EARTHQUAKE HAZARD EVALUATION IN THE PACIFIC NORTHWEST

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USGS CONTRACT NO. 14-08-0001-16723
Supported by the EARTHQUAKE HAZARDS REDUCTION PROGRAM

OPEN-FILE NO. 81-965

U.S. Geological Survey
OPEN FILE REPORT

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Introduction

This report covers the contract year October 1, 1979 through September 30, 1980 for contract number 14-08-0001-16723, "Earthquake Hazard Studies in the Pacific Northwest". As the final report under this contract, we will briefly summarize the accomplishments and present status of this research over the last three years. Support under this contract covered operation of the western Washington seismograph network and earthquake hazard related studies resulting from the network operation. A major aspect of this project is the establishment of an accurate and complete data base of instrumentally observed and located earthquakes in western Washington. Most of the resources of this project go to support network operation and routine data reduction.

In the past three years, the network supported by this project has grown to 23 stations regionally covering the western part of the State of Washington. In addition, other projects have supported the installation of stations near Mt. St. Helens, on the Olympic Peninsula, and in the south Cascade range. A clear regional pattern of seismicity has been identified which places some general constraints on seismic hazard evaluation. The most significant geophysical event of this entire period has obviously been the eruption of Mt. St. Helens. The network proved invaluable in the earliest identification of seismicity related to that eruption, the only clear preliminary warning of the impending events. Subsequently, the regional network has formed the stable backbone of monitoring efforts, supplemented by additional temporary and permanent network stations. Since the St. Helens eruptions, much of our workload has been dominated by the requirements of the volcano monitoring effort. Nevertheless, a number of additional activities are being carried out or completed. These include the preparation and publication of yearly summary bulletins, the routine operation and maintenance of field stations, development of the digital on-line data recording system, preparation of routine reports, investigation of more significant earthquakes, and additional special research tasks. In the three year contract period, we have completed hypocenter bulletin summaries through 1978, completed development and installation of the digital on-line data acquisition system, added several new stations, completed investigation of a significant Puget Sound earthquake in 1978, prepared a preliminary report on Mt. St. Helens seismicity and eruption, prepared and co-hosted a conference on Puget Sound seismic hazards, and developed a method for efficiently computing travel times in earth models with laterally varying velocity structure. The St. Helens eruption sequence and subsequent seismic activity have amply demonstrated the importance and utility of the regional network. Supplementation of this network with stations in the south Cascade range, near Mt. St. Helens, and on the Olympic Peninsula along with stations in eastern Washington now provide a statewide coverage for earthquake studies never previously achieved.

Network Operation

Generally, stable operation of the network continued through this report period. With the increase in earthquake activity near Mt. St. Helens, four additional stations were planned for the regional network in the southwest part of the State. Two of those stations were installed in this report period. A program of recyclying seismometers which have been in the field for extended time periods was initiated. Implementation of full triggered digital network recording on our DEC 11/34 and 11/70 computer systems was accomplished during this report period. Much effort funded by this and several other projects has been expended in achieving this goal. Digital recording has substantially improved the time resolution available for phase picking. In addition, it has opened up new avenues of research including the possibility of applying a variety of signal analysis techniques to learn more about the sources of local earthquakes and to automatically discriminate event types and and pick phases.

Seismicity and Earthquake Hazards

The Mt. St. Helens eruption has produced in excess of 10,000 locatable earthquakes. This large number coming in so short a period of time, has produced a data handling problem of sizable proportions, setting back our schedule of processing of regional earthquakes. Data for 1979 are in the process of final verification and 1980 data are complete except for the 2nd quarter eruption period. As of 1980, we plan to produce a statewide bulletin based on uniform processing. Regional velocity models must be used for various parts of the network.

Mt. St. Helens seismicity has been monitored closely and has in fact proved to be a valuable short-term predictor for volcanic eruptions. Detailed reports on the eruption behavior and seismicity of St. Helens are being prepared under other project support and will not be considered here. However, Appendix A is a reproduction of a preliminary article on seismic aspects of the eruption published in Nature magazine.

A good understanding of regional seismicity has been obtained by reviewing over eight years of network data from western Washington. On a large scale, the most intense small earthquake activity is roughly coincident with the Puget Sound depression, extending northward to the Strait of Georgia and terminating southward at about the southern limit of Puget Sound. The most significant finding, having significance for earthquake hazards, is the division of hypocenters into shallow and deep suites. The deep suite forms a rather uniform planar surface dipping about 15 degrees in a northwesterly direction. These earthquakes appear to provide indirect evidence of a dipping lithospheric slab beneath Puget Sound, although they do not appear to be directly caused by slip on a thrust surface. A quiet zone between 30 and 40 km depths beneath Puget Sound separates the deep suite from a highly populated shallow suite of earthquakes. Many characteristics of the shallow suite are significantly different from the deep suite suggesting the conclusion that the causes of these two suites are fundamentally different. Appendix B summarizes a report prepared for the Fall 1980 Puget Sound earthquake hazards conference. In this Appendix, some of the implications for earthquake hazards are stated.

We have completed analysis of a main shock-aftershock sequence which occurred in March of 1978 in the south Puget Sound basin. The aftershock zone, though small, is in approximate agreement with a dominantly strike-slip focal mechanism suggesting a N20W right lateral fault surface. There is no known fault upon which this earthquake can be placed. The results of our investigation are summarized in a manuscript reproduced in Appendix D.

Finally, an enhanced 1978 bulletin for western Washington was published by the State Department of Natural Resources. Because this bulletin contains some new material,it is reproduced and included as Appendix C of this report.

Digital Data Acquisition

A major effort has taken place in developing the digital data acquisition capability for our statewide network. This effort has been shared between several projects. The St. Helens activity has forced us to enhance this capability at a faster rate than otherwise might have been the case. The result is that we now have full on-line recording capability and interactive high-speed graphics terminal picking and preliminary processing of the data. We continue to operate two Develocorders under this project at half-speed. This has proved necessary as a backup system and also to ensure that we acquire certain important pieces of data such as coda durations which are still truncated by the digital system. Also, we continue to have problems from time-to-time with missed events on the digital system and the film ensures that we do not lose data in such instances. We are continually working on correcting all known bugs in the digital system.

Special Studies

With the advent of digital recording, progress in seismology will involve taking increasing advantage of the information in the complete seismogram. A basic requirement is for machine identification of various classes of transient events, for example explosions vs. 'tectonic' earthquakes, or transient telemetry noise vs. seismic events. We have initiated a project to investigate the utility of linear predictive filtering and pattern recognition to discriminate between various classes of seismic events. The study is being carried out by Duane Hesser. This research is stimulated by success in applying similar theories to the problem of speech recognition -- both analysis and synthesis of speech.

An interesting set of two long-term swarms occurred between 1970 and 1975 near Seattle. These have never been studied in detail so we have started a project, being carried out by Tom Yelin, to look carefully at the time history, locations, magnitude characteristics, and focal mechanisms of these earthquakes.

Finally, we are preparing a review of Mt. St. Helens seismicity, and that of the other Cascade volcanoes Mt. Rainier and Mt. Baker, based on alomst 8 years of Develocorder film records.

Summary and Recommendations

The contract period of the last three years has been one of significant change as well as consolidation of previous gains. The broad features of regional seismicity are fairly clear and the separation of earthquakes into deep and shallow zones has been a major finding, of considerable importance for earthquake hazard related studies. The eruption of Mt. St. Helens has dominated the second half of the current contract report period, and has stimulated substantial growth of the network effort in Washington. A period of consolidation is now required to complete reports of our current findings, complete processing of data which was delayed by the heavy burden of St. Helens activity, to solve many minor operational problems related to the rapid growth of the statewide network and switch to digital data acquisition, to further explore the implications of the St. Helens eruption and to complete integration of our statewide network operation.

APPENDIX A

Seismic Aspects of the Mt. St. Helens Eruption

Reprinted from Nature, Vol. 285, No. 5766, pp. 529-536, June 19 1980

Eruption of Mt. St. Helens:

Seismology

from the Geophysics Program*, University of Washington

ON May 18, 1980 at 0832 local time a major geological event occurred with the cataclysmic eruption of Mt. St. Helens in Washington's Cascade Range. The eruption followed two months of intense seismic activity, surface deformation, and sporadic, but minor steam and ash eruptions. These geophysical and geological precursors signaled the reawakening of the volcano after a period of quiescence since activity was last recorded in 1856 (Crandell & Mullineaux *Science* **187**, 438; 1975; Crandell & Mullineaux, *US Geol. Survey Bull.* **1383**-c, 25p; 1978).

