seismic station, which will utilize broadband instruments installed in sealed containers in mine tunnels to achieve SRO-type data at a minimum cost. Eventually we hope to replace key stations of the Nevada network with digital stations, and to develop master-event location routines that will permit analysis of Nevada earthquakes with fewer stations than are required at present.

Data Analysis

A large amount of effort during this reporting period was directed toward clearing up the data catalogs. Readings were checked, bad data removed or corrected, and quarry blasts were taken out of the data lists. The file is now in satisfactory shape, and the remaining step is to merge data from the Reno and Mina files with that from the Statewide network. The 1975 Laboratory Bulletin is now ready for printing, and the 1976 and 1977 issues are almost finished.

A new computer routine has been written for hypocenter and magnitude determination, which permits the operator to correct seismogram readings in an interactive mode. Once the analysis backlog is eliminated, this procedure should keep the Bulletin current. We are also testing a procedure whereby events selected for detailed analysis will be digitized from the analog magnetic tapes. This procedure will utilize the Laboratory's PDP-11-34 computer, plus A/D converters, plotters, and other equipment already on hand.

Noteworthy Seismic Activity

The fall of 1978 was marked by a flurry of activity along the eastern boundary of the Sierra Nevada, from Reno to Bishop. This activity started with an earthquake swarm in the volcanic area west of Mono Lake on 24 August. The largest events were on 25 and 31 August, with M = 3.2 and 3.0, respectively. The sequence began to die out at the end of August (see section VI for description of Mono activity).

On 4 September, an earthquake sequence began in Diamond Valley, California, apparently on a terminal cross fault at the south end of the Carson Range, about 40 km south of Carson City, Nevada. The two largest events of this sequence on 4 September had M = 4 1/2 and 5, and were felt in Minden, Gardnerville, Carson and the Lake Tahoe area. Section II gives preliminary results of a field study of these earthquakes.

On 4 October, a magnitude 5 1/2 earthquake occurred between Lake Crowley and Bishop, California, and was followed by an intensive aftershock sequence. The earthquake caused numerous landslides in the epicentral area, and fissures in the road were observed in upper Rock Creek, south of Lake Crowley. It was strongly felt in Mammoth, Bishop, Tuolumne and Fish Lake Valley, and felt reports were received from as far away as Fresno. Minor cracking of buildings was reported in the epicentral area. The University of Nevada dispatched a team on 4 October to set up a small seismic network in the epicentral area, and by 5 October an eight-station array was telemetering signals to two tape-recording systems. These stations operated for about 10 days. In addition, a smoked-paper recorder and a digital event recorder were installed in Rock Creek, another digital recorder was set up at Wheeler Crest, and a third digital system installed at Mina. A preliminary fault-plane solution indicates primarily normal faulting, on a plane striking about N 30° W and dipping 55° SE, or on a plane striking about N 10° E and dipping 40° W. Analysis of the field data is in progress.

On 9 October, another swarm occurred at Steamboat, at the foot of Mount Rose, just south of Reno and at the north end of the group of faults running along the east side of the Carson Range. The largest earthquake of this sequence had magnitude 2.6, occurred at night on 10 October, and was strongly felt locally. Residents reported marked changes in the flow of hot ground water: a well north of Steamboat began geysering, and water covered the US 395 highway in the same area. Focal depths of these events were quite shallow, 4-8 km, suggestiong a relationship to the hot spring activity.

On 20 October, swarm activity again picked up in the area east of Mono Lake, and the sequence continued for about two weeks. The largest magnitude was 3.4, for an event on 24 October.

From the end of November to the present time (12 February 1979), activity within the western Great Basin has been at a very low level. For example, the number of local and near-regional events recorded by Nevada stations during December 1977, which was a normal month for 1977, was about 50% higher than the number recorded in December 1978.

Personnel

Alan Ryall returned to the University of Nevada in August, after a two-year appointment as a program manager with the Defense Advanced Projects Agency in Washington. He will be a co-Principal Investigator on contract 14-08-0001-16741, with J. D. VanWormer. F. D. Ryall has also resumed work as a part-time research associate on this project.

II. EARTHQUAKES IN DIAMOND VALLEY, CALIFORNIA, SEPTEMBER 1978

By

J. D. VanWormer

An earthquake sequence starting on September 4 was located in Diamond Valley about 40 km south of Carson City (Figure II-1). Three foreshocks (M = 2.1, 2.3, 2.8) occurred 18 hours prior to the first of the two larger events in this series. Other than an earthquake 5 km east of the active area on 10 July 1978 there was apparently no prior activity in Diamond Valley.

A University of Nevada field team installed a broadband three-component digital event recorder and a smoked paper seismograph in the epicentral area to enhance location of aftershocks. Epicenters in Figure II-1 had readings from one or both of the portable stations and the network. In our preliminary investigation we used a simple layer over a half-space for a crustal model - possibly inadequate, especially for the nearby stations EVR and SMO which were sited on alluvium of unknown depth.

Distribution of the epicenters is in a NE - SW direction which is subparallel to gross topographic features trending N35°E to N50°E in the region -- such as the East Fork of the Carson River (Figure II-1) and several other streams which head in the Sierra Nevada and flow into the Great Basin.

Focal mechanisms for thirteen events were determined and all but a few are compatible with the main shock projection shown in Figure II-2. Those few exceptions can be fit by the same solution as in figure II-2 with the strike of the planes oriented several degrees further clockwise. Additional data from USGS stations on the west side of the Sierra Nevada will be added to the focal mechanisms. At this time our interpretation of Figure II-2 is that of a N50°E fault dipping 60°SE with left lateral motion. This fault probably

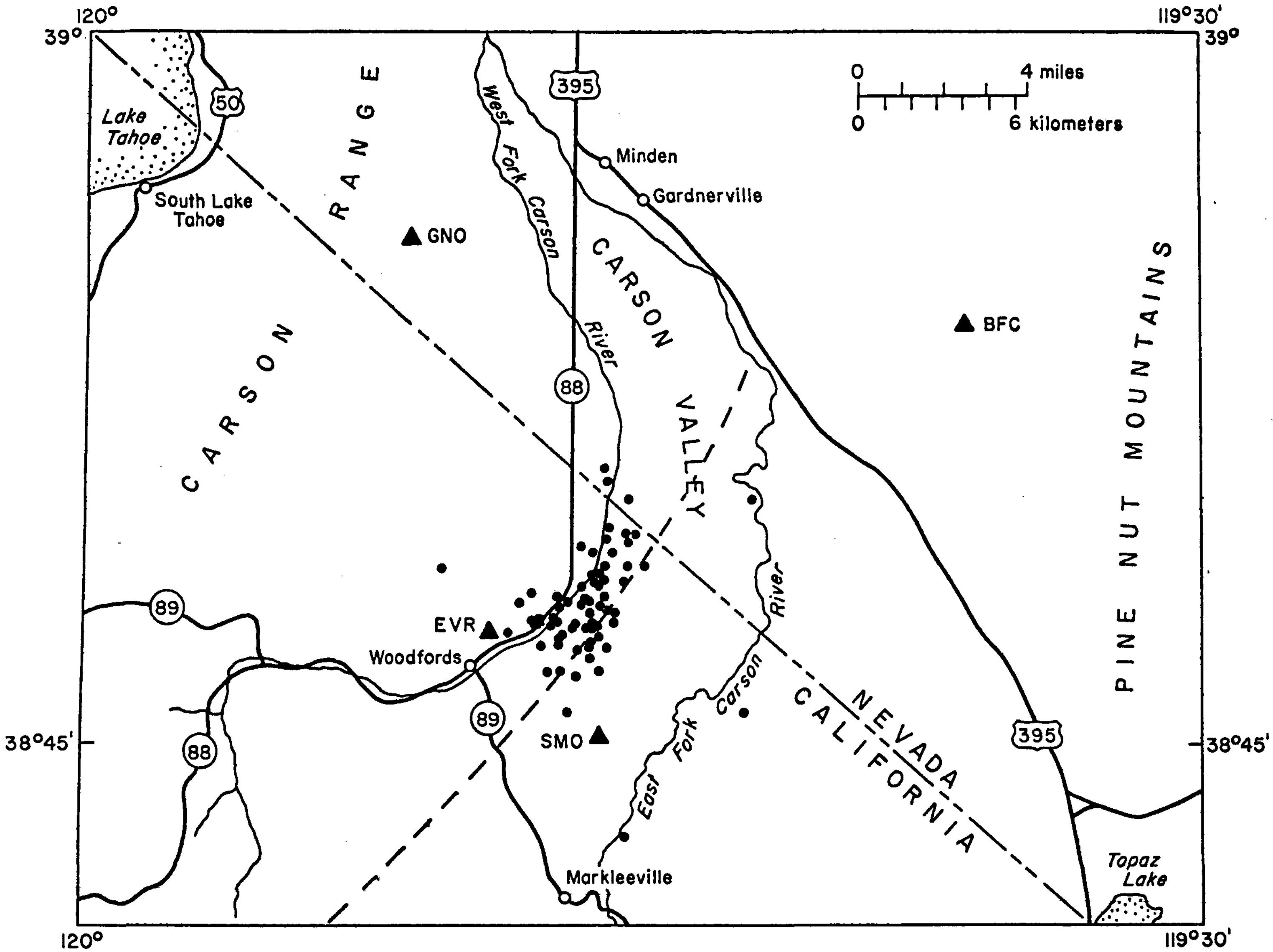

Figure II-1. Aftershocks of the 4 September 1978 Diamond Valley, California, earthquake, determined using one or both of the temporary stations EVR and SMO. Dashed line -- lineament identified on high-altitude U-2 photographs.

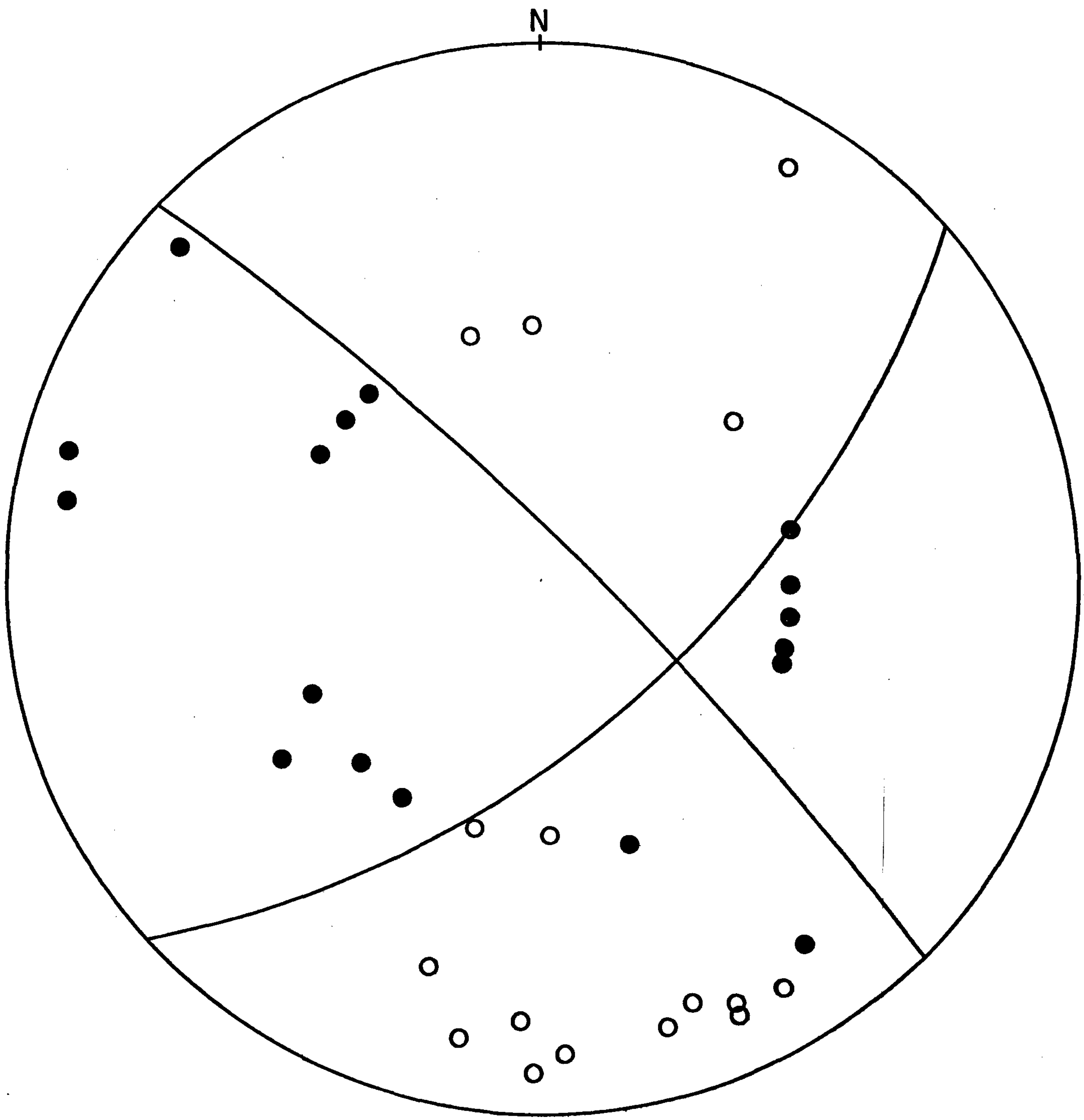

Figure II-2. Lower-hemisphere equal-angle projection for the main shock on 4 September 1978 at Diamond Valley, California. Solid circles -- compressions, open circles -- dilatations.

terminates the Genoa Fault which borders the east side of the Carson Range and is spectacularly visible from most of the Carson Valley. Geologic maps of California (e.g., Jennings, 1977) show the southern portion of the Genoa fault as an inferred fault that curves from a N-S orientation to a NE-SW orientation as it enters Diamond Valley and goes up the West Fork of the Carson River. On high altitude U-2 photographs there is a prominent linear feature which strikes SW from the East Fork of the Carson River, from just south of Gardnerville through the southern portion of the group of epicenters and continues southwestward well into the Sierra Nevada for a total length of 25 km. (Dashed line in Figure II-1.) We do not know if this feature is an unmapped fault but consider it significant that it has approximately the same strike as: 1) the epicenters; 2) one of the focal planes; and 3) several of the other prominent topographic features in the region. Both Jennings (1977) and Moore and Archbold (1969) show short faults of NE - SW orientation around the Diamond Valley area. Therefore, it is entirely plausible that these earthquakes occurred on a NE - SW terminal fault rather than on the N - S Genoa Fault.