The cataclysmic explosions of May 18 caused an estimated $2 billion or more in damage, although the volcano lies in a relatively remote area. The cost in human life has been substantial with 22 confirmed dead and 60 to 70 still missing at the time of writing. A large sector of the north and northeast side of the mountain was devastated by pyroclastic flows, mudflows and tephra fallout. The direct blast from the explosions leveled entire forested areas on the north side; the affected area is estimated to be 400 km^2. Two river systems with sources near the mountain have been extensively altered by mudflows and flooding. The morphology of the volcano has drastically changed from a nearly symmetrical cone to an assymmetric edifice approximately 400 m lower in height, although much of the south and west sides of the volcano remain relatively untouched by the explosion.

Seismic activity was the first indication of the reawakening of Mt. St. Helens, beginning abruptly with an earthquake of magnitude 4 at 1547 local time on March 20, 1980. This earthquake was located just north of the summit by the regional seismograph network which included one station 3.5 km west of the summit. Since this was the largest earthquake recorded in the southern Washington Cascade range during seven years of instrumental observations, an aftershock study was begun on March 21 in an effort to examine seismo-tectonic processes near Mt. St. Helens. To improve the seismic coverage in the area, three portable seismic recorders were installed within 15 km of the summit, and a second telemetered station was added to the permanent network 35 km northeast of the epicenter.

A rapid increase in the number of small shocks made it clear that an unusual earthquake sequence was beginning at Mt. St. Helens. The initial aftershock activity failed to follow the usual decay in the number of events with time, and on March 22 a second magnitude 4 earthquake occurred in the same region. By March 24, additional earthquakes larger than magnitude 4 had occurred and the general seismicity increased to the point that a volcanic mechanism was required to explain the concentrated, high rates of seismicity. Additional temporary seismograph stations were installed to provide data adequate for obtaining accurate hypocenter locations in the hope that careful tracking of the hypocenters would increase our overall ability to monitor the volcanic hazard. Twenty four hour observation of the seismographic records began on March 24, and this effort has continued to the present as part of the hazard warning effort. A final, dramatic increase of seismic activity occurred on March 25, when the rate of seismicity reached its peak. Seismic stations within 8 km of the summit were continuously saturated, and individual earthquakes could no longer be distinguished from background seismic levels. More distant stations were used to resolve individual earthquakes for determining occurrence rates, magnitudes, and other earthquake parameters.

On March 27, two days after the seismicity peak, the first steam eruption occurred at 1236 local time. Moderate steam and ash eruptions continued for the next few weeks, declining in frequency until by April 23 only occasional small steam bursts were observed. On May 8 steam and ash eruptions resumed, occurring periodically for several days. Between May 14 and the cataclysmic eruption on May 18 there was only minor eruptive activity.

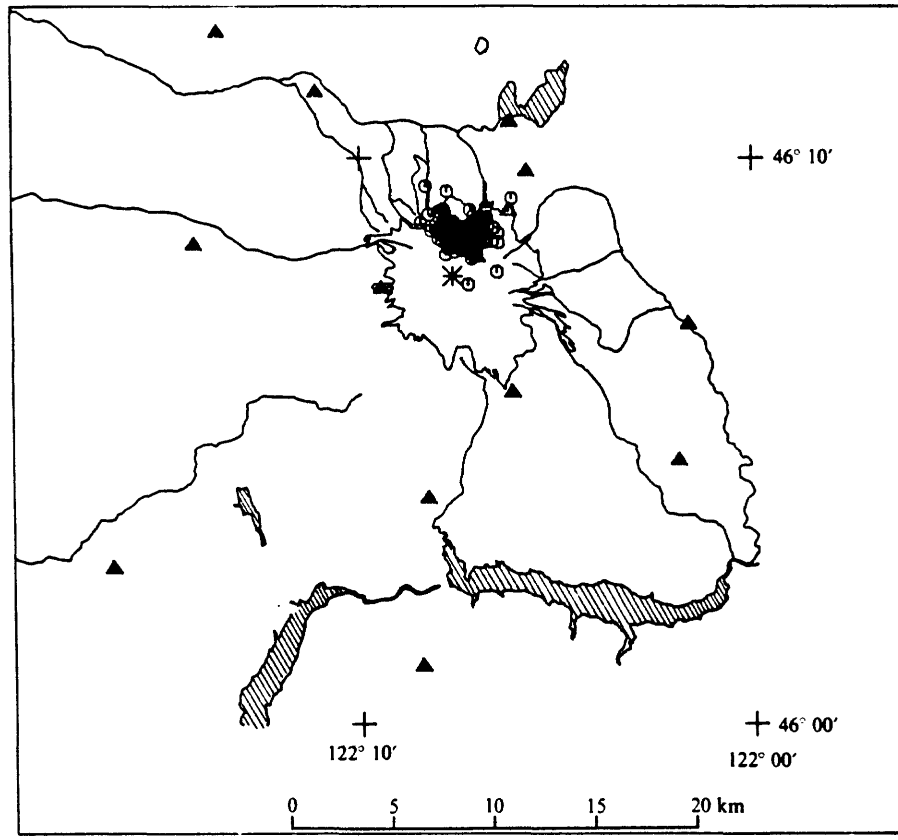
As the seismic energy release beneath St. Helens occurred at a high rate, count statistics for the whole episode have been kept only for earthquakes exceeding magnitude 3.2. After reaching a peak of 8 to 10 earthquakes per hour at this magnitude threshold during the evening of

**The seismic monitoring of Mt. St. Helens has involved a large number of individuals, many of them students and staff of the University of Washington Geophysics Program. This preliminary, descriptive report was compiled by the following people, listed alphabetically: R.S. Crosson, E.T. Endo, S.D. Malone, L.J. Noson, and C.S. Weaver. Crosson is a Professor of Geophysics, Malone is a Senior Associate, and Noson is a network seismologist, all with the University of Washington. Endo and Weaver are geophysicists with the US Geological Survey, Menlo Park, California, and both are currently on assignment in Seattle. Significant contributions to the seismic monitoring were made by J.M. Coakley and E.E. Criley (both USGS) and by J.W. Ramey and E.H. Wildermuth (both UW).*

March 25, the rate of activity declined irregularly until the explosive event of May 18. Figure 1 shows a smoothed curve of the rate of occurrence against time. The rate of seismic energy release generally follows the count curve although the decrease is not as great. This reflects the fact that large earthquakes continued at a slightly increasing rate during April and May, while the smaller events declined in frequency. Earthquakes larger than magnitude 4 occurred at an average rate of 5 per day in early April and 8 per day during the week preceding May 18, while the number of events larger than magnitude 3 went from 77 per day to 28 per day during the same period. The largest earthquakes recorded were approximately magnitude 5 and occurred late in the sequence. We estimate the total seismic energy release to date to be equivalent to a single magnitude 6.7 earthquake.

Several periods of harmonic tremor were observed. Normally, a nearly monochromatic 1 Hz signal, lasting from a few minutes to half an hour, was observed on stations within 30 km of the mountain. In several cases these signals were large enough to be observed on seismic stations 250 km distant. There was no apparent correlation of these monochromatic tremor periods and eruptions or unusual earthquake activity. During the intense earthquake activity of March 25-26 harmonic tremor would have been completely masked by the earthquake signals.

By May 1, a total of 15 seismograph stations were operating within a radius of 32 km of the summit. The station distribution is excellent for control of hypocenter coordinates though the velocity model is still poorly known for the immediate area. Virtually all of the earthquakes occurred in an area of 5 km radius centered approximately 2 km directly north of the summit crater (Figure 2). Depths ranged from 0 to about 5 km with a few events possibly as deep as 10 km beneath the average topographic surface.

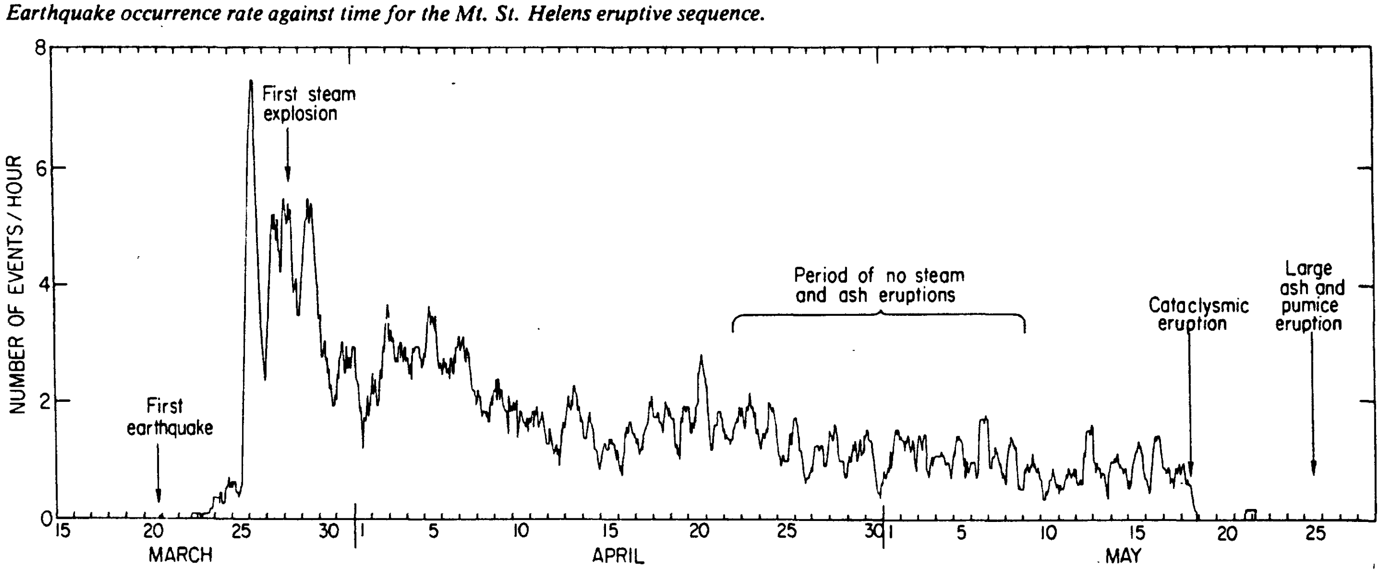


Map of epicenters above approximately 3.2 for period May 1, 1980 to May 18, 1980. Epicenters are open circles, seismograph stations are solid triangles, and bodies of water are shaded. Tree-lines and rivers are drawn. Dark area is epicenter cluster centered 2 km north of the summit.

At this preliminary stage of investigation, we have not been able to obtain good depth measurements of very shallow earthquakes, but it seems probable that many moderate earthquakes (magnitudes 3 to 4) occurred at shallow depths near the base of the volcanic edifice or up in the cone itself.

The blast of May 18 was not preceded by any anomalous seismic activity on a time scale of hours to days. At 0832 local time, an earthquake occurred at a depth of 3 km beneath the volcano. This event may have triggered a landslide off the north side of the mountain which led immediately to the explosion. The details of the explosion and its relation to the earthquake and landslide have not yet been worked out. A standard Wood-Anderson seismograph in Seattle recorded a magnitude 5.1 event at this time though the signals are more complicated than expected for a single earthquake. After the initial seismic event was over (it lasted for over 8 minutes) the earthquake activity dropped back to a level of only one or two discrete events per minute. This period of relative quiesence lasted for over three hours when both the earthquake activity and volcanic tremor increased. There was a steady increase in the level of seismic activity from 1140 PDT until 1530

Earthquake occurrence rate against time for the Mt. St. Helens eruptive sequence.



PDT when all seismic stations within 100 km were completely saturated and strong tremor was recorded 250 km away. Around 1730 PDT the tremor and earthquake activity abruptly diminished.

Since May 18 the earthquake activity dramatically declined until by the end of May there were only a few small earthquakes per day in the vicinity of the mountain. There was a moderate earthquake swarm coincident with an ash eruption on May 25. Low amplitude seismic noise, often with tremor-like characteristics, has been recorded nearly continuously since the May 18 eruption; although the noise is usually only monitored on the two stations still operating on the flanks of the mountain.

Comparison of the St. Helens sequence with the eruptive behaviour of other volcanoes may yield clues to the physical processes involved and to the predictable aspects of these processes. A particularly interesting example is the eruption of the Kamchatka volcano Bezymianny in 1956 (Gorshkov *Bull. Volcan.* **20**, 77; 1959). This volcano went through a cycle remarkably similar to that of Mt. St. Helens: a) a period of almost one month of volcanic earthquakes, b) strong ash eruptions lasting over one month, c) a stage of moderately declining activity lasting nearly 3 months, d) a gigantic explosion approximately six months after initial activity, and e) a post-eruptive stage of about six months of declining but sporadic activity. Except for the time table which is longer and the fact that earthquakes were estimated to be of greater depth (up to 50 km) in the case of Bezymianny, these two volcanic histories are sufficiently similar to suggest the possibility that a moderately predictable process is involved. The explosion of Bezymianny was in fact accompanied by a strong earthquake although the exact time sequence is not as well known as at Mt. St. Helens. The resultant craters of the two volcanoes are also very similar in size and shape.

Our preliminary conclusions are that seismicity provides an intermediate term warning of explosive volcanic hazard (scale of weeks to months) but no apparent short term warning (hours to days). The rate processes which may be extracted from the seismic data such as the strain energy release rate may be valuable in establishing the overall magma injection characteristics and other variables in the volcanic cycle when a sufficiently good understanding of the physical processes is available. Other measurements such as ground deformation must be made to provide basic information upon which to model the entire process. Unfortunately, it is still not clear that reliable short term prediction is feasible. Considering the wealth of seismic data that we have obtained, along with the variety of other observations made on Mt. St. Helens, a unique opportunity exists to probe the inner workings of an explosive volcano. □

Volcanology

*from Robert L. Christiansen**

THE explosive eruption of Mount St. Helens completely destroyed its north flank, opening a crater 1.5 km wide, and producing an eruption cloud that deposited a blanket of ash over a large area of the northwestern United States. The eruption, the culmination of a series of seismic and eruptive events that began in late March, was notable for the rapidity with which activity began and progressed and for the magnitude of energy released, both seismically and eruptively. Although further eruptions (including the eruption of lava into the volcano's crater) are likely, it seems probable that the greatest energy release occurred within two months of the initial earthquake of the sequence.

Activity began with a single shock of magnitude 4 on March 20 and grew within 5 days to a swarm in which magnitude 4+ earthquakes occurred at a rate of more than 8 per hour. An interesting decrease in seismicity (although to rates including more than 5 earthquakes of magnitudes 4 + per day — high by any ordinary standard) occurred during the day and a half before the first eruption, which was a crater-forming burst beginning at 1238 on March 27.

After a pause until about 0300 the following morning, the volcano erupted again, this time for a sustained period of nearly two hours. Similar eruptions continued for the following four days, with both short, essentially single-burst eruptions and sustained longer eruptions. The eruptions were all probably steam-generated and produced only lithic-crystal ash that apparently was derived by shallow explosions within a 350-year old summit dome. A moderate amount of this ash was distributed 50 km away and some was reported as far as 100 km to the east, but most of it fell within 5-20 km of the volcano's summit.

Phreatic eruptions continued after April 1 but were mainly of short duration and occurred at successively longer intervals. They ceased temporarily after a small eruption that produced ash on the volcano's upper flank on the morning of April 22. Up to that time the summit crater,

The new crater formed by the explosive eruption.

REVIEW OF SEISMICITY IN THE PUGET SOUND REGION FROM 1970 THROUGH 1978

Robert S. Crosson

Brief Summary

October, 1980

APPENDIX B

Review of seismicity of Puget Sound region, 1970-78

In an attempt to improve our knowledge of earthquake hazards in the Puget Sound region, earthquakes recorded with the western Washington regional seismograph network from 1970 through 1978 were reviewed. The most obvious characteristic of the spatial distribution of earthquakes is the diffuse zone of high seismicity in the central Puget Sound region. Within this central basin distribution, several clusters of earthquakes exist which are either long term swarms, aftershock sequences, or just persistent source zones (Figure 1). An apparent epicenter lineation passes through the southwest corner of the central basin earthquake zone. This lineation is due mainly to small earthquakes ($M \lesssim 2$) and its significance remains uncertain.

A significant division of earthquakes into shallow and deep suites (Figure 2) is based on spatial separation, energy release statistics, and <u>b</u> value determinations as well as focal mechanism evidence (Figures 3, 4, 5, 6, and 7). The deep suite forms a sub-planar zone which dips at an azimuth of about 60° between the depths of 40 and 70 km (Figure 8). This group of earthquakes may be subduction related although the focal mechanisms and spatial distribution do not yield simple interpretations.

Central basin earthquakes of the shallow suite have a bi-modal depth distribution (Figure 9), influenced to an extent by the existence of swarms. This bi-modal distribution is not so clearly apparent in the energy release distribution. However, both energy release and occurrence rate are maximum in the interval from 20 to 25 km depths for the shallow suite.

Earthquakes above magnitude 4 are confined largely to the central Puget Sound basin and north to the Strait of Georgia, with a distinct preference for the deepest earthquakes to be on the west side of Puget Sound (Figure 10). Magnitude statistics indicate that the deep suite of earthquakes appears to have a significantly lower b value than the region as a whole, indicating a population enriched in larger magnitude earthquakes. It is obviously dangerous to extrapolate directly to large magnitude earthquakes (magnitude 6 and 7) but evidence to date indicates that potentially destructive Puget Sound earthquakes occur in the zone from 40 to 70 km depths.