III. SEISMIC ZONING IN THE WESTERN GREAT BASIN

By

Alan Ryall and J. D. VanWormer

Abstract

Recent seismic zone maps by Algermissen and Perkins (1978), the Applied Technology Council (1978) and the Uniform Building Code (International Council of Building Officials, 1976) give highest risk values to the zone of major historic earthquakes in central Nevada, but relatively low risk to a zone of major faults along the eastern boundary of the Sierra Nevada. Evidence is presented to show that the latter faults constitute the most serious seismic hazard at the present time to the population of northern Nevada and eastern California, and it is suggested that official seismic zone maps be changed in accordance with this evidence.

Introduction

A major goal of the National Earthquake Hazards Reduction Program (report of the Executive Office of the President, 22 June 1978) is to prepare national maps giving an assessment of the relative frequency and characteristics of earthquakes in the US. According to the report, "these maps are needed to establish national priorities for earthquake hazards reduction activities, for model building codes, and as a basis for incorporating earthquake hazards reduction provisions -- where appropriate -- in a wide variety of Federal programs. . . While researchers address the fundamental problems, a series of maps will be produced to meet immediate and growing needs. These will be revised as new information becomes available."

In this paper, seismic zoning proposed for the Nevada region and incorporated into the current Uniform Building Code (UBC; International Council of Building Officials, 1976) is discussed in the light of current knowledge about the seismic cycle and earthquake potential within major rupture zones in this region. The discussion centers on a recent study by Algermissen and Perkins (1976), as well as an Applied Technology Council (ATC; 1978) report, "Tentative Provisions for the Development of Seismic Regulations for Buildings."

Proposed Seismic Zoning Maps

The UBC, which is used as the basis for building ordinances in most Nevada jurisdictions, contains a "Seismic Zone Map of the United States" that is very similar to a more detailed map presented by Algermissen and Perkins (1976). In the latter study, probabilistic estimates of maximum acceleration in rock are calculated by a method that involves three main steps: (1) delineation of seismic source area; (2) analysis of the statistical characteristics of historical earthquakes in each seismic source area; and (3) calculation and mapping of the extreme probability $F_{max,t}(a)$, of acceleration for some time, t. "Source areas" included zones where shocks of MM intensity 5 or greater have occurred during the historic period, plus areas adjacent to these zones where evidence of Holocene faulting is present. Quaternary or older faults not associated with historic earthquakes were not considered to be source areas.

Results of this analysis for the California-Nevada region are illustrated by a map showing horizontal acceleration (percent of gravity) that has a "90 percent probability of not being exceeded in a 50-year period" (Figure III-1). Following directly from the assumptions stated above, the zone of highest probable acceleration is the one in which five major ($M \geq 7$) earthquakes have occurred in Nevada and eastern California during the historic period (Figure III-2: 1852?

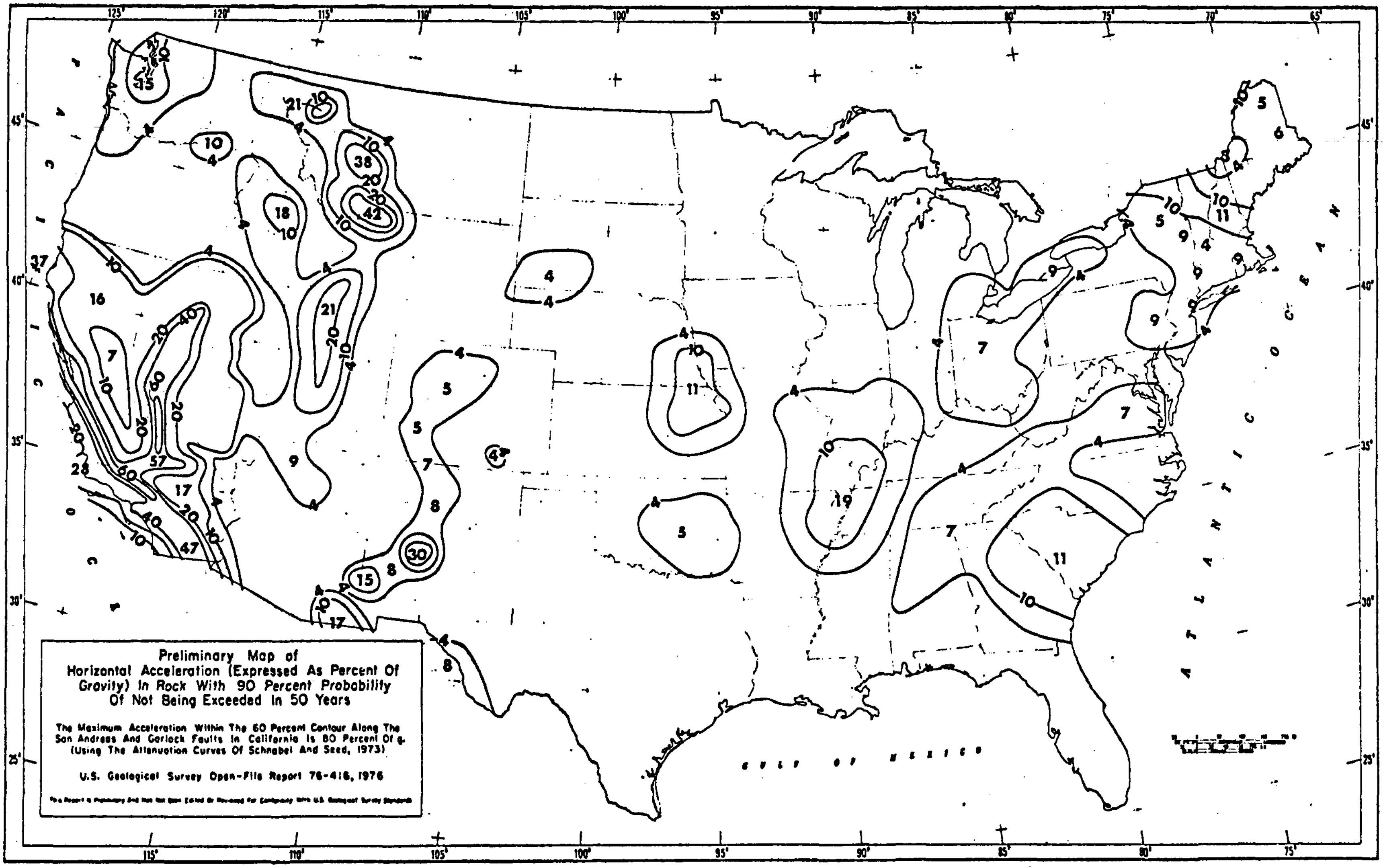

FIGURE III-1 SEISMIC RISK DEVELOPED BY ALGERMISSEN AND PERKINS

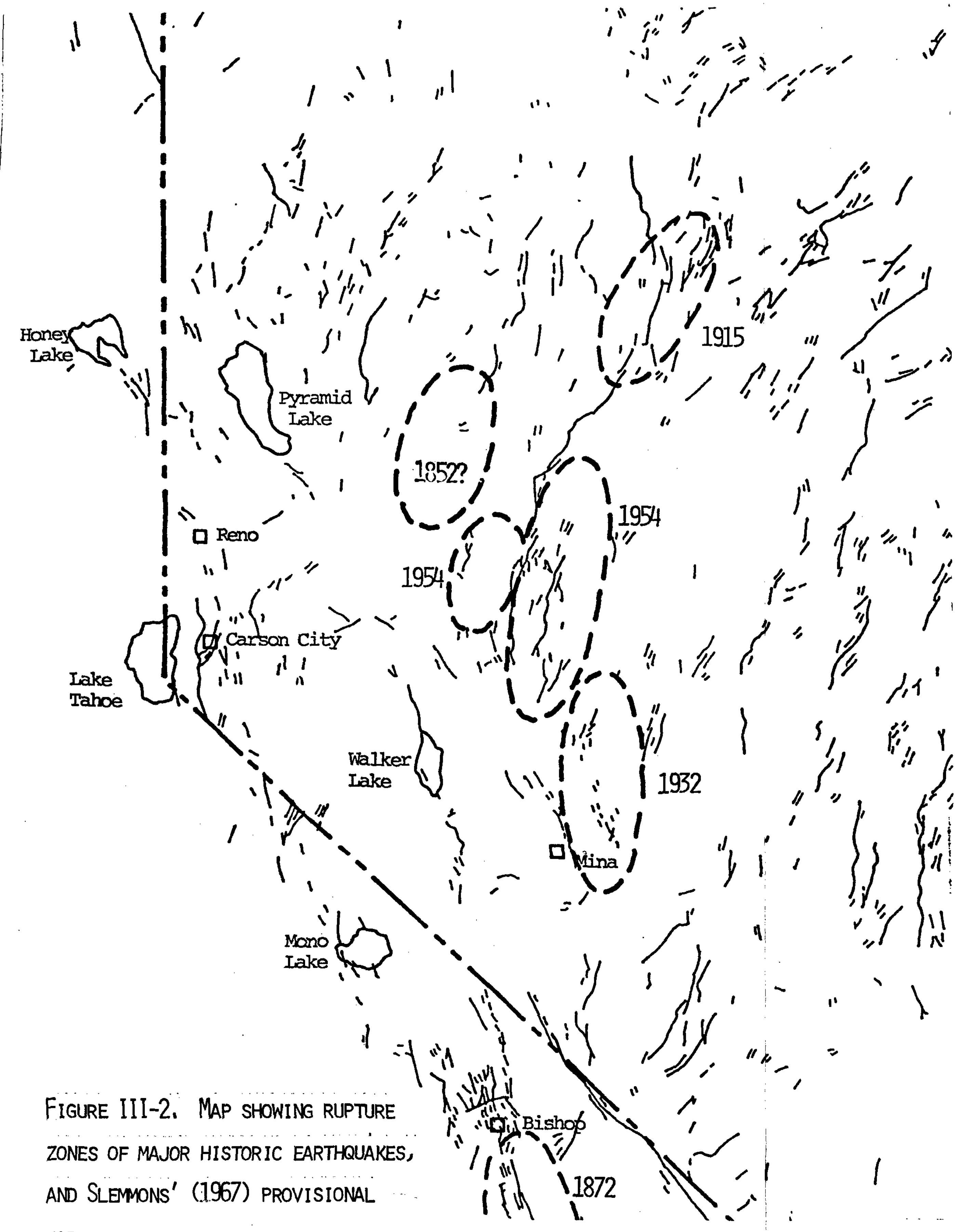

FIGURE III-2. MAP SHOWING RUPTURE ZONES OF MAJOR HISTORIC EARTHQUAKES, AND SLEMMONS' (1967) PROVISIONAL MAP OF ACTIVE FAULTS.

Stillwater area; 1872 Owens Valley; 1915 Pleasant Valley; 1932 Cedar Mountains; 1954 Dixie Valley-Fairview Peak). Whithin this zone the maximum probable acceleration is 0.4-0.6 g, while for the remainder of Nevada and eastern California it ranges from 0.04-0.2 g. Similarly, the UBC stipulates that structures within the zone of major historic shocks must be designed for base shear that is one-third higher than the rest of the region.

The 1978 ATC report presents seismic zone maps showing "effective peak acceleration" (EPA) and "effective peak velocity-related acceleration" based on the study by Algermissen and Perkins (1976) as well as other proposed seismic zone maps, and modified so that the boundaries between seismic zones correlate with political subdivisions (i.e., county boundaries). The ATC map of EPA for Nevada-eastern California region is shown on Figure III-3. In discussing the philosophy behind these maps, the ATC report notes that critics might argue that the historical record is far too short to justify the weight that is put upon the pattern of major historic earthquakes. However, "the most widely used procedures assume that large earthquakes occur randomly in time, so that the fact that a large earthquake has just occurred in an area does not make it less likely that a large earthquake will occur next year."

The ATC map of EPA for the Nevada-eastern California region is shown on Figure 2. Most of Nevada, unlike the Algermissen-Perkins map, is assigned the maximum EPA of 0.4 g. However, Ormsby and Storey Counties in western Nevada have an EPA of 0.3 g, and Douglas County, Nevada, as well as most of the Sierra Nevada in California have EPA values of 0.15-0.2 g.

The Seismic Cycle in the Western Great Basin

Recent work by several authors suggest that the Algermissen-Perkins, UBC and ATC maps present an incorrect assessment of seismic hazard in the Nevada region. An

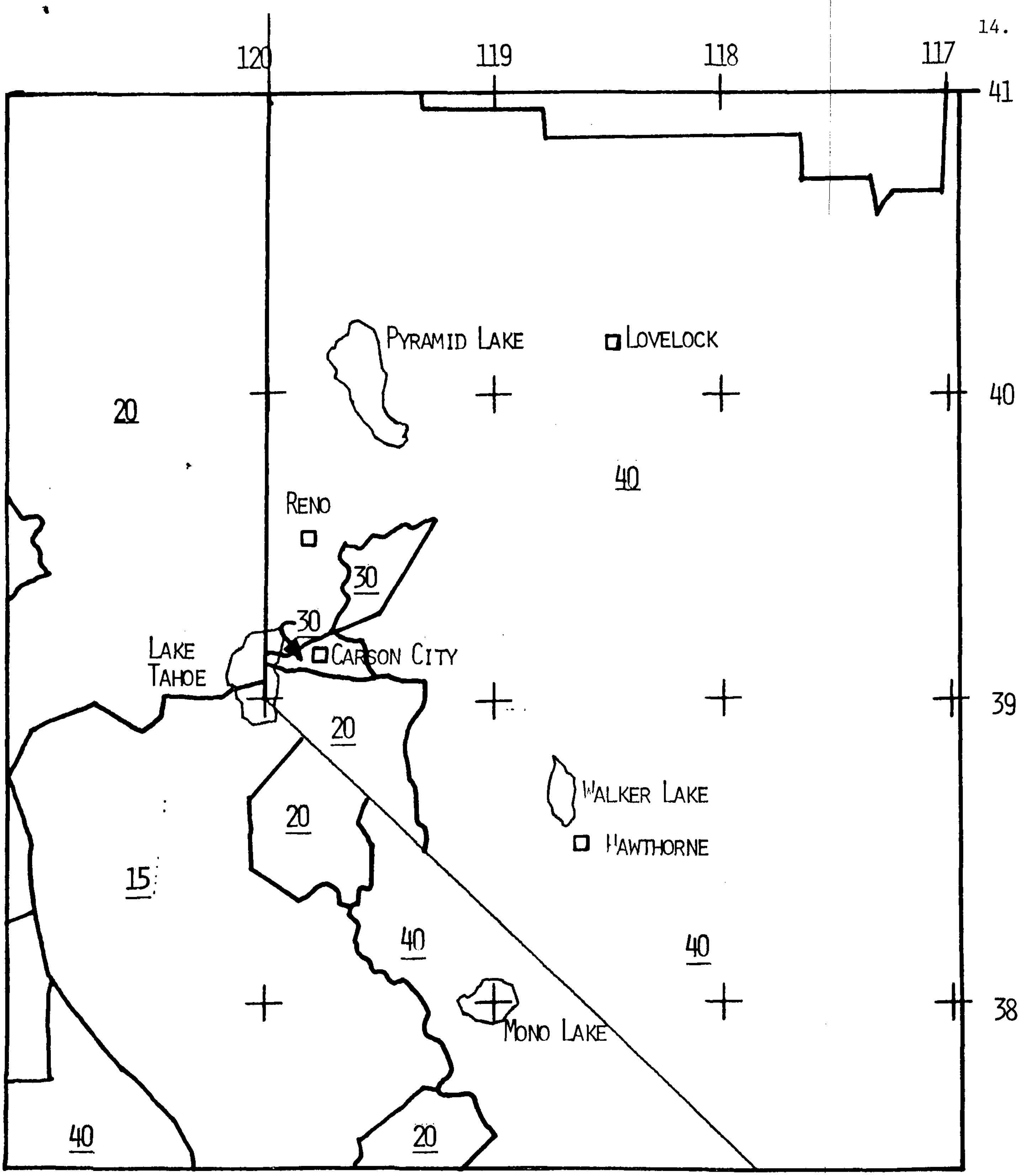

Figure III-3. Seismic risk map from 1978 Applied Technology Council report. Underlined values are "Effective Peak Acceleration," in percent of g.

early study (Ryall et al., 1966) concluded that the tectonic processes causing earthquakes and faulting in the western United States are distributed over broad regions, and that gaps in the seismicity pattern tend to be filled in by successive large earthquakes. Later, Ryall (1977) found that the "seismic cycle" -- corresponding to the re-rupture time for major faults -- is of the order of thousands of years long in the Great Basin. A typical large earthquake ($M \geq 7$) is followed by a decaying aftershock sequence that lasts for about a century, and seismicity in the rupture zone then stabilizes at some minimum level for a long period of time. Foreshock activity, consisting of a moderate level of seismicity, has been observed in the impending rupture zone of two historic earthquakes -- the 1915 Pleasant Valley and 1954 Dixie Valley-Fairview Peak zones -- during a period of at least several decades prior to the main shock.