A suitable regional tectonic model has still not emerged from these data. The seismically quiet zone from 30 to 40 km depths beneath Puget Sound could well represent a weak stress decoupling between shallow and deep parts of the lithosphere, possibly where shear strain rates due to subduction are highest. Among the major problems facing us are the better resolution of the vertical and lateral crustal seismic velocity distribution, explanation of the localization of both shallow and deep seismicity beneath Puget Sound, and the establishment of direct evidence for or against continued subduction beneath western Washington.

ALL EARTHQUAKES .LT.35 KM DEPTH, 1970-78

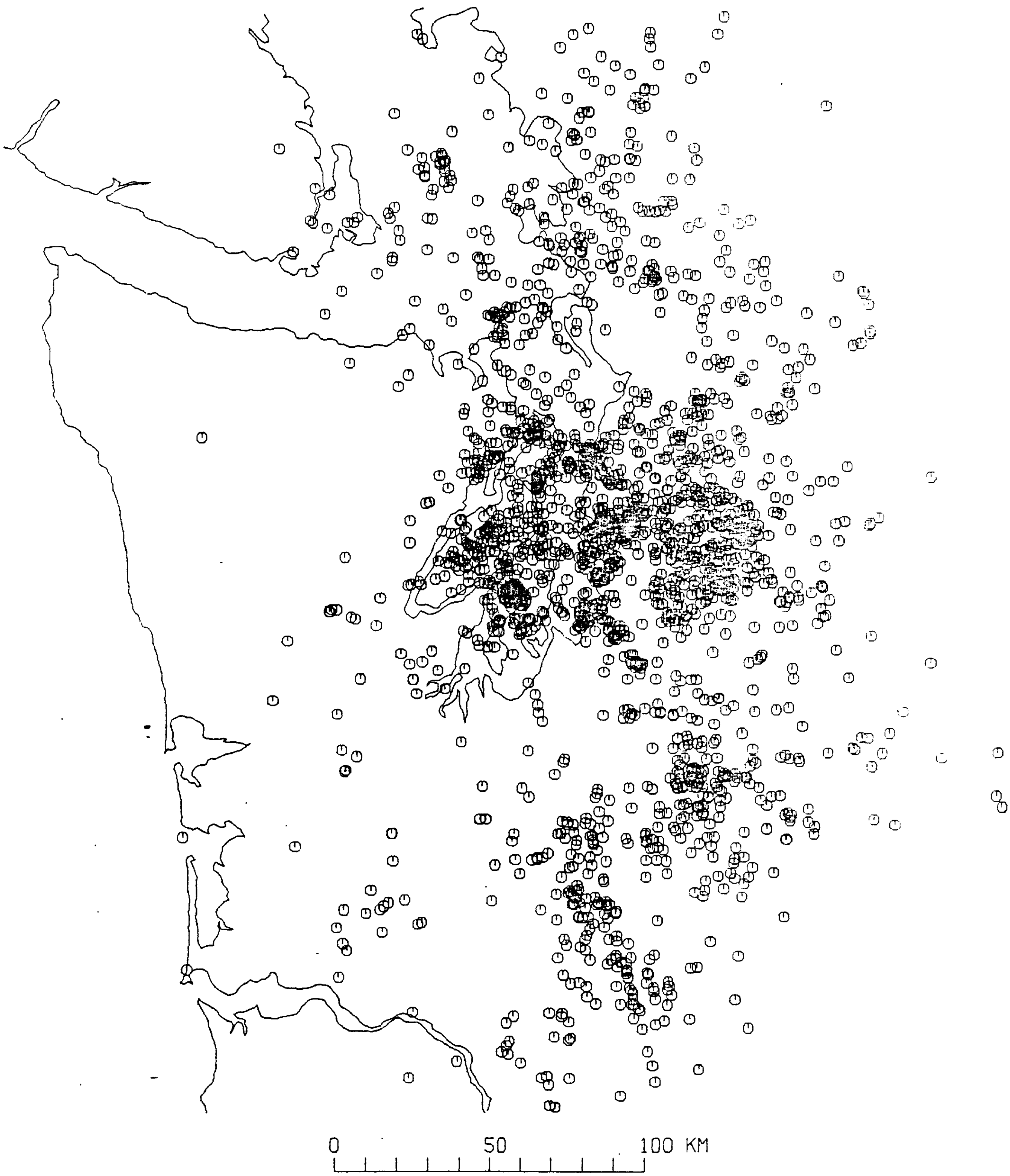


FIGURE 1

ALL EARTHQUAKES .GE.35 KM DEPTH, 1970-78

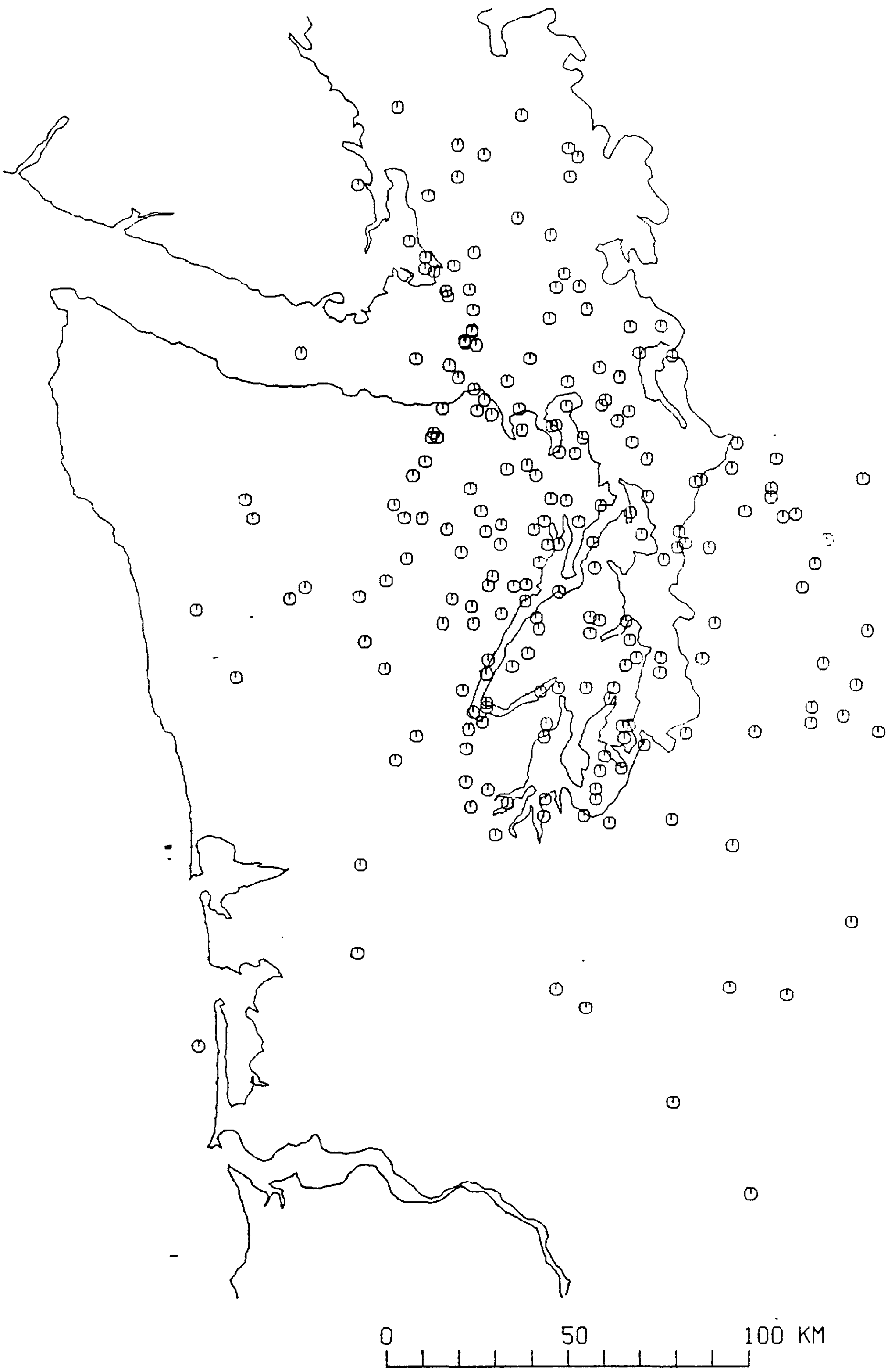


FIGURE 2

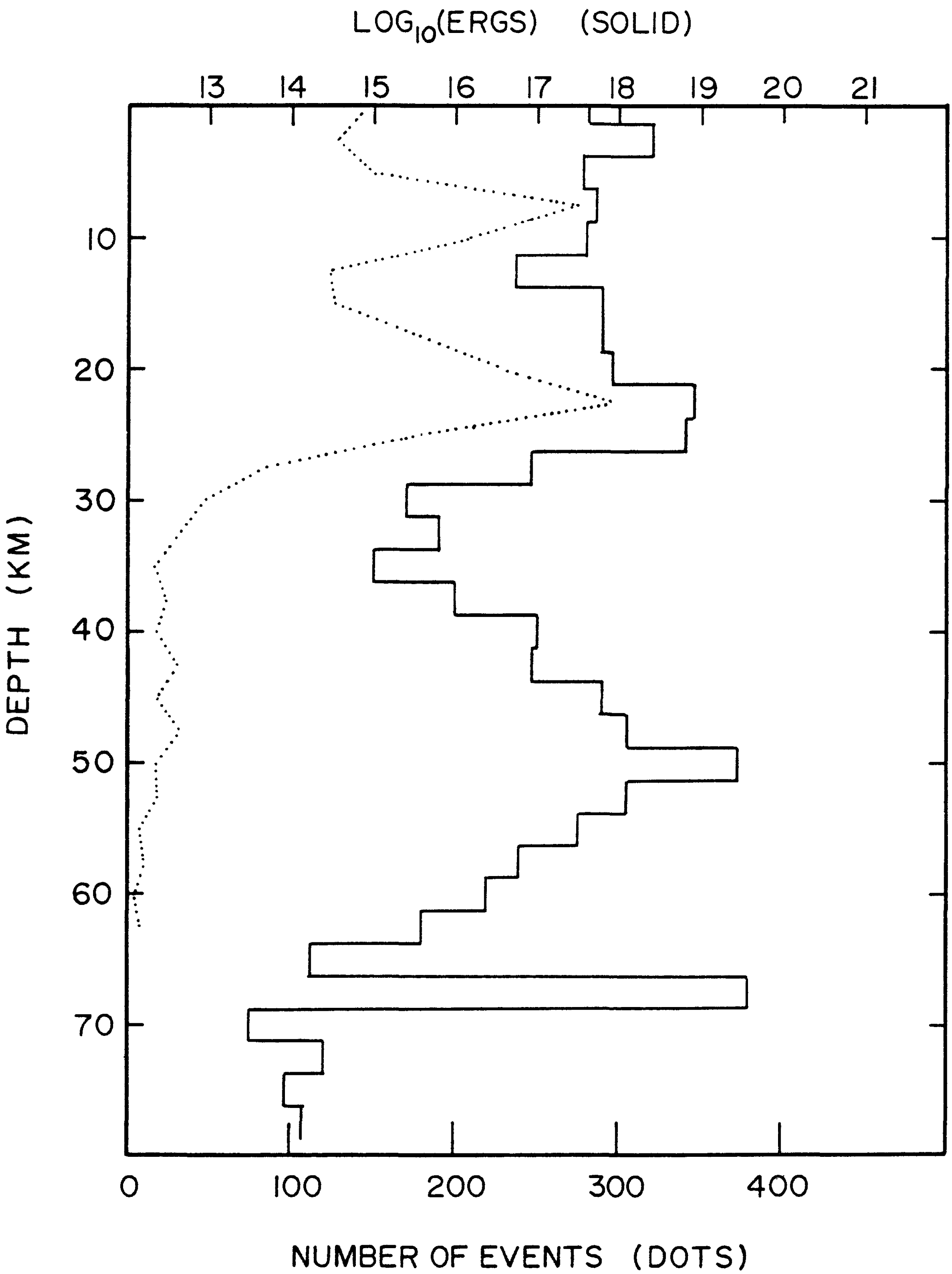

LOG10(ERGS) (SOLID)
13
14
15
16
17
18
19
20
21
10
20
30
40
50
60
70
DEPTH (KM)
0
100
200
300
400
NUMBER OF EVENTS (DOTS)

FIGURE 3

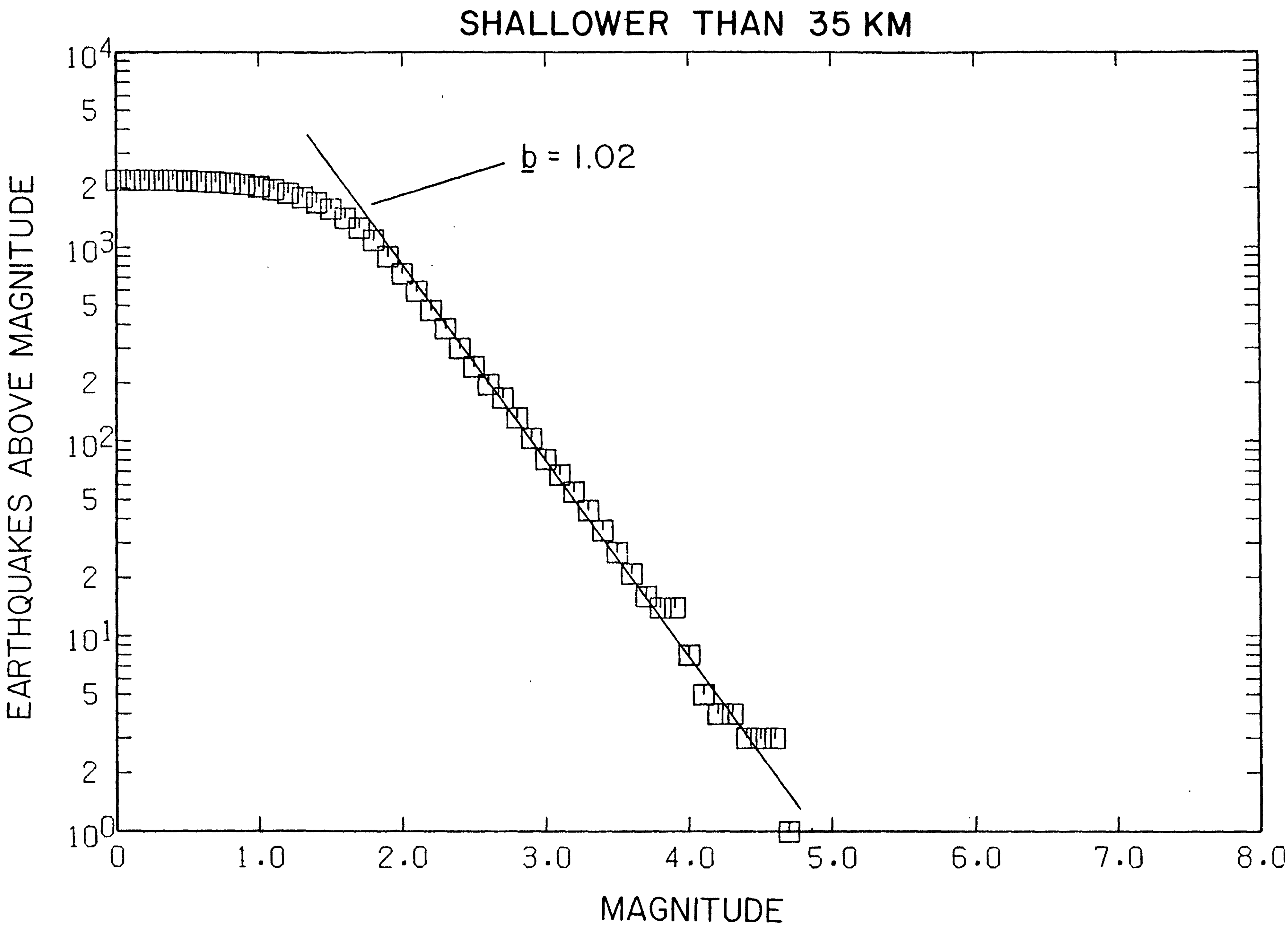

SHALLOWER THAN 35 KM
b = 1.02
EARTHQUAKES ABOVE MAGNITUDE
MAGNITUDE
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