Because of the very long interval between successive large earthquakes involving displacements on a given cluster of faults, the distribution of historic earthquakes with MM intensity of 5 or greater, used by Algermissen and Perkins (1976) to construct their probable acceleration map, is completely inadequate for determining seismic hazard in the Nevada region. Contrary to present zoning dogma, rupture zones of the most recent great earthquakes in this region could actually be the seismically "safest" areas in the Great Basin if the seismic cycle suggested by Ryall (1977) is correct, since major earthquakes would not be expected to recur in these particular zones for perhaps thousands of years.

Recent studies by Wallace (1977, 1978), of fault scarp morphology in north-central Nevada, support the conclusions given above. Wallace estimated the most recent age of displacement for fault scarps in 19 clusters of faulting, varying in length from 8 to 60 km, within an area of 17,000 km^2 in north-central Nevada. We concluded that no more than seven major events had occurred in this area during Holocene time, leading to an average recurrence rate of 3.4×10^{-5} events per year per 1,000 km^2. He stated that this rate may represent an upper limit for the western Great Basin, since the density of faults large enough to produce major earthquakes is as great in north-central Nevada as anywhere else in the province. Of importance to the question of seismic zoning, he observes that fault scarp morphology in the rupture zones of large historic earthquakes does <u>not</u> suggest faulting at a greater rate than in surrounding areas.

Over an eight-year period, the University of Nevada Seismological Laboratory recorded and analyzed more almost 3,000 small earthquakes in the western Great Basin -- generally in an area of about 225,000 km^2 that contains Holocene faulting (Wallace, 1978). Of approximately 90 events that occurred within Wallace's 17,000 km^2 fault scarp study area, more than a third are within or adjacent to the rupture zone of the 1915 Pleasant Valley earthquake. The remainder are more or less randomly scattered about the area, and appear to represent a background level of seismicity that is observed over most of the western Great Basin. Thus, with the possible exception of an extension of the 1915 zone toward the north, present seismicity does not suggest an impending major earthquake in any of the zones of faulting studied by Wallace.

Wallace (1978) also reports rates of uplift of range blocks: 0.8 m per 1,000 years found by R. Speed for the White Mountains, and 0.5 m per 1,000 years obtained by Wallace for the Stillwater Range. Based on the assumption that an event with $M = 7$ would involve an area of approximately 1,000 km^2 and an uplift of 3 meters, these rates uplift rates lead to recurrence rates of $1.6\text{-}2.7 \times 10^{-4}$ such events per year per 1,000 km^2.

Comparison of Recurrence Rates

Wallace's (1977, 1978) results provide an opportunity to compare recurrence rates determined from fault scarp morphology with those obtained from lists of instrumentally recorded earthquakes. In the study by Ryall _et al._ (1966), recurrence rates for the Nevada region were based on an 84,000 km^2 area defined by the distribution of historic seismicity. As a result, the calculated recurrence times in that study are inappropriate to a discussion of major earthquakes, which could occur within most of the region containing Holocene faulting, i.e. an area of 225,000 km^2. If we suppose that the level of seismicity within this region remains at a constant level but moves from one rupture zone to another as stress is built up and released by large earthquakes, then to calculate the return period for major shocks the occurrence statistics should be applied to the entire 225,000 km^2 region of Holocene faulting. Douglas and Ryall (1975) extended the earlier study, and found that the recurrence relationship for all western Nevada earthquakes recorded during the 1932-1969 period was $\log N = 6.43 - 0.91 M$, where N = the cumulative number of earthquakes recorded during the 38-year period with magnitude equal to or greater than M. This corresponds to a return period of about 45 years for events in the western Great Basin with $M \geq 7.2$, and if we use 225,000 km^2 as the area to which this statistic applies, the rate of occurrence of major shocks is about 1.0×10^{-4} per year per 1,000 km^2.

Ryall (1977) presents a recurrence curve based on approximately 2,000 earthquakes recorded in the Nevada region from 1970 to 1974. This curve has two distinct branches, the steeper of which is associated with events that have $M > 3.8$ and could be affected by insufficient time to observe large earthquakes. For the smaller earthquakes, the recurrence rate is $\log N = 4.847 - 0.784 M$, which leads to a return period of 31 years for earthquakes with $M \geq 7.2$, and to a rate of 1.4×10^{-4} per year per 1,000 km^2 for such events.

Seismic Risk in the Reno-Carson City Area

Ryall (1977) and Wallace (1978) identify several zones in the western Great Basin that represent gaps in the pattern of historic seismicity and have potential for large earthquakes in the future. Several of these, such as the White Mountains gap, the eastern Sierra zone, and lineaments or fault zones in the area north of Reno, Nevada, are marked by epicenter lineups or by the frequent occurrence of earthquake swarms.

The Reno-Carson City-Lake Tahoe area is the most populated area in northern Nevada, and lies along the boundary between the eastern edge of the Sierra Nevada and the western edge of the Great Basin. According to D. B. Slemmons (written communication, 1973) the closest and most hazardous fault zone affecting the Reno urban area is a broad zone of complex shattering that crosses bedrock areas in the Marlette Lake area and alluvial deposits near the base of Mount Rose, extending northward into the older alluvial deposits of south Reno. In the downtown area of Reno several north-trending escarpments up to 15-20 feet in height are observed which are continuous with the zone of fault scarps to the south, and are probably fault controlled. In the Mount Rose area, Cordova (1969) found three to five movements on faults during Holocene time, which suggests a re-rupture time of 2,000 to 3,000 years for these faults.

South of Reno, this fault zone continues for more than 70 km along the eastern front of the Carson Range, through Carson City to Diamond Valley, California. In the vicinity of Genoa, Nevada, Pease (1979) has found two distinct movements on this fault in the last 4,000 years and 3-4 movements during Holocene time. The most recent movement had vertical displacement measured at two locations of 4-7 meters, and the previous movement amounted to 1 1/2 - 2 meters. Based on Wallace's (1977) method of measuring debris slopes, Pease estimates that the most recent movement may have occurred just over a century ago, but other evidence could place this event at times ranging up to 1,000-2,000 years ago.

Of particular importance to seismic zoning, swarms of earthquakes at the two ends of this fault zone are a frequent occurrence. In September and October, 1978, for example, earthquakes with M = 5.2 and 2.6, respectively, occurred in Diamond Valley at the south end of the zone and at the base of Mount Rose at the north end. It is interesting to note that this fault zone, as well as other active and potentially hazardous faults in the Reno-Carson City-Lake Tahoe area, are in a zone designated as relatively low-risk in both the Algermissen-Perkins (1976) and the ATC (1978) reports.

Discussion

All of the available evidence -- from the historic record of large earthquakes, geologic studies of fault scarps and uplift of mountain blocks, and current earthquake statistics -- point to the same conclusions: (1) the re-rupture time for major fault zones is of the order of thousands of years; (2) after a major earthquake, aftershocks continue for about a century, gradually decaying to a regional background level of seismicity; (3) for at least several decades before a large earthquake the impending rupture zone has a moderate level of seismicity, including felt earthquakes.

If, as Wallace (1978) suggests, a major earthquake involves a rupture zone of about 1,000 km^2, then the recurrence rates he cites give average re-rupture times ranging from 3,700 years (uplift of the White Mountains) to 29,000 years (fault scarp morphology in north-central Nevada). Along the frontal fault system of the Carson Range between Reno, Nevada, and Diamond Valley, California, estimated re-rupture times vary from 2,000-3,000 years for faults in the Mount Rose area (Cordova, 1969) as well as for the Genoa fault to the south (Pease, 1979).

Instrumental data for the 1932-1969 and 1970-1974 periods give re-rupture times of 7,000-10,000 years. The spread of these values is not surprising, considering the variability of the different measurements, as well as the possibility that the rate of faulting may not have been constant, either for the entire western Great Basin, of for the entire Holocene epoch. It is interesting that the shortest rupture times are found for the eastern Sierra zone, which in the northern part of the province is mapped as a relatively low-risk area by Algermissen and Perkins (1976), the UBC (1976) and the ATC (1978) report.

Considering the present state of knowledge in evaluating long-term seismic potential we are not seriously suggesting that the belt of historic seismicity in central Nevada be redesignated as a lower-risk area, even though there is good evidence to suggest that the various historic rupture zones in that belt may be quiescent for many centuries or even thousands of years.

On the other hand, failure of the responsible agencies (US Geological Survey, ATC, ICBO) to designate a number of major, active fault zones in western Nevada and eastern California as areas of the highest seismic risk is in our opinion a serious oversight. Among the faults in this category are the Carson fault zone from Diamond Valley, California, to Reno, Nevada, as well as a number of other major fault zones in northern California and eastern Nevada (Last Chance fault, Mohawk Valley fault, Pyramid Lake fault, Honey Lake lineament). These faults are capable of producing major (M > 7) earthquakes, have a sufficient level of seismicity to indicate a state of high stress, and together constitute the most serious seismic hazard at the present time to the population of northern Nevada and northeastern California.

IV. RESULTS OF NETWORK ANALYSIS

By

J. D. VanWormer and Alan Ryall

Abstract

Comparison of precise epicentral determinations based on local network recordings with faults and lineaments indicates that many faults that cut Quaternary deposits in the western Great Basin are currently active. In addition, major structural lineaments are often found either to be currently active or to bound active seismic areas. In some areas the epicenters are dispersed but agree with the shatter pattern of mapped faults. The addition of new data has improved the picture of active seismic zones substantially over that available three years ago, and demonstrates the value of a long-term data base.

Introduction

Nearly 2,000 hypocenters have been determined using data from local networks in the areas around Reno and Mina, Nevada. Figure IV-1 shows the distribution of these events, together with inferred rupture zones of major earthquakes (Ryall, 1977), and an overlay shows Slemmons' (1967) provisional map of active faults in the same region. The earthquake distributions cover different recording periods: May 1973 to October 1978 for the Reno network and July 1974 to October 1978 for the Mina net.

While Figure IV-1 provides no information on seismicity outside the two networks, it does permit a detailed comparison within the network areas. Significant correlations are described below, from south to north.

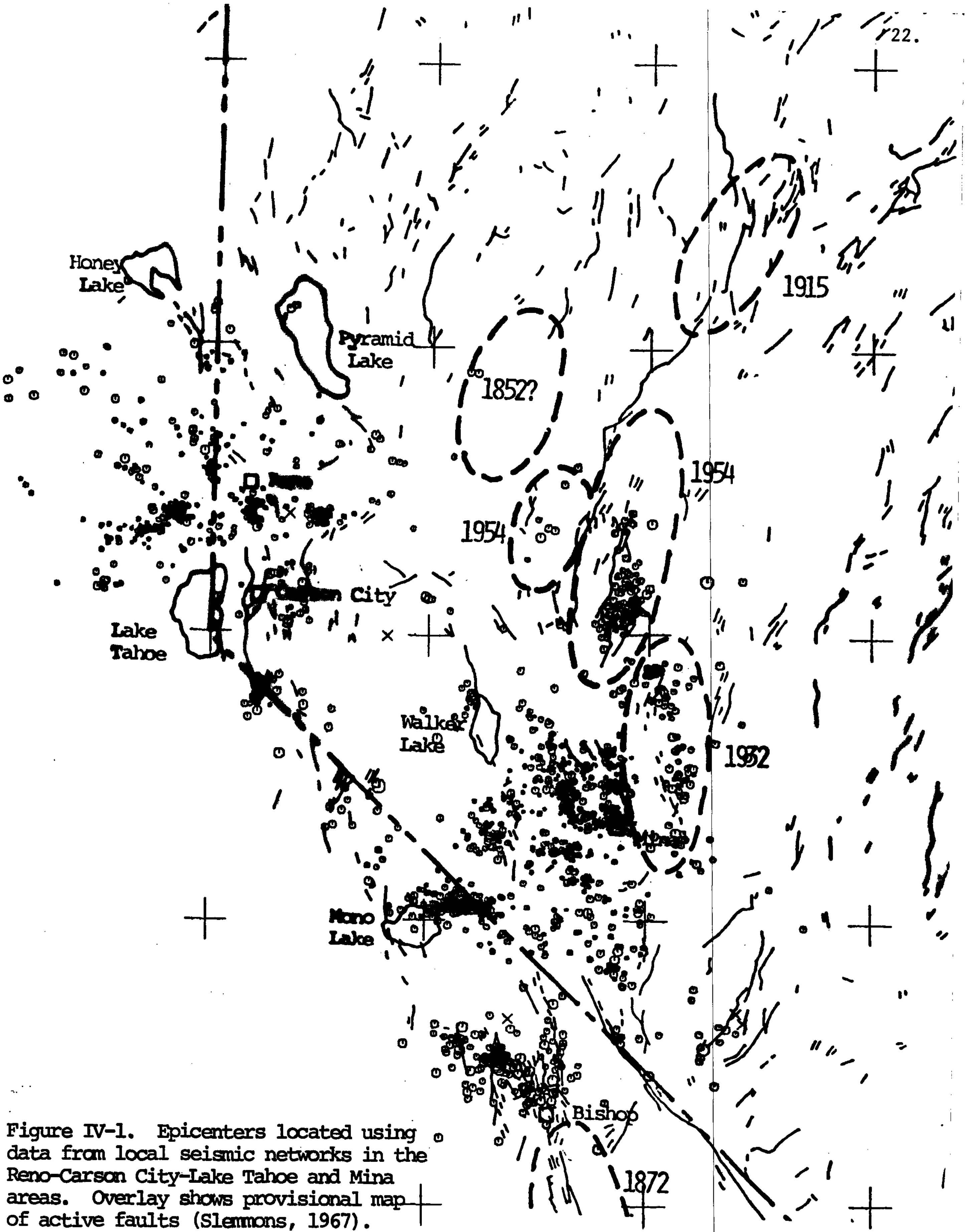

Figure IV-1. Epicenters located using data from local seismic networks in the Reno-Carson City-Lake Tahoe and Mina areas. Overlay shows provisional map of active faults (Slemmons, 1967).

Mina Area

The large group of epicenters northwest of Bishop, California are dispersed, but correlate well with a diverging cluster of faults at the north end of the 1872 Owens Valley rupture zone. The M = 5 1/2 earthquake of 4 October 1978 was located in the middle of a NW-SE trending group of epicenters that lie along the eastern front of the Sierra Nevada, where the faults are short and predominantly of north-south orientation. The focal mechanism for the 4 October shock had one plane striking N 30° W and dipping 55° NE; the other plane had strike N 10° E and dipped 40° W. Either plane would fit the mapped faults.

Between this group of epicenters and the prominent east-trending cluster in the area east of Mono Lake, there is little seismicity, and this lack of activity correlates with a lack of faults on Slemmons' map (Figure IV-1). This relatively quiescent area includes the Long Valley Caldera, for which Steeples and Pitt (1976) reported that a month-long survey of microearthquakes in 1973 revealed very little activity within the caldera.

The marked east-west cluster of epicenters at the east end of Mono Valley is a zone of frequent earthquake swarms, and over five years of monitoring 72% of the activity in this area has occurred in the late summer and fall months (see section VI). This zone of intense microearthquake activity runs through the Adobe Hills volcanic center, which accounted for the most voluminous eruptions in the Mono area during the last 4 m.y. (Gilbert et al., 1968) and which is inferred by Ekren et al. (1976) to be a buried cauldron complex. The earthquakes follow an east-west zone that includes the greatest thicknesses of basalt in the area, locally exceeding 600 feet, and the possibility exists that the seismicity is connected with volcanic processes.

North of the Mono seismic zone and west of the Wassuk Range (west of Walker Lake) there is another area of low seismicity. According to Gilbert and

Reynolds (1973), this is an area that prior to 7.5 m.y. ago was characterized by faulting but since that time has been deformed by warping, with little faulting (Figure IV-2). They state that this area is bounded on the northwest by a northeast trending lineament defined by the en-echelon termination of major Quaternary north-trending normal faults, and on the southeast it is bounded by the northeast-trending "Mono Basin-Excelsior Mountains zone", which they depict as a continuous left-lateral shear zone. The pattern of seismicity in the Mono area is east-west, as described above, and does not agree with Gilbert and Reynolds' hypothesis of a northeast-trending shear zone. Within their area of warping Figure IV-1 shows low seismicity, although epicenter lineups are evident in Reese River Canyon at the north end of the Wassuk Range, and along the east side of Aurora Peak, 30 km south of Walker Lake. To the northwest, Figure IV-1 has inadequate coverage to indicate the northeast-trending lineament suggested by Gilbert and Reynolds, but some evidence of an earthquake lineup can be seen on a map of epicenters located using the Statewide network for 1970-1977 (Figure IV-9).

In the area southeast of Walker Lake are many dense clusters of earthquakes, in an area which Ryall et al. (1966) and Wallace (1978) have identified as a "seismic gap" between the 1872 Owens Valley and 1932 Cedar Mountains/1934 Excelsior Mountains earthquakes. Ryall and Priestley (1975) discussed the dispersed character of earthquake activity in this highly seismic area, and suggested that this was an area in which a high degree of crustal fracturing might lead to release of tectonic strain by a continuing series of small-to-moderate earthquakes and fault creep. If so, they concluded, the Excelsior Mountains earthquake of 1934 (M = 6 1/4) might represent the maximum magnitude event for this area.

While the dispersed activity shown on Figure IV-1 tends to agree with the interpretation by Ryall and Priestley, when the epicentral map is studied in detail

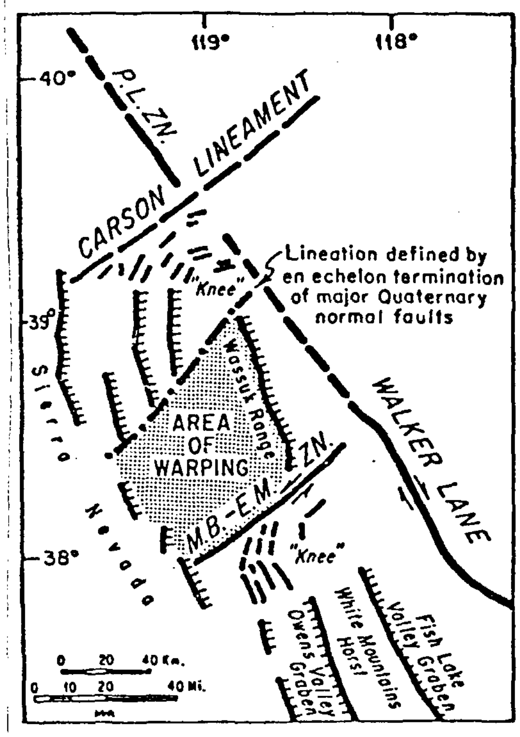

Figure IV-2. Sketch map showing Gilbert and Reynolds' (1973) interpretation of major fault zones and lineaments near the western margin of the Great Basin, and the pattern of Quaternary faulting and warping. PL ZN is zone of faulting in the Pyramid Lake area; MB-EM ZN is Mono Basin-Excelsior Mountains structural zone.

another possible interpretation emerges. In the north part of this area, epicenters in the Garfield Hills follow a zigzag series of northeast and northwest lineups, and these lineups tend to follow alluvial contact with the hills. South of the Excelsior Mountains two northwest lineups of epicenters extend into Teels Marsh, and a northeast lineup follows the northwest side of the Candelaria Hills. Speed and Cogbill (1979) find that average net slip on faults in this area has been comparable to that of Dixie Valley and other seismically active regions in the Great Basin. Together, this series of epicentral clusters makes up a zigzag, northerly trending zone 40 km in length, which is not unlike that described by Ryall and Malone (1971) for the Fairview Peak aftershock zone. While there are problems with a north-trending zone that crosses a major east-trending structure -- the Excelsior Mountains -- it is not inconceivable that a large earthquake could occur here.

To the east, the area of high seismicity around the Garfield Hills is bounded by a major fault zone trending north-northwest along the western boundary of the Gabbs Valley Range. This zone, over 90 km long, does not correlate with the pattern of seismicity on Figure IV-1, except that for about 30 km it forms a boundary for the Garfield Hills active area.

It is interesting to note that the 1932 Cedar Mountains fault breaks (overlay on Figure IV-1), as well as the aftershock zone of this earthquake (Figure IV-9), lie between major east-west lineaments hypothesized by Ekren _et al_. (1976) on the basis of topographic, geologic and magnetic features. The Pancake Range lineament to the south is inferred by Ekren _et al_., to be more than 300 km long, extending from central Nevada into California; the Pritchards Station lineament is about 230 km long in central Nevada. According to Ekren _et al_., "the tangential association of volcanic centers and cauldrons with the lineaments implies a deep-seated crustal control. . . Whether the lineaments are partly a result of conjugate faults developed at the inception of the Walker Lane and other major northwest-trending faults in the southwestern Great Basin, or whether they owe their origin to an even more regional or even continentwide fracture system is an unresolved question."

Figure IV-3 shows an east-west cross-section for A, B and C quality hypocenters for the area from 38° N to the north edge of the Excelsior Mountains. Those events deeper than 15 km, at longitude 118.4° W, are almost all due to a cluster of earthquakes in the Excelsior Mountains. Figure IV-4 shows an east-west cross section for the area north of the Excelsior Mountains to latitude 39° N. Both of these figures show striking vertical groups of hypocenters - contrary to the pattern that would be expected for dipping fault planes.

Reno Area

Two features of Figure IV-1 are noteworthy relative to seismicity of the Reno-Tahoe-Carson City area. First, as noted in section III, clusters of earthquakes occurred in the fall of 1978 at the north and south ends of a 70-km long, major fault zone that bounds the eastern flank of the Carson Range. This fault, which lies in an area zoned as relatively low-risk on maps presented by Algermissen and Perkins (1976), the Applied Technology Council (1978) and the Uniform Building Code (1976), has had several major offsets during Holocene time, is capable of a large (M = 7-8) earthquake, and with its proximity to population centers probably constitutes the zone of highest seismic risk in Nevada at the present time.

Epicenters east and northeast of Carson City lie in an area where Moore and Archbold (1969) have mapped numerous north-trending faults within the Pine Nut Range. A few epicenters in this area trend northeast along the Carson lineament (Shawe, 1965), and a swarm of earthquakes in June, 1976 (largest M = 3.2), occurred near Virginia City, near the intersection of the Carson lineament with north-trending epicentral lineups in the Pine Nut Range.

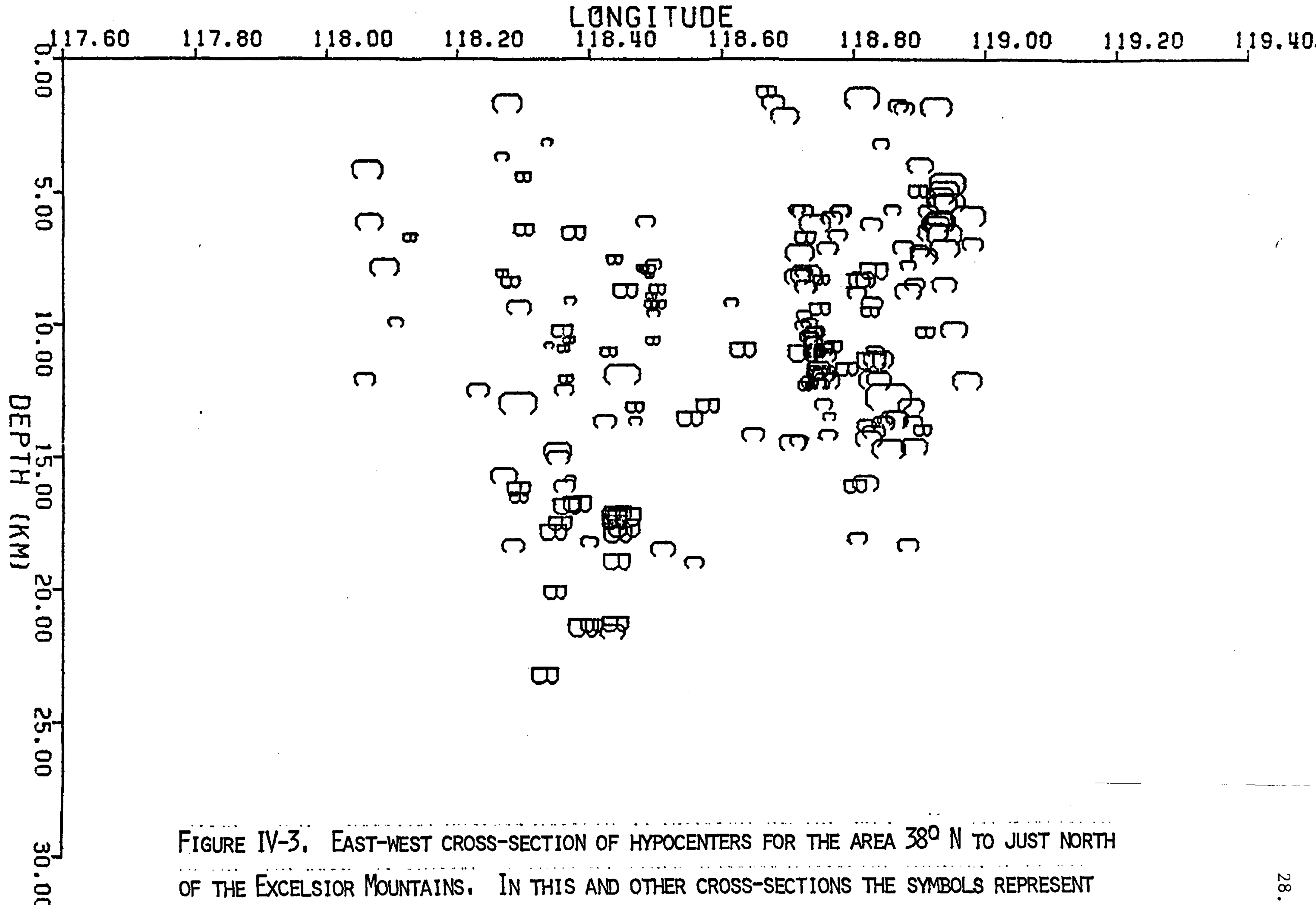

FIGURE IV-3. EAST-WEST CROSS-SECTION OF HYPOCENTERS FOR THE AREA 38° N TO JUST NORTH OF THE EXCELSIOR MOUNTAINS. IN THIS AND OTHER CROSS-SECTIONS THE SYMBOLS REPRESENT THE QUALITY (A, B, C) OF THE HYPOCENTRAL DETERMINATION, AND ARE SCALED TO MAGNITUDE.