FIGURE 4

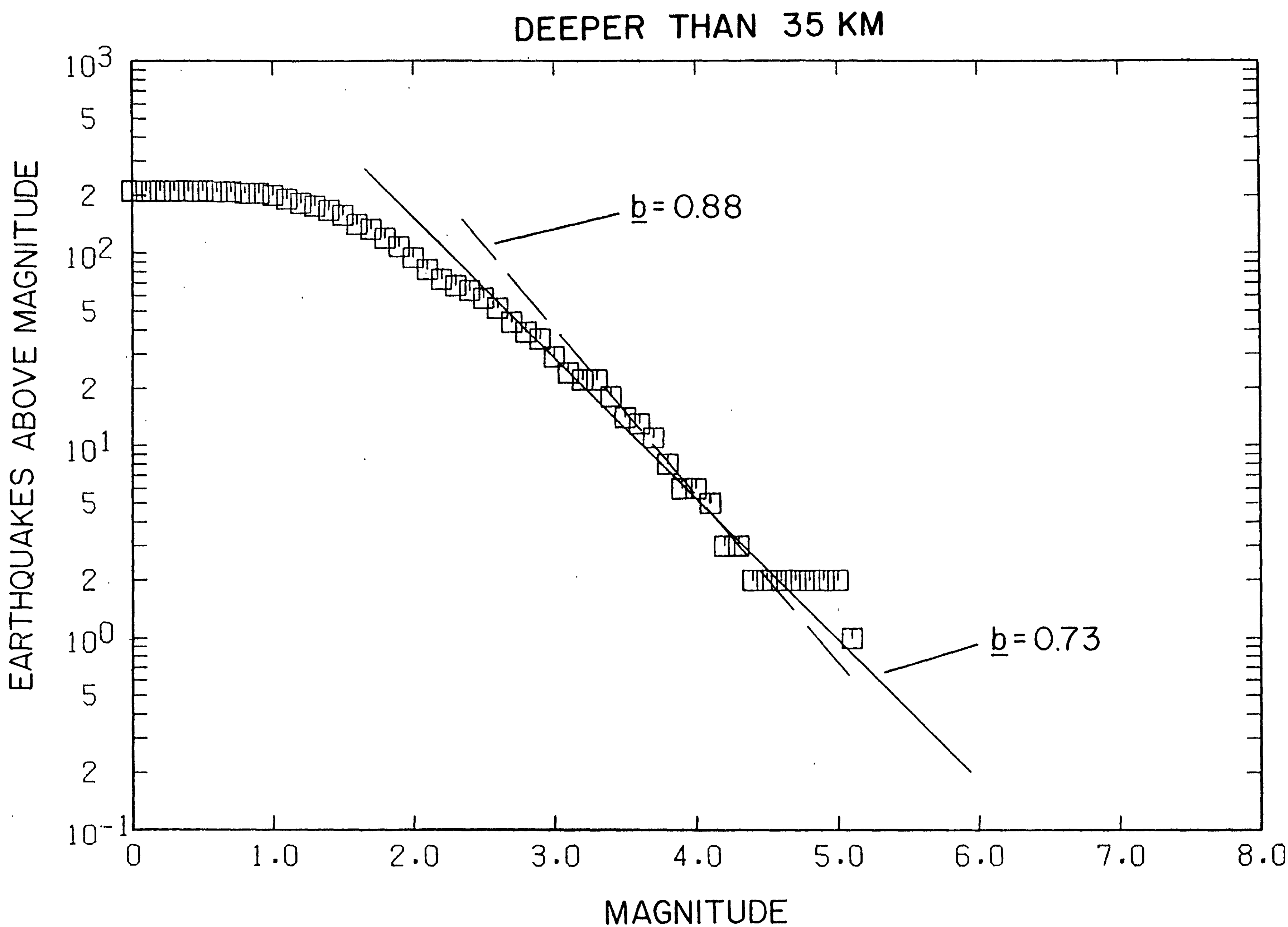
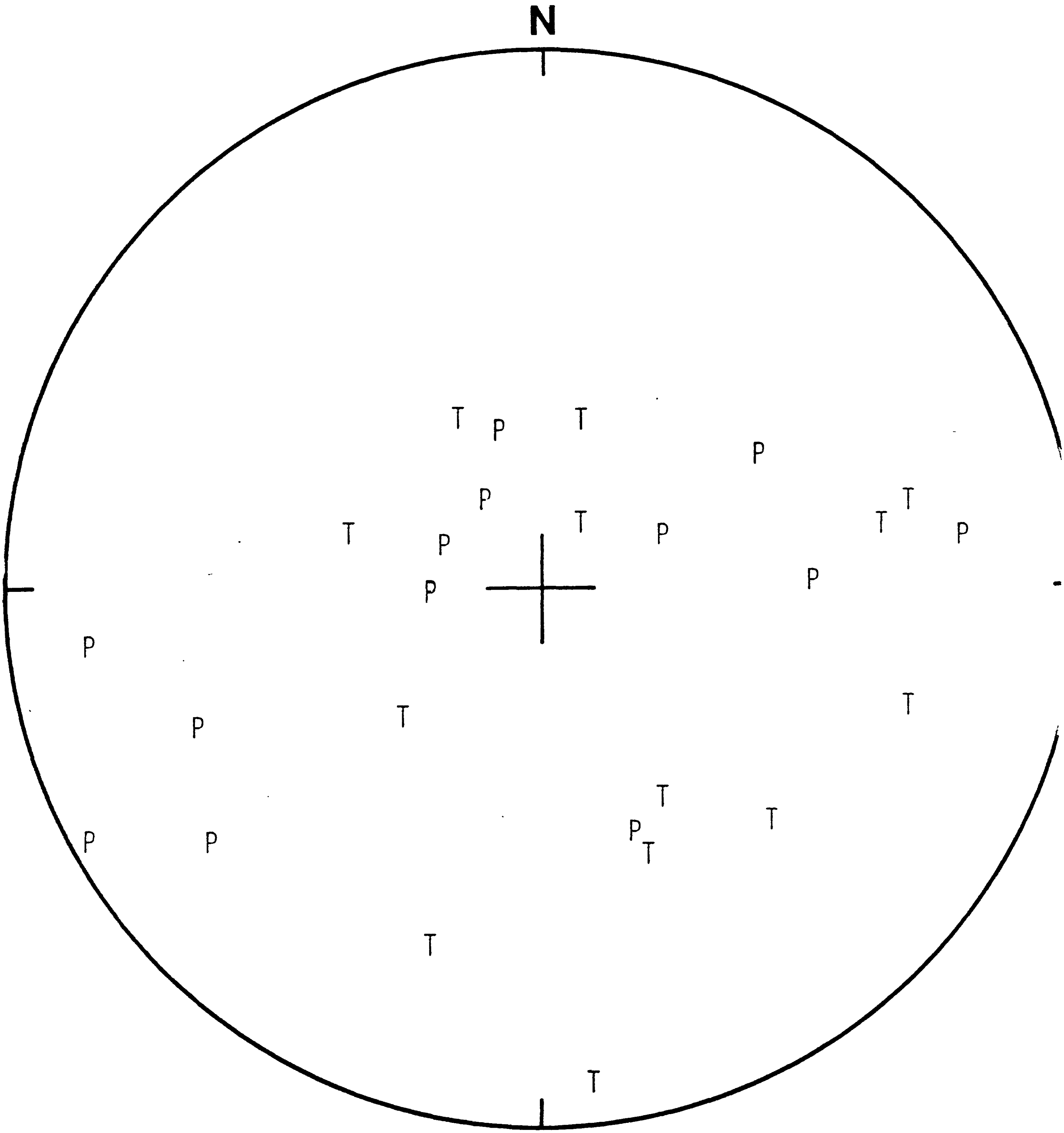

DEEPER THAN 35 KM
EARTHQUAKES ABOVE MAGNITUDE
MAGNITUDE
b = 0.88
b = 0.73
10^3
5
2
10^2
10^1
10^0
10^-1
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