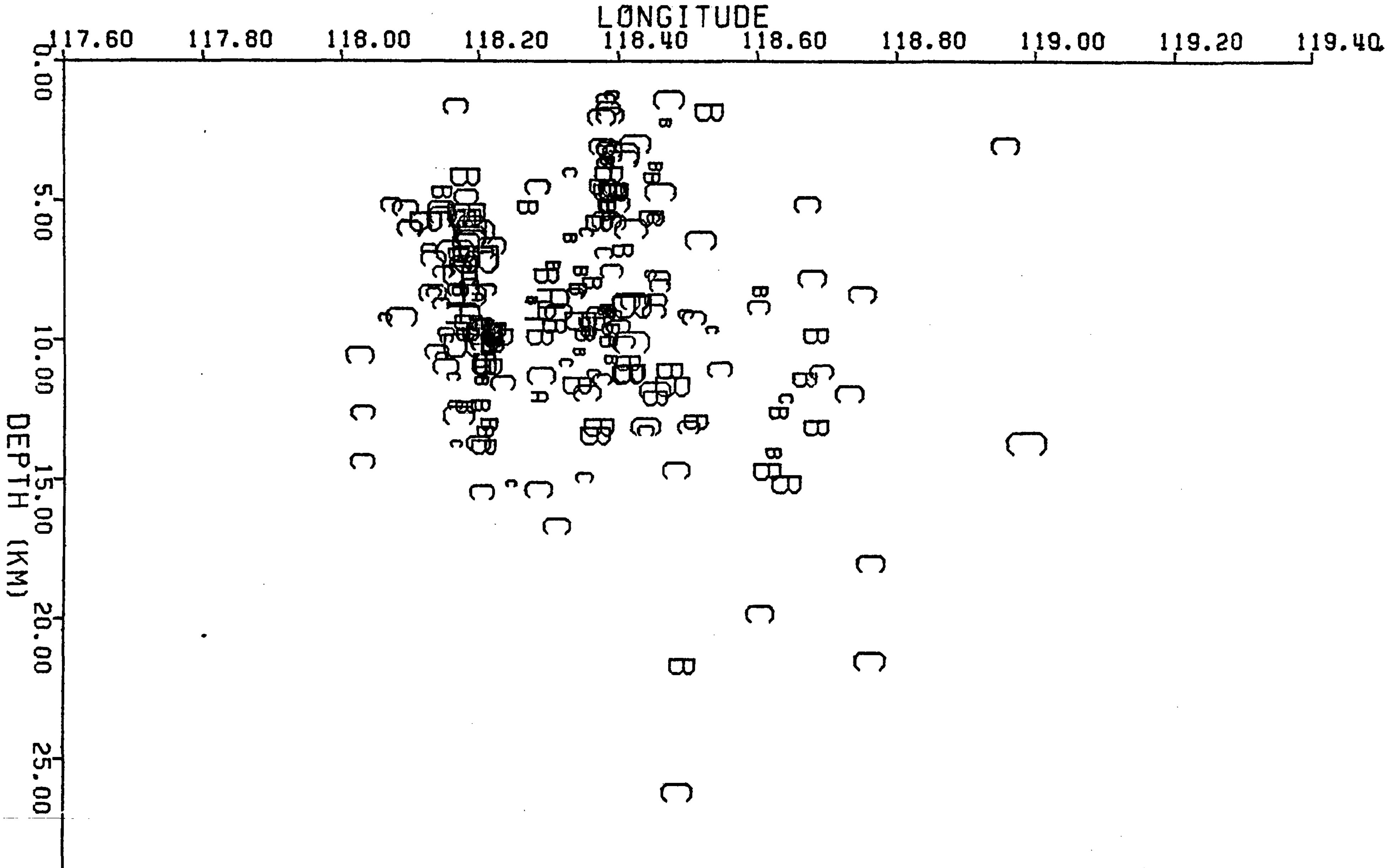

FIGURE IV-4. CROSS-SECTION FOR AREA NORTH OF THE EXCELSIOR MOUNTAINS TO LATITUDE 39° N.

Earthquakes around Reno-Truckee are shown in more detail in Figure IV-5, together with faults, lineaments (Jennings, 1977; Bonham and Papke, 1969), bedrock (stippled areas) and seismic stations. In the area of the 1966 Truckee earthquake (M = 5.7), current seismicity is distributed over a zone about 25 km long, trending generally WSW-ENE. This zone follows a structural low from Donner Pass through Donner Lake, then turns north through Bennett Flat northwest of Truckee, and continues to the northeast through a structural depression north of Prosser Hill to Hobart Mills. There the zone is spread in a northwest-southeast direction, which may be related to the aftershock zone of the 1966 earthquake. The fault that runs northeast from this epicentral zone is the one that ruptured in 1966; it passes through one of the abutments of Stampede Dam and continues through Hoke Valley and Dog Valley for another 10 km to intersect with the Last Chance fault. Based on a recent reinterpretation of data from the University of California seismic network, using the 1966 Truckee earthquake as a master event, Bell et al. (1976) relocated the 1948 Verdi earthquake (M = 6), and found it to be located at this same intersection. On Figure IV-5 there is a cluster of earthquakes at the intersection of these two faults (near the state line 20 km west of Reno), which could be aftershocks of the 1948 earthquake.

North-trending faults in a shatter zone on the east flank of Mount Rose (Figure IV-6) are a source of frequent earthquakes that are large enough to be felt in the Reno area. Figure IV-5 shows the swarm of earthquakes that occurred on 10 October 1978 at Steamboat, 10 km south of Reno and within this zone of distributed faults. This is the north end of the fault zone mentioned above, which bounds the eastern side of the Carson Range for a distance of about 70 km south of Steamboat.

East of the Steamboat swarm Figure IV-5 shows the cluster of earthquakes that occurred in June, 1976 near Virginia City, discussed above.

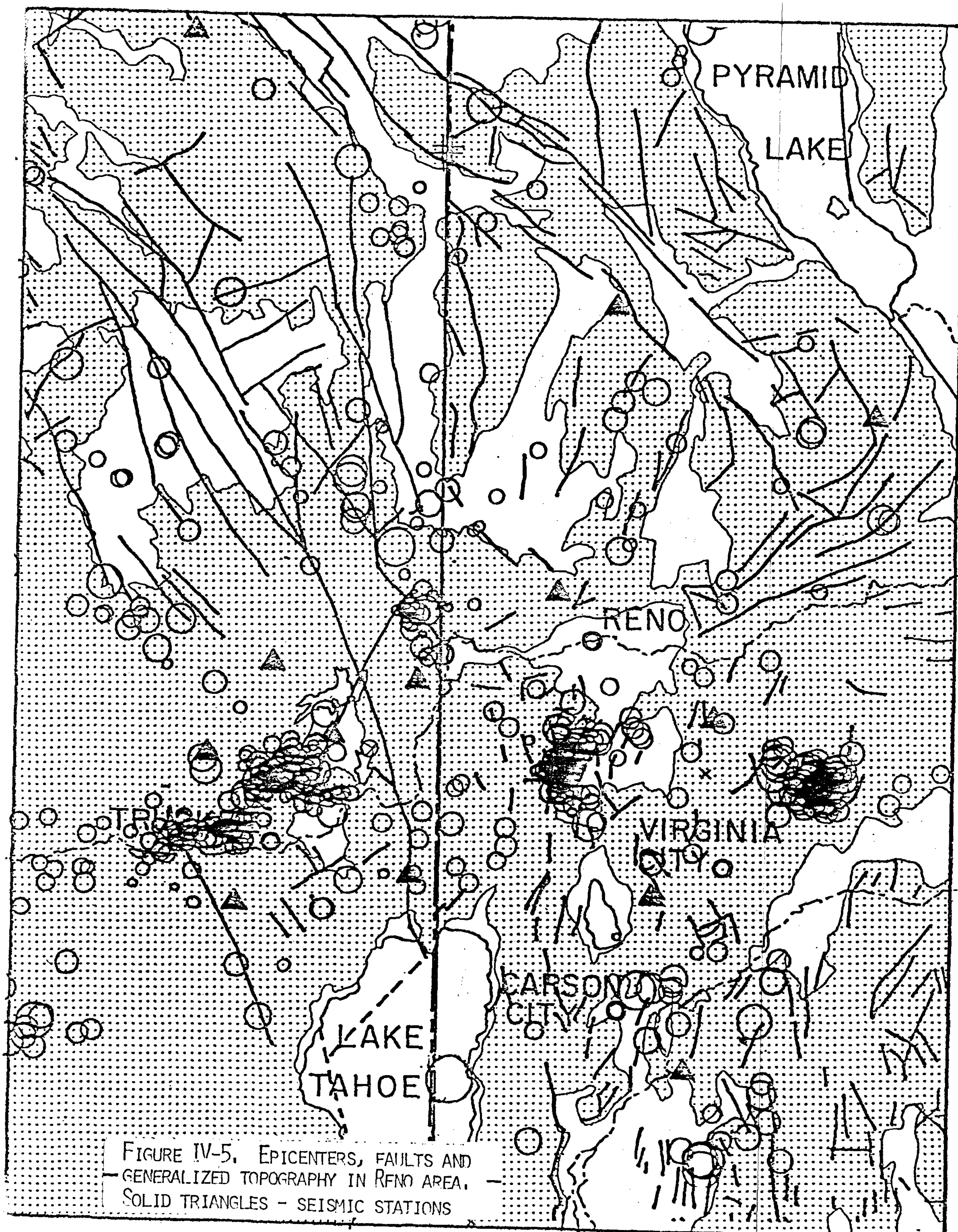

FIGURE IV-5. EPICENTERS, FAULTS AND GENERALIZED TOPOGRAPHY IN RENO AREA. SOLID TRIANGLES - SEISMIC STATIONS

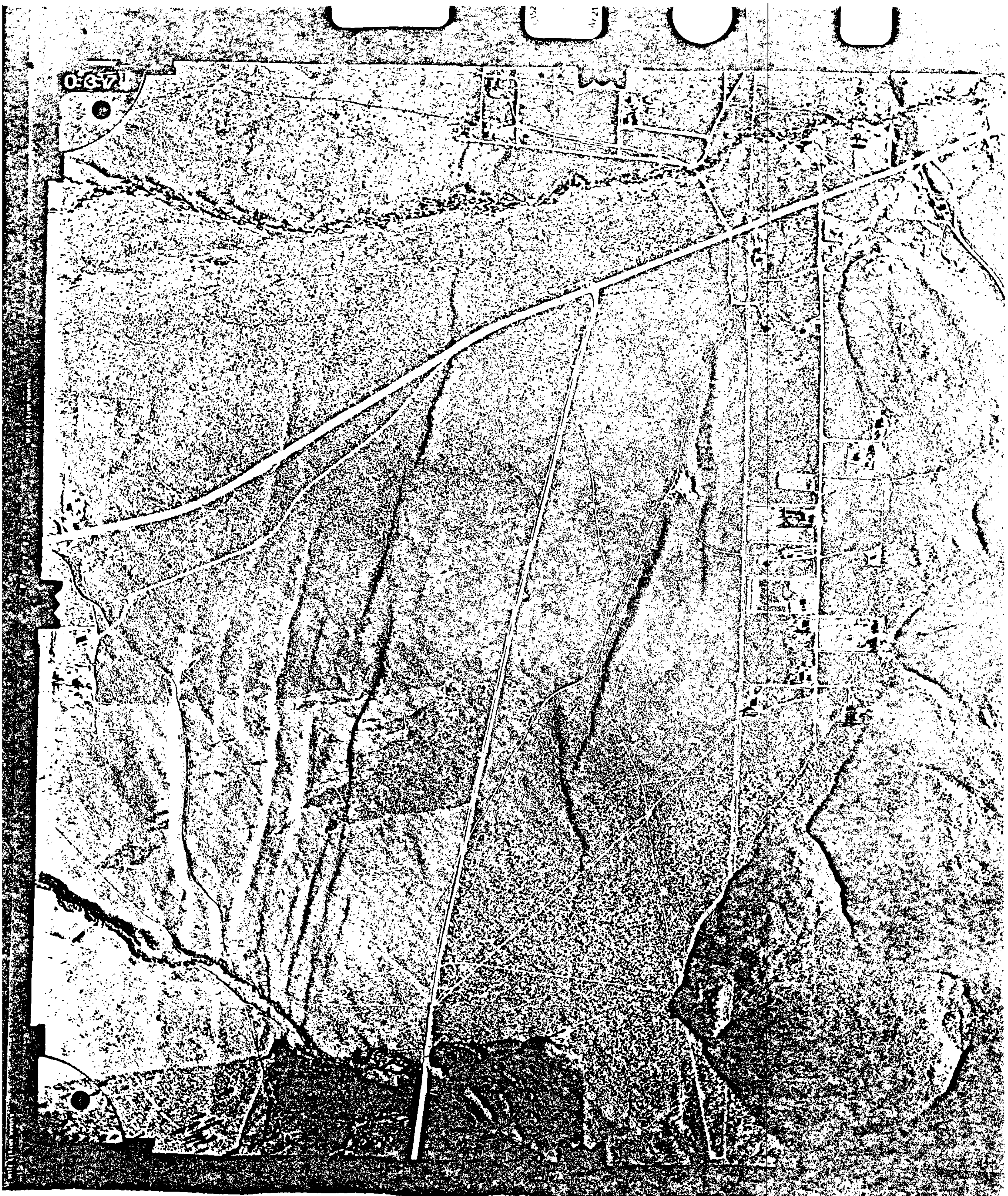

Figure IV-6 Low sun-angle aerial photograph of faults south of Reno along the eastern base of Mt. Rose. North is at the top of the photograph; illumination is from the right.

Figures IV-7 and IV-8 show east-west cross-sections for events recorded by the Reno network for areas, respectively, north and south of latitude 39° N. These figures again illustrate the tendency of clustered events to occur in vertical groups rather than on dipping planes. This observation will be further studied.

Large-Scale Fracture Patterns

Ryall (1977) presented an analysis of epicenter lineups for the period 1970-1974, constructed by drawing lines through groups of epicenters that appeared to show some lineation on epicenter maps for 6-month periods of time. We have now completed analysis of most of the data collected through 1977, and Figure IV-9 shows the map of epicenters for 1970-1977. Because station spacing for the statewide network is not as close as it is within the local Reno and Mina networks, epicenters shown on Figure IV-9 are more scattered than those on Figure IV-1. In spite of the scatter, lineups of epicenters on maps for 6-month periods were clear enough to update the map published by Ryall. This map is shown on Figure IV-10.

While the interpretation of epicenter lineups is somewhat simplified, the pattern on Figure IV-10 suggests that at depth in the crust earthquakes are occurring along complementary northwest- and northeast-trending fractures that in some places are quite different than faulting observed at the surface. In a recent paper, Bell and Slemmons (1979) compare the pattern of complex shears in the Walker Lane (Nevada and California) with the pattern of shears developed at various stages of deformation in laboratory experiments with clay (Tchalenko, 1970). Tchalenko and Ambraseys (1970) also compared this laboratory shear model with the 1968 Dasht-e Bayaz, Iran, earthquake fractures. In this model, based on the Coulomb failure criterion, failure surfaces are inclined at + $\phi/2$ (Riedel shears) and 90° - $\phi/2$ (conjugate Riedel shears) to the general direction of

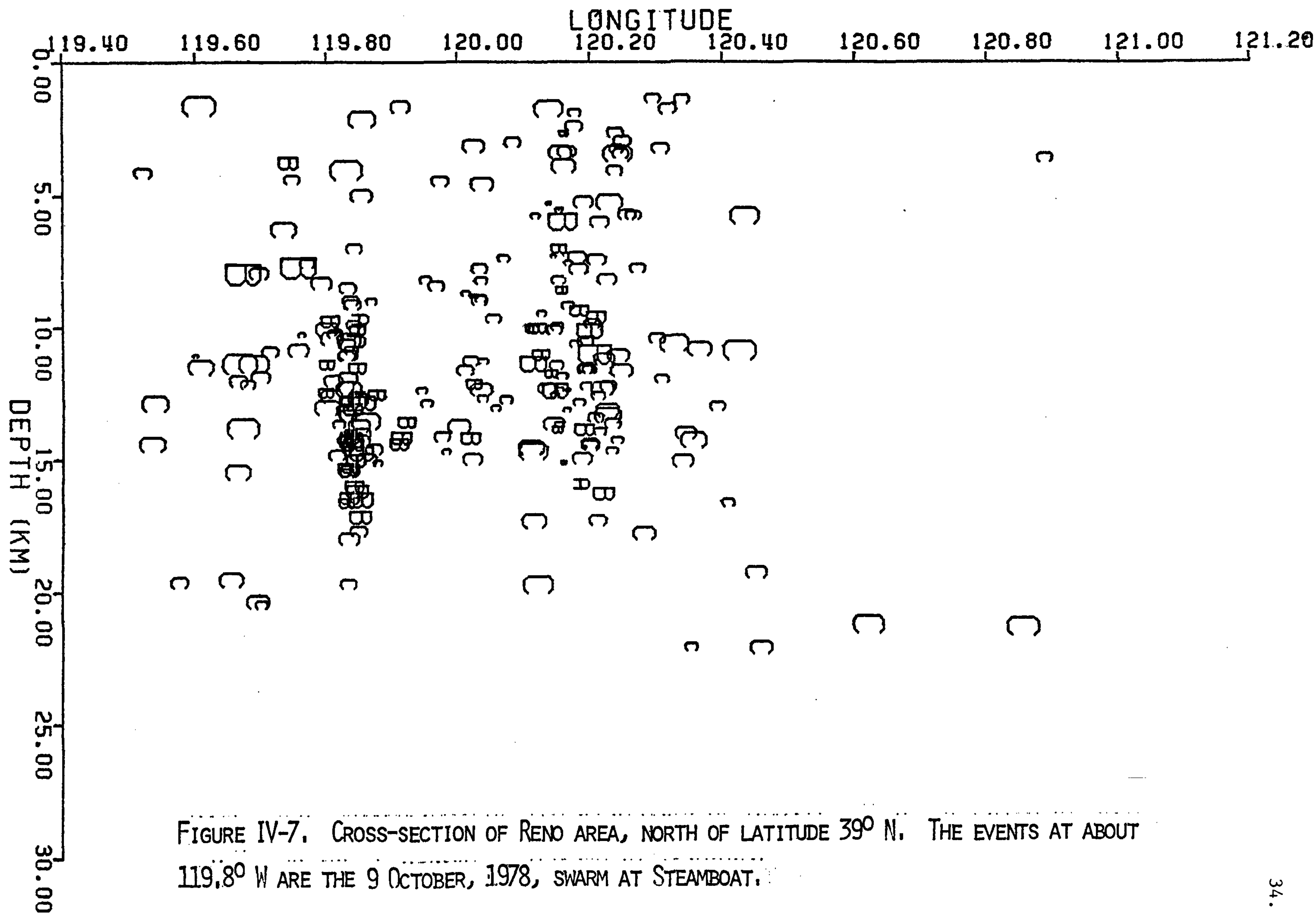

FIGURE IV-7. CROSS-SECTION OF RENO AREA, NORTH OF LATITUDE 39° N. THE EVENTS AT ABOUT 119.8° W ARE THE 9 OCTOBER, 1978, SWARM AT STEAMBOAT.

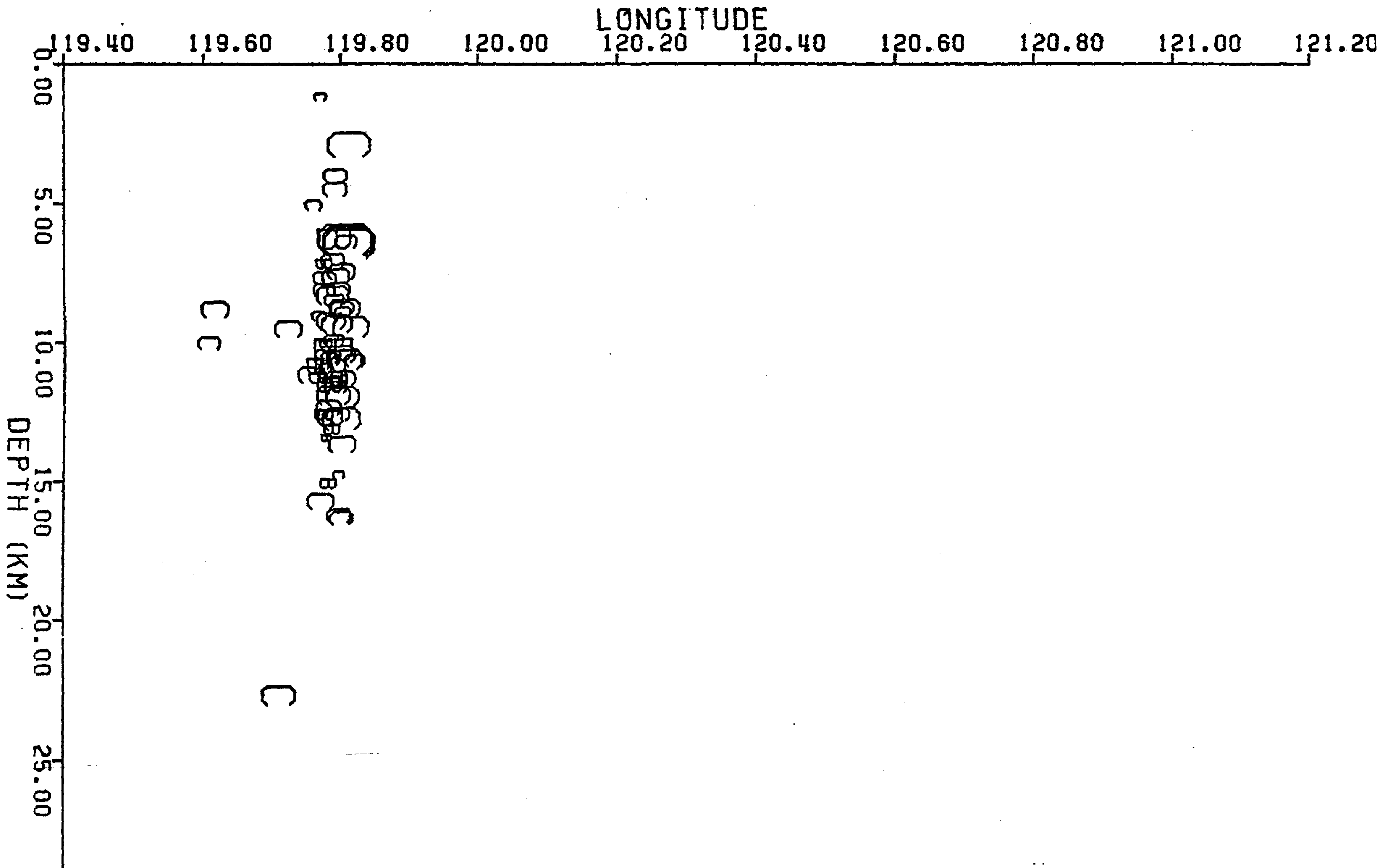

FIGURE IV-8. CROSS-SECTION OF RENO AREA EARTHQUAKES SOUTH OF LATITUDE 39° N. THE VERTICAL GROUP IS THE SEPTEMBER, 1978, SEQUENCE AT DIAMOND VALLEY, CALIFORNIA.

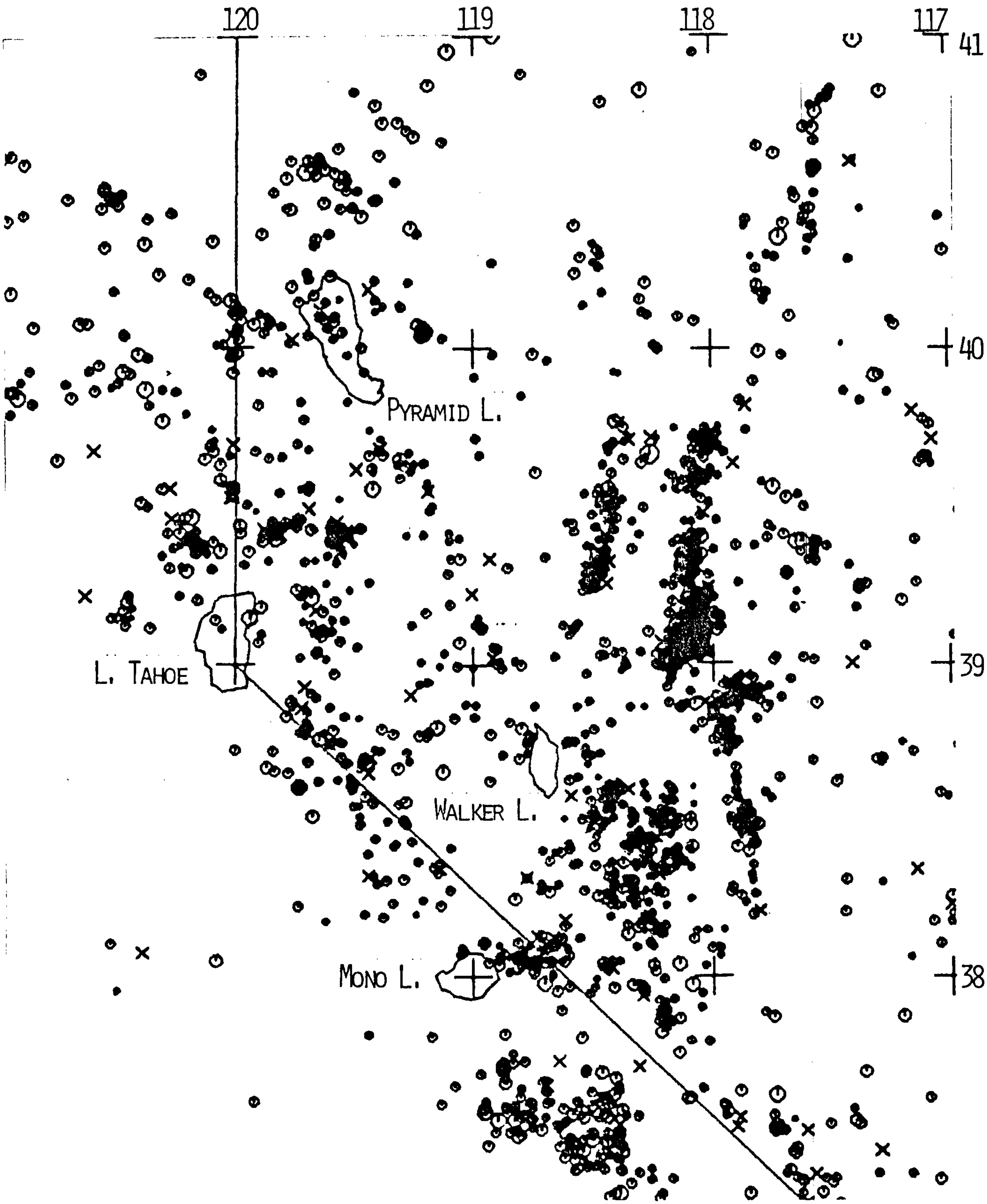

FIGURE IV-9. EPICENTERS FOR 1970-1977, DETERMINED USING DATA FROM THE NEVADA STATEWIDE NETWORK.

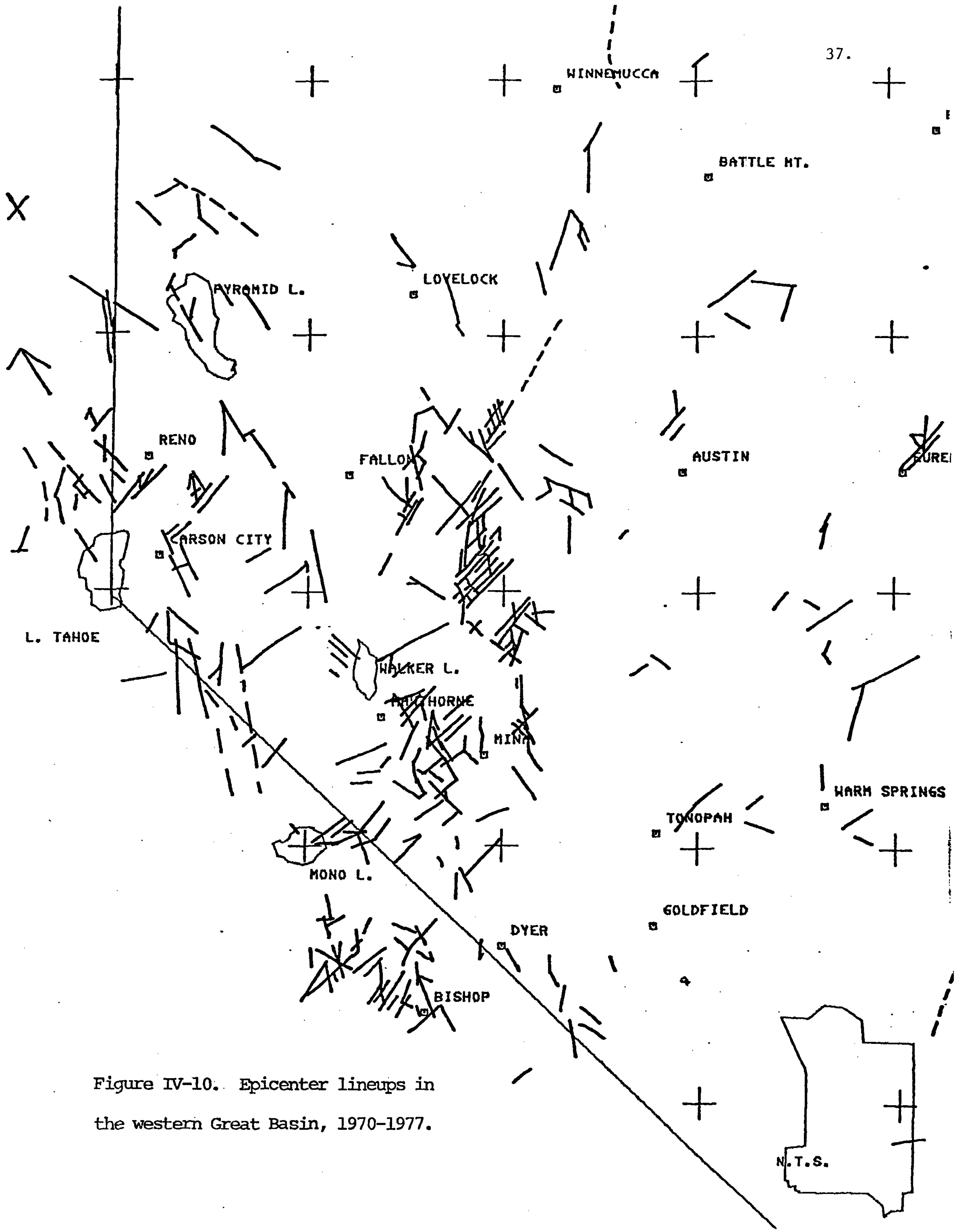

Figure IV-10. Epicenter lineups in the western Great Basin, 1970-1977.

movement, where ϕ is the peak angle of shearing resistance (Riedel, 1929). In some cases both R and R' are observed, while in other cases only one of the shears (usually R) is found. For large deformations that tend toward direct shear conditions, new shear planes are formed in a direction approximately opposite to the Riedel shears, that is, about $-\phi/2$ to the direction of movement. These shear planes are denoted by P. In some cases, tension fractures, denoted by T, are formed in place of or in addition to the Riedel shears. They develop at about 45° to the direction of movement, steeper than the R shears but in the same general orientation (Tchalenko and Ambraseys, 1970). During the laboratory shearing experiment, a series of structures is formed (Figure IV-11), starting with separate Riedel shears and ending when these shears coalesce into a single principal displacement shear.