FIGURE 5

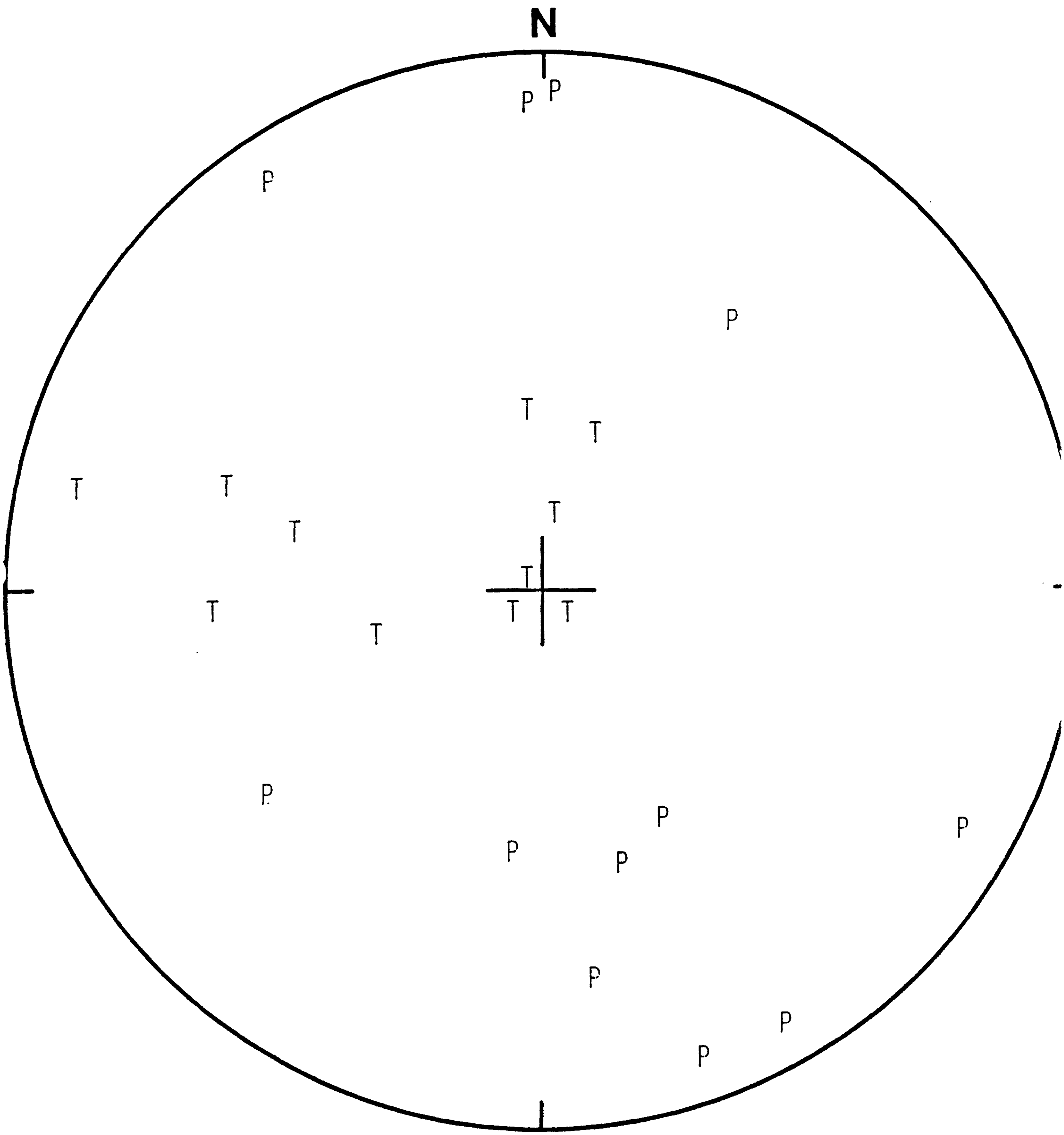
1974-78; MAG .GE. 3.0; DEPTHS .GT. 35 KM



LOWER HEMISHPERE; EQUAL ANGLE

FIGURE 6

1974-78; MAG .GE. 3.0; DEPTHS .LE. 35 KM



LOWER HEMISPHERE; EQUAL ANGLE

FIGURE 7

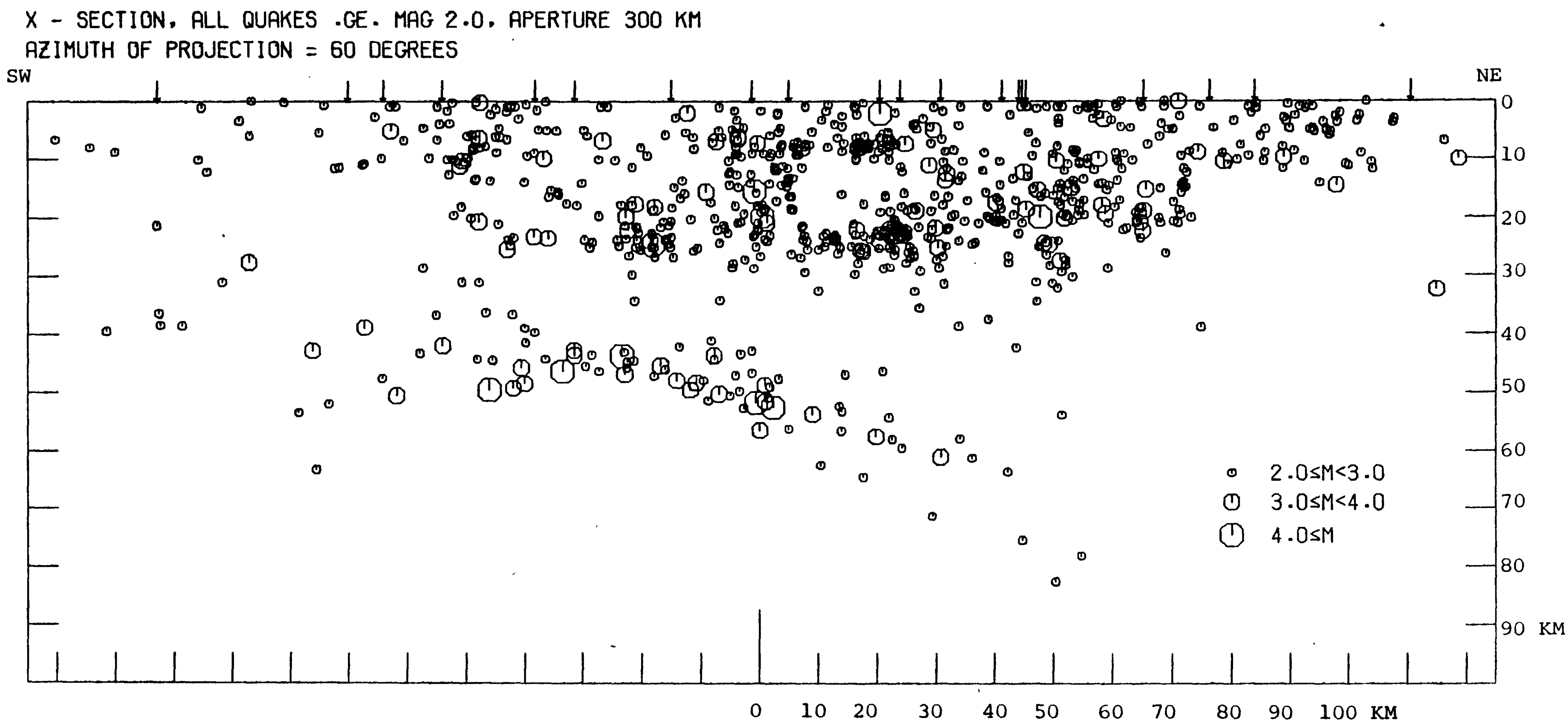

X - SECTION, ALL QUAKES .GE. MAG 2.0, APERTURE 300 KM
AZIMUTH OF PROJECTION = 60 DEGREES
SW
NE
0
10
20
30
40
50
60
70
80
90 KM
0 10 20 30 40 50 60 70 80 90 100 KM
2.0≤M<3.0
3.0≤M<4.0
4.0≤M