From preliminary determinations, the pattern of fractures displayed in Figure IV-10 for the central Nevada seismic zone correlate with the orientation of conjugate Riedel shears (R') that would be expected for this region, based on an average focal mechanism for earthquakes in this zone. In addition, the pattern displayed in the zone of large historic earthquakes in central Nevada is similar to the pattern obtained in the laboratory just before peak shear strength is reached. In other parts of the western Nevada region, northwest-trending epicenter lineups are similar to those obtained in the laboratory in late stages of deformation, when the separate shears coalesce into a single principal shear. The Riedel shear model may have interesting application to the problem of earthquake prediction, if the laboratory results can be extrapolated to regional seismicity patterns. Work on this problem is continuing.

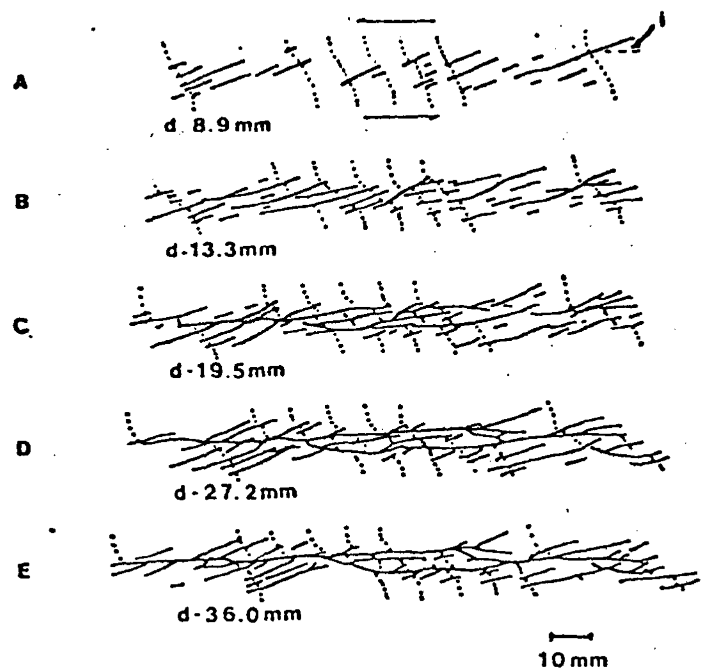

Figure IV-11. Sequence of structures in Riedel exeperiment, d = total board movement. Shears are inclined at angle i at each stage of movement. Stage A appears just before peak strength with an average inclination angle of 12°. Stage B is post peak shear with some 8° shears. Stage C includes some shears at -10° and some Riedel shears connect. Stage D is pre-residual structure with the first continuous shears at angles of 0-4°. Stage E is residual structure with nearly all displacements along a single principal displacement shear (Tchalenko, 1970).

V. THE SUSANVILLE, CALIFORNIA, EARTHQUAKE SEQUENCE OF JUNE, 1976

By

Amy Mohler

Introduction

An earthquake sequence northeast of Susanville, California, began with a shock of M = 4.5 at 10h 15m GMT on 20 June 1976. Thirty-nine aftershocks with M > 1.5 occurred between 20 June and 10 July. As this aftershock sequence continued, we decided to install a temporary seismic array in the epicentral region to monitor the activity. The largest aftershock, on 24 June at 15H 45m had M = 4.1; this event occurred just before the temporary array was installed.

Instrumentation

Short-period vertical-component seismometers were installed at Fredonyer Peak (FRD), just east of Eagle Lake, and at Shaffer Peak (SHP), north of Honey Lake. These stations were relayed to a recording unit located at the third station on Susanville Peak (SUE), just northeast of Susanville.

Signals from the three stations were recorded together with WWVB time code on magnetic tape. The array operated until 7 July, 1976, recording more than 4,700 aftershocks. Transmission from FRD was lost after the first day of recording, and station SHP transmitted data only through 28 June. Station SUE remained operational throughout the entire recording period, with only a few hours of excessive background noise.

Analysis in Progress

First motions for the main shock are shown on a lower-hemisphere projection in Figure V-1, using data from the Nevada seismic network and several University of California stations. Due to poor azimuthal coverage a focal mechanism for this

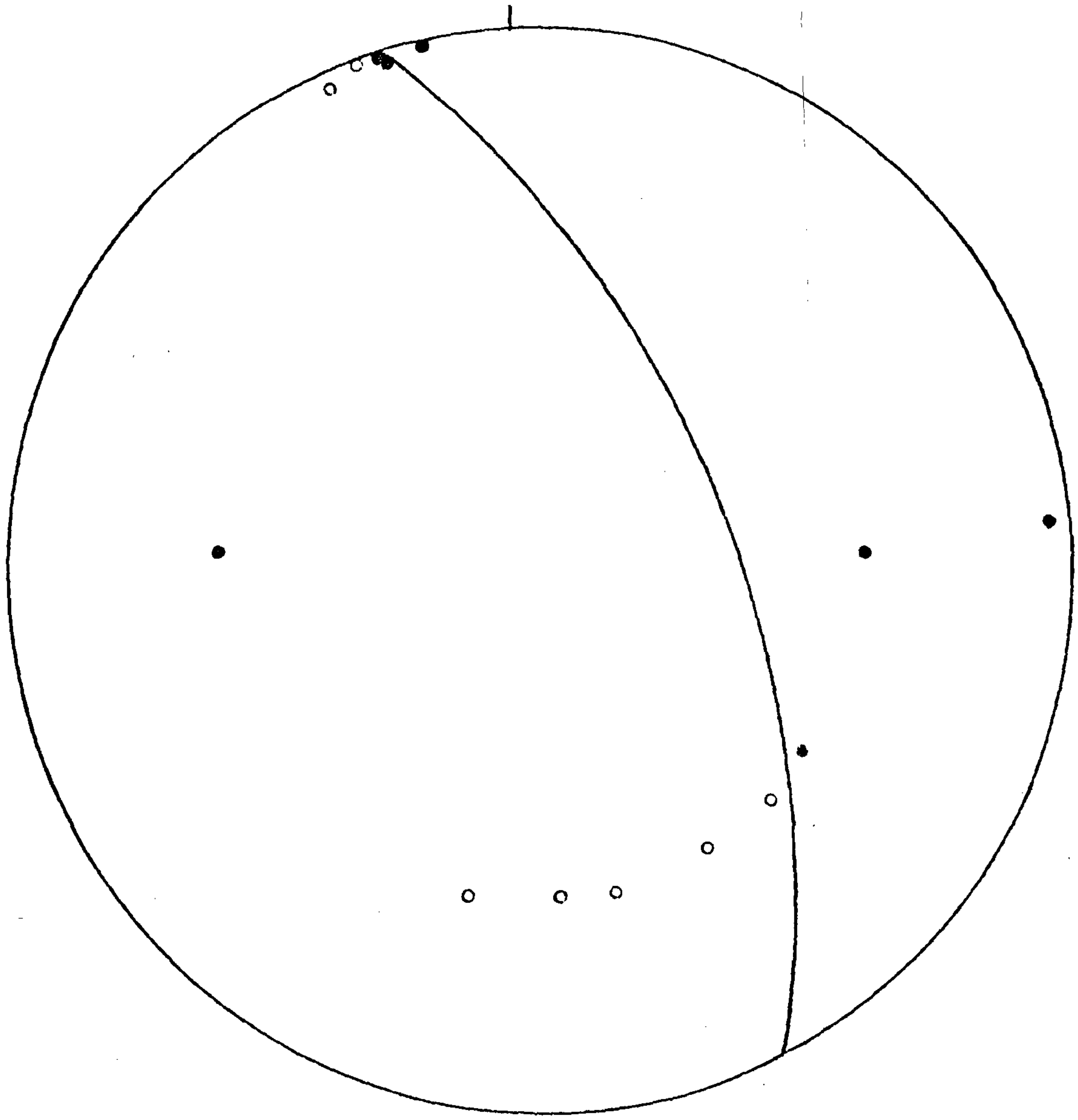

Figure V-1. Lower-hemisphere equal angle projection of Susanville first motions (main shock). Closed circles -- compressions, open circles -- dilatations. Plane strikes N 18° W, dips 60° SE.

event cannot be determined at this time. One plane striking N 18° W and dipping 60° E is well constrained by the available data, while the conjugate plane is indeterminate. The US Geological Survey and the California Department of Water Resources have seismic stations located in the western foothills of the Sierra Nevada to the southwest of Susanville, while the University of California has stations west of the epicenter. Data from these stations will be analyzed and incorporated into the analysis.

First motions recorded at station SUE are both dilatational and compressional, although dilatations predominate, especially for the larger shocks. Of the 39 events mentioned above with $M > 1.5$, 21 show dilatations and the remainder have indeterminate first motion, indicating that the station must have been near a nodal plane.

Of the events with $M > 1.5$, 37 were located using a routine (NEVLOC2) developed at the University of Nevada, with data from 16 stations, including the field stations, the Reno-Truckee local network, and two University of California stations. The epicenters, shown on Figure V-2, lie in a highly faulted region north of Susanville. The most significant faults in the area are the Antelope Mountains fault, a mapped fault whose activity has been ascertained, and the Litchfield fault, whose location is approximate. Surface outcrops in the area consist primarily of Tertiary and Quaternary volcanics, and many of the smaller "faults" denoted in the figure by dashed lines may extend only to shallow depth in the volcanic pile. The main shock and largest aftershock are designated by closed circles on the figure, while other aftershocks are shown by open circles. Most of the epicenters lie in an area where there is no clear pattern to the mapped faults compared to adjacent areas.

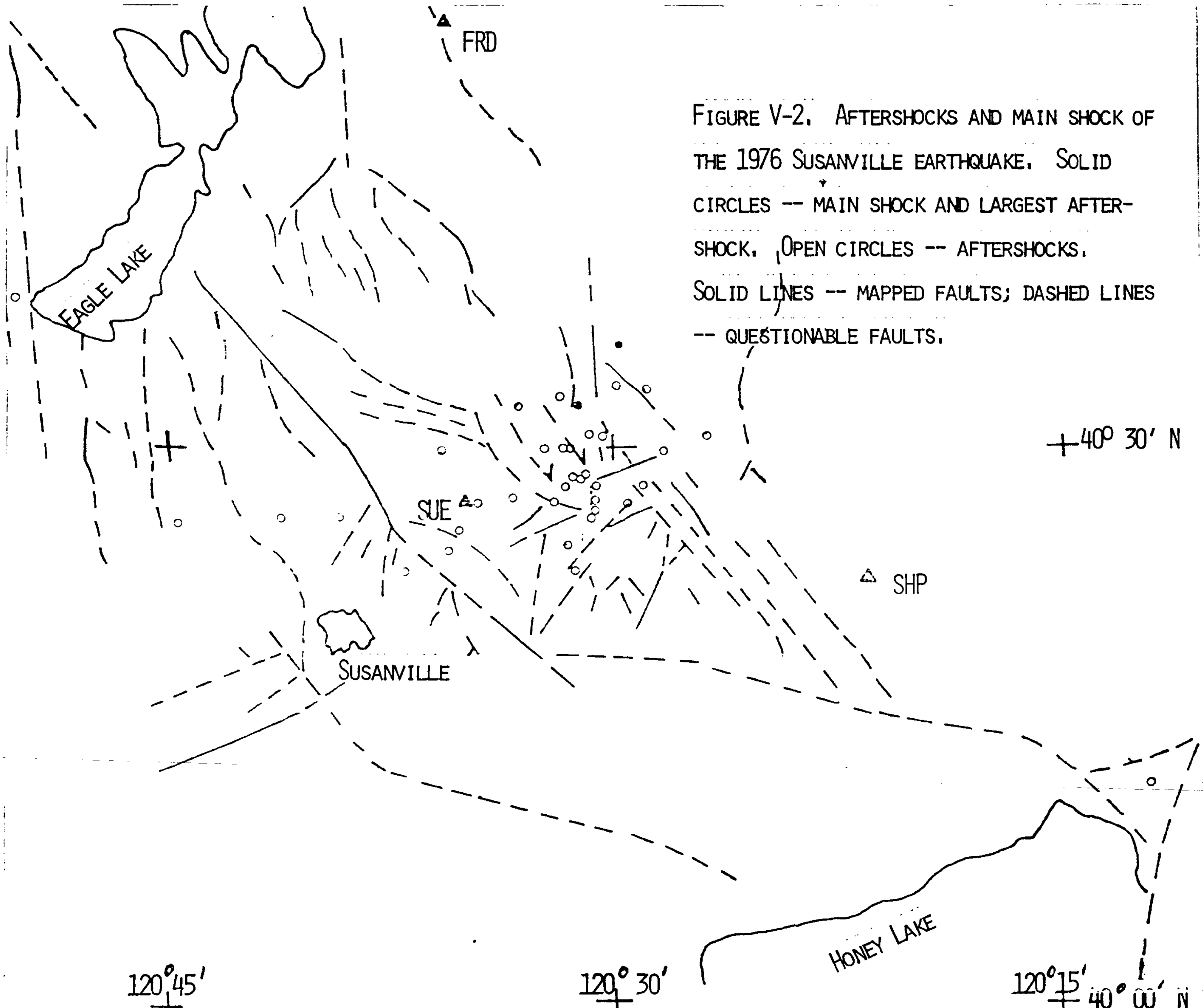

FIGURE V-2. AFTERSHOCKS AND MAIN SHOCK OF THE 1976 SUSANVILLE EARTHQUAKE. SOLID CIRCLES -- MAIN SHOCK AND LARGEST AFTERSHOCK. OPEN CIRCLES -- AFTERSHOCKS. SOLID LINES -- MAPPED FAULTS; DASHED LINES -- QUESTIONABLE FAULTS.

In addition to analysis of the spatial distribution of this sequence, the temporal distribution of aftershocks is being analyzed to ascertain the possibility of triggering by the earth tides. Ryall _et al_. (1968) pointed out that the optimum situation for observing tidal triggering of earthquakes is one in which (1) many earthquakes occur within a limited period of time; (2) the earthquakes are located in a focal zone of limited extent, and (3) the orientation of the causative stress system remains relatively constant over the time period studied. The Susanville sequence meets these conditions.

In all, 4,724 aftershocks have been timed to the nearest minute, and these times are being analyzed to determine whether or not there is a significant periodic component to the times of occurrence of the earthquakes (Figure V-3). An attempt will also be made to determine whether or not there is a significant correlation between the times of peak activity and the various tidal components.

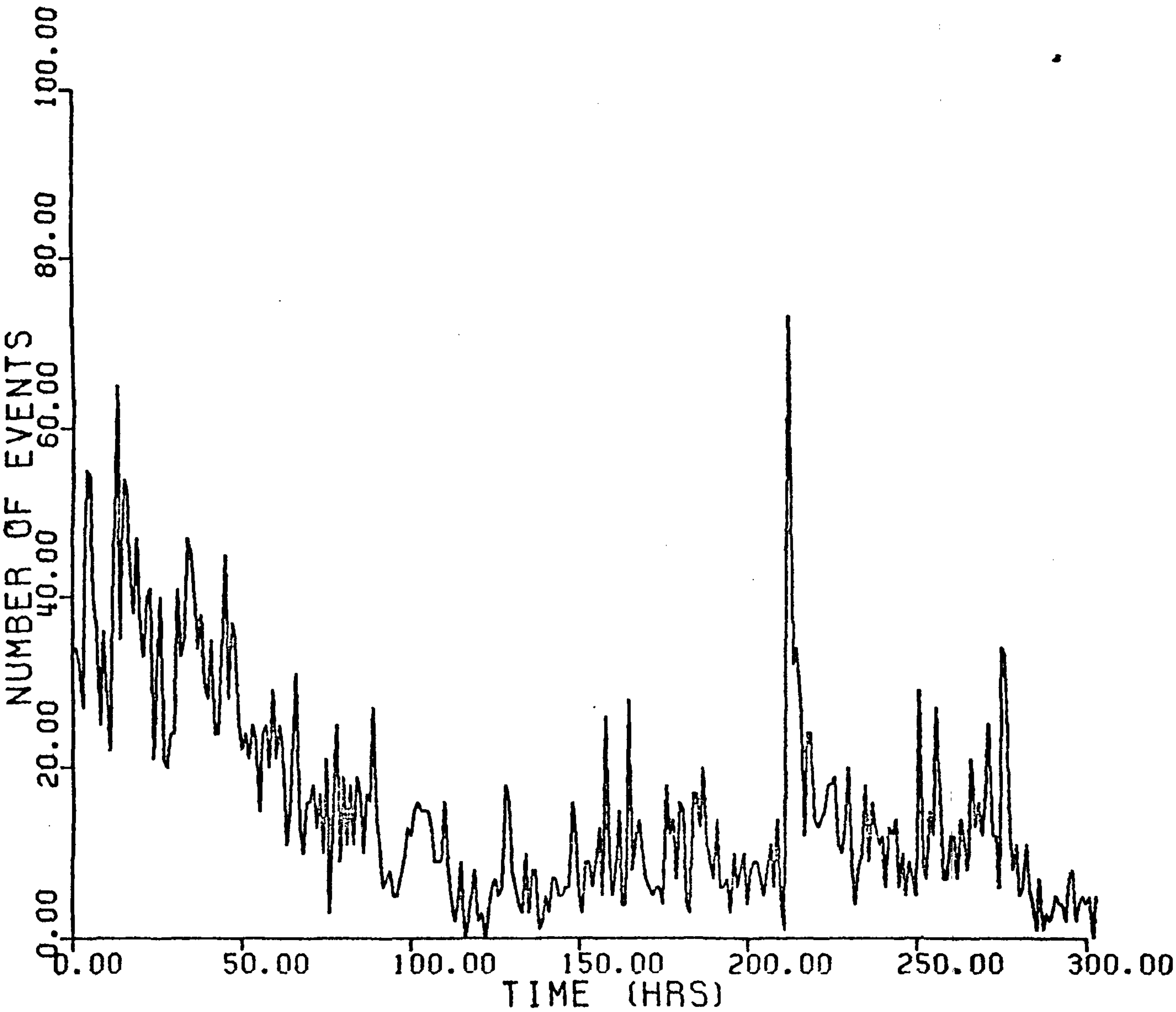

Figure V-3. Number of events per hour recorded at station SUE for the period 25 June 1976 0000Z to 7 July 1976 1200Z.

VI. SEISMICITY AND VOLCANISM IN THE MONO BASIN, CALIFORNIA

By

Alan Ryall and Floriana Ryall

Abstract

Preliminary analysis has been completed of 269 small (M = 1.1-4.0) earthquakes located in an area just east of Mono Lake. Most of these earthquakes are within a 20-km long east-west zone that coincides with numerous volcanic cones, and with the greatest thickness of basalt flows in the Mono area. The earthquakes display some characteristics (focal depths, recurrence rates) that are normal for earthquakes in the western Great Basin, but they have a remarkable tendency to occur in pairs, multiples, and swarms. They have also tended to concentrate during the months of July-October over the five-year period covered by this study.

Introduction

Mono Basin is a post-Miocene structural depression located east of the central Sierra Nevada in eastern California. The basin is surrounded by volcanic rocks of Pliocene, Pleistocene and Holocene age. According to Lajoie and Carmichael (1967) and Gilbert et al. (1968), following eruption of the Bishop tuff about 700,000 years ago from a probable source in Long Valley (35 km south of Mono Basin), a series of domes and cones erupted along a general north-south line in the western part of the Mono depression. Dating by two methods of the Mono Craters, just south of Mono Lake, indicates ages in the range 1,500-10,000 years. The most voluminous eruptions during the last 4 m.y. occur in a zone that extends eastward from Mono Lake. This zone includes the greatest thicknesses of basalt, which locally exceed 600 feet; the basalts thin to the north and south of this zone and feather out to single, thin flows at the margins of the basalt field. K-Ar ages of these basalt range from 2.6 to 4.5 m.y.

According to Gilbert et al. (1968) faults in the Mono Basin and western Excelsior Mountains form a structural "knee", with faults to the south of the knee striking north-northwest and faults to the northeast striking east-northeast. In general, this area is responding to northwest-southeast extension of the Great Basin, resulting in left-lateral oblique slip on faults striking east to northeast, and right-lateral oblique slip on faults striking northwest to north. The "knee" itself trends west-northwest through the Adobe Hills toward Mono Basin and is reflected in a series of small horsts and grabens, as well as in the youngest topography of the area on the bottom of Mono Lake. Gilbert et al., attribute the eruptions in the Adobe Hills to extension developed within this structural "knee".

Local Seismic Monitoring at Mono Lake

In 1974 the University of Nevada, in cooperation with the US Geological Survey, installed a network of 24 stations in the area south of Walker Lake, Nevada, and north of Mono Lake, to investigate faults in an active seismic region that might be suitable for an earthquake control experiment. One of the original stations of this network was installed about 10 km east of Mono Lake and has operated continuously to the present time (February 1979). An earthquake swarm occurred near the Mono station in July and August 1974, and in early 1975 two more stations were added to the Mono area to improve focal determinations. In July 1975 another swarm occurred in the same area, and later that year the local seismic network was increased to six stations. In 1977, after no swarms had been observed for two years, five of these stations were taken out.

Signals from all stations of the Mono Lake-Walker Lake network were telemetered to Reno, Nevada, where they were recorded on magnetic tape. In addition, selected stations were monitored on Helicorders, but as a rule this did not include the

Mono stations. Events selected from these visual recordings for detailed analysis were played off the magnetic tape onto multi-channel strip-chart records at a scale of 1 cm per second of real time. In analysis of the tape playbacks, arrival times of phases P_g and S_g were estimated to the nearest 0.01 second. Hypocenters were determined using the computer program HYPO71 (Lee and Lahr, 1972), with a crustal model consisting of a 28-km thick layer with P-wave velocity 6.0 km/sec, over a halfspace with velocity 7.85 km/sec (Ryall and Jones, 1964).

Results of Analysis

From March 1974 to November 1978, a total of 269 events were analyzed and found to be located in a zone trending east for about 50 km, from the west edge of Mono Lake to the northeast corner of Adobe Valley. Most of the earthquakes are clustered in the eastern 20 km of this zone (Figure VI-1). Calculated depths for these events were of variable quality, depending on the number of stations operating in the Mono area at a given time, but most of them were in the range 6-14 km. Magnitudes determined from coda length ranged up to 4.0. A recurrence curve indicated that the level of detection was about M = 1.6, and there was a deficiency of earthquakes with M > 2.6. The slope of the recurrence curve, or "b-value" was 0.80-0.85, which agrees with other values found for the Nevada region (Ryall and Savage, 1969).

Clustering of Events

A remarkable characteristic of earthquakes in the zone east of Mono Lake is that they tend to occur in clusters or swarms. Even more remarkable is that the swarms tend to occur at about the same time each year. Thus, there were swarms clustered in both space and time during August and September, 1974, July, 1975, August to early September, 1978, and mid-October to early November, 1978. Additional groups that were distributed in space but clustered in time occurred in July, 1974 and

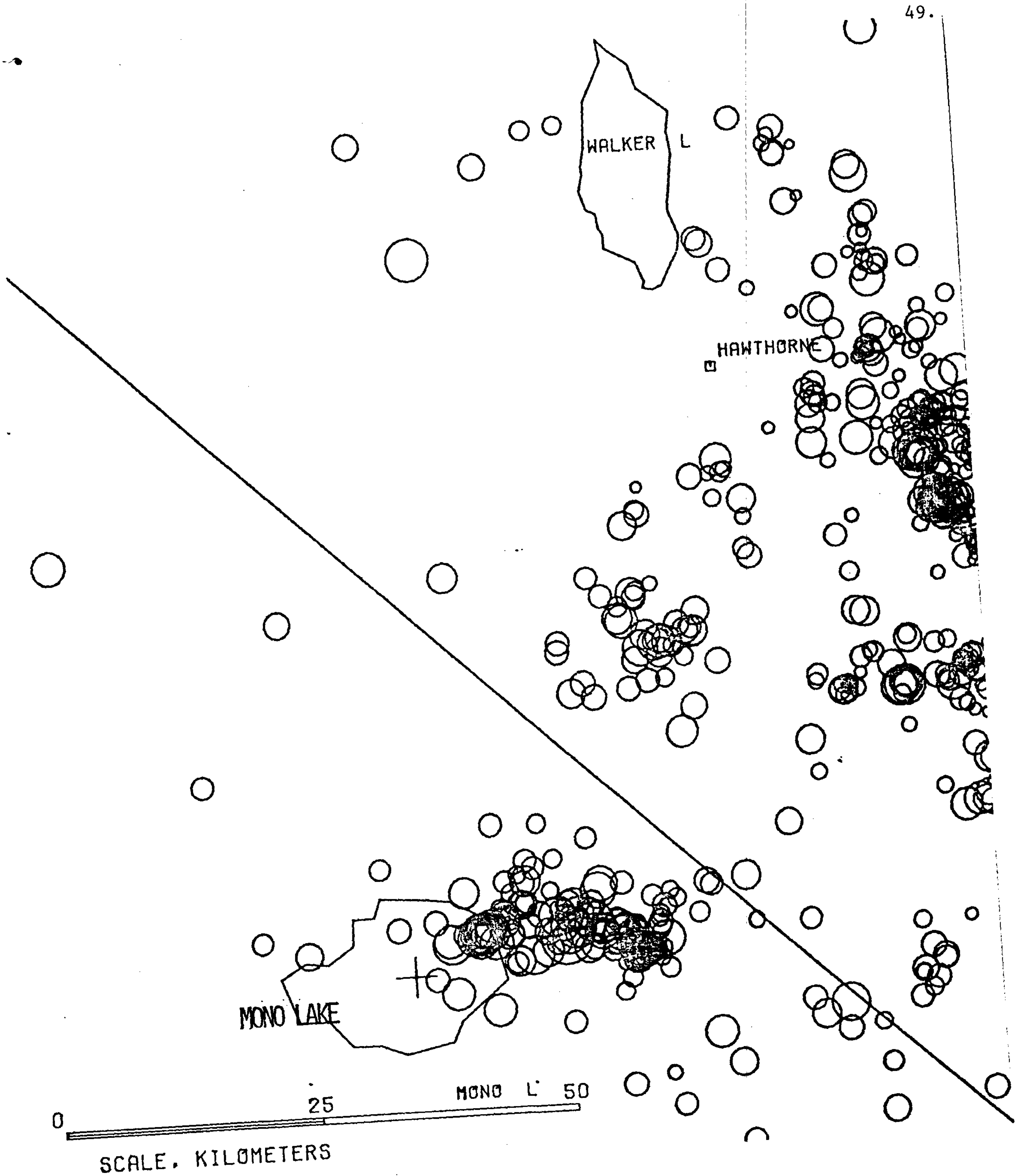

Figure VI-1. Earthquakes in the area of the Mina network, for the period June 1974-September 1978.

August and September, 1977. Of the total of 269 events recorded in this area from March, 1974 through November, 1978, 72% occurred in the four months of July through October, and during five years of recording, only one year (1976) did not have as prominent an increase in Mono earthquakes during the summer and early fall.

A tendency for Mono earthquakes to occur in multiples has also been noted. For example, of 49 events in the 1978 swarms with magnitudes from 1.7 to 3.4, 15 contained pairs, 2 triplets, and 2 quadruple events. The criteria for events to be considered as paired were that they occurred within 60 seconds of each other, and that they had identical step-out times or other characteristics to indicate that they had occurred in the same place. Analysis of this phenomenon is continuing, and will focus on the data collected before 1978.

Discussion

Earthquakes in a zone running east from Mono Lake occur within an area of volcanic cones and basalt flows ranging in age from 2.6 to 4.5 m.y. These earthquakes display remarkable clustering behavior, usually occurring in swarms during the months of July-October, with the frequent occurrence of pairs or multiples of events. As pointed out by Richins (1974), swarm activity appears to be characteristic of seismicity in geothermal areas in the Nevada region, and the possibility exists that earthquakes in the Mono area are connected with volcanic processes.

Except for the clustering behavior, there is not much unusual about the Mono shocks. Focal depths of 6-14 km are normal for earthquakes in the western Great Basin and somewhat shallower than focal depths in geothermal areas (Ryall and Savage, 1969; Richins, 1974). The b=value of about 0.8 for Mono earthquakes is less than those (0.93-1.18) found by Ryall and Priestley (1975) for the Excelsior Mountains and Cedar Mountains to the northeast and east respectively, but similar to their value (0.84) for the northern Owens Valley to the south. A fault plane solution has not yet been obtained for the Mono events.

Work is in progress to refine this preliminary analysis. We also plan to replace some of the stations that were removed from the Mono Basin and to continue recording earthquakes in that area.

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