FIGURE 8

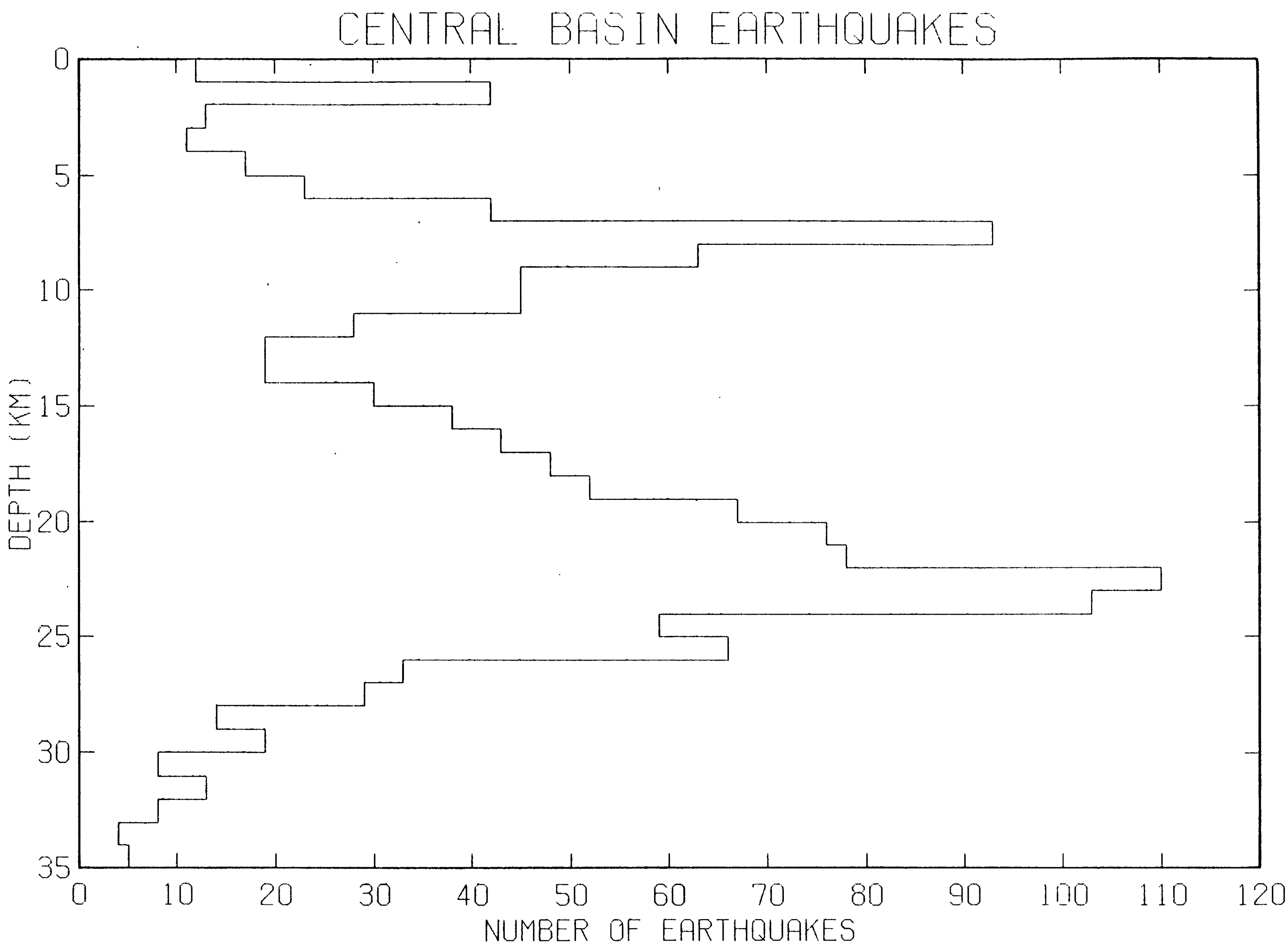

CENTRAL BASIN EARTHQUAKES
DEPTH (KM)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80
90
100
110
120
NUMBER OF EARTHQUAKES

FIGURE 9

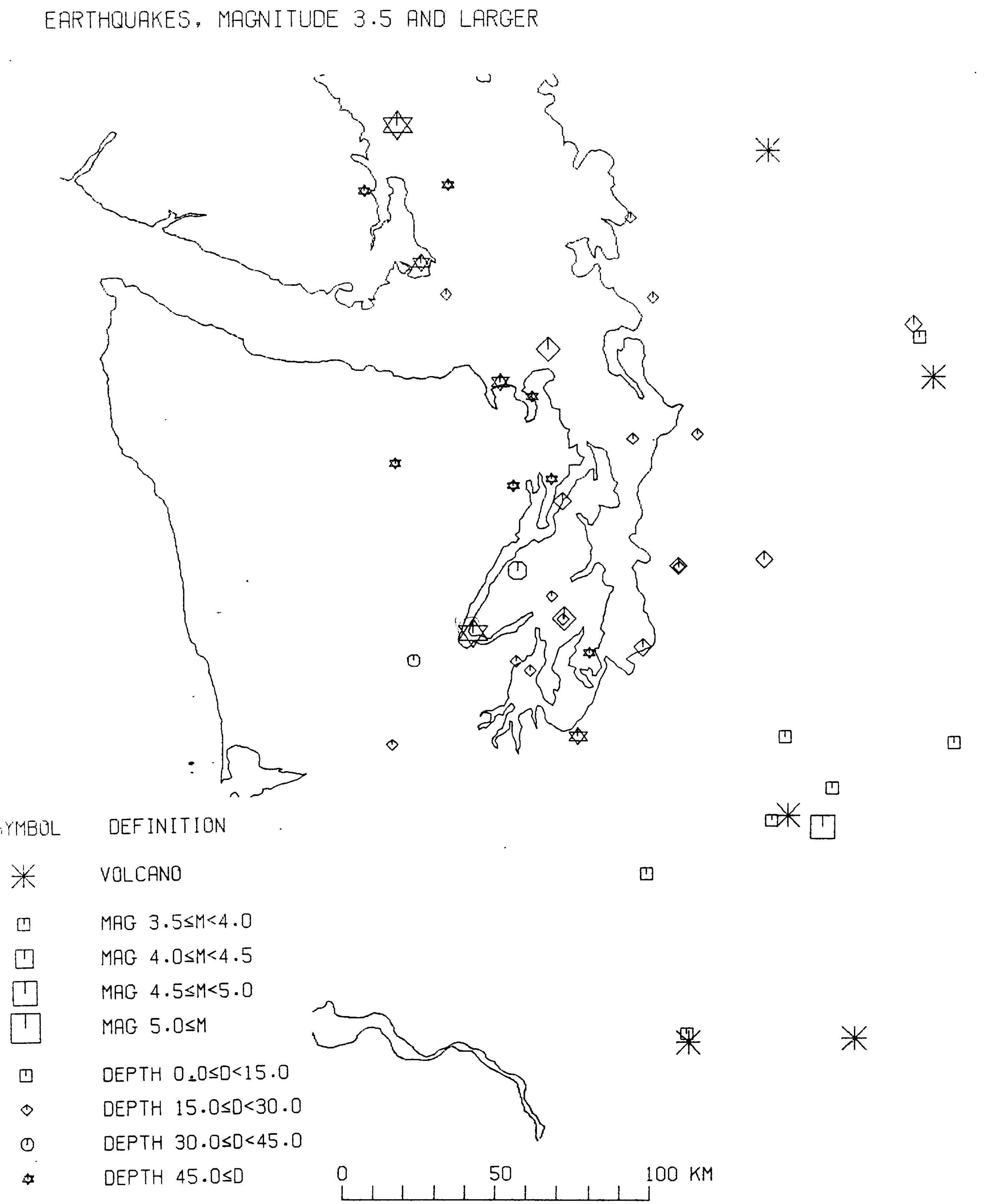

EARTHQUAKES, MAGNITUDE 3.5 AND LARGER
YMBOL DEFINITION
VOLCANO
MAG 3.5≤M<4.0
MAG 4.0≤M<4.5
MAG 4.5≤M<5.0
MAG 5.0≤M
DEPTH 0.0≤D<15.0
DEPTH 15.0≤D<30.0
DEPTH 30.0≤D<45.0
DEPTH 45.0≤D
0
50
100 KM

FIGURE 10

APPENDIX C

Compilation of Earthquake Hypocenters - 1978

STATE OF WASHINGTON
DEPARTMENT OF NATURAL RESOURCES
BERT L. COLE, Commissioner of Public Lands
RALPH A. BESWICK, Supervisor

DIVISION OF GEOLOGY AND EARTH RESOURCES
VAUGHN E. LIVINGSTON, JR., State Geologist

INFORMATION CIRCULAR 72

COMPILATION OF EARTHQUAKE HYPOCENTERS IN WESTERN WASHINGTON - 1978

By

LINDA LAWRANCE NOSON

and

ROBERT S. CROSSON

1980

For sale by Department of Natural Resources, Olympia, Washington
Price $.50

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ILLUSTRATIONS

TABLES

COMPILATION OF EARTHQUAKE HYPOCENTERS IN WESTERN WASHINGTON - 1978

By

LINDA LAWRANCE NOSON

and

ROBERT S. CROSSON

SUMMARY

The Geophysics Program at the University of Washington operates a continuously recording, telemetered seismograph network located west of the Cascade Mountains and centered along the Puget Sound Lowland. Station locations (fig. 1) have been chosen to best record earthquakes in the lower Puget Sound basin, an area of historically high seismicity. This report is the seventh in an annual series designed to provide a standardized compilation of earthquake locations, determined by using network data. Locations for 367 earthquakes recorded in 1978 are listed in Appendix I. Machine plotted maps show the distribution of epicenters by magnitude (fig. 2) and depth (fig. 4). Figure 3 shows the distribution of epicenters for events greater than magnitude 2.8.

The number of events successfully located each year depends on numerous factors: The number of stations operating, location of earthquakes relative to recording stations, earthquake magnitude, experience of personnel handling data, and of course, the number of earthquakes that occur in the area monitored. Ignoring the inherent variability of the data set may lead to incorrect interpretations. When used carefully, the data in this report may enhance evaluations of seismic hazard potential, as well as contribute to basic studies in seismology, earth structure, and tectonics.

INTRODUCTION

The seismograph network operated by the University of Washington consists of 21 short-period telemetered seismograph stations and one on-site recording World Wide Standard Station at Longmire, Washington (LON). Stations extend from Mount St. Helens (SHW) at 46° N. latitude north to Mount Baker (MBW) at 49° N. latitude, an area approximately 300 km N-S by 150 km E-W. Each station (except LON) consists of a single component vertical short-period seismome-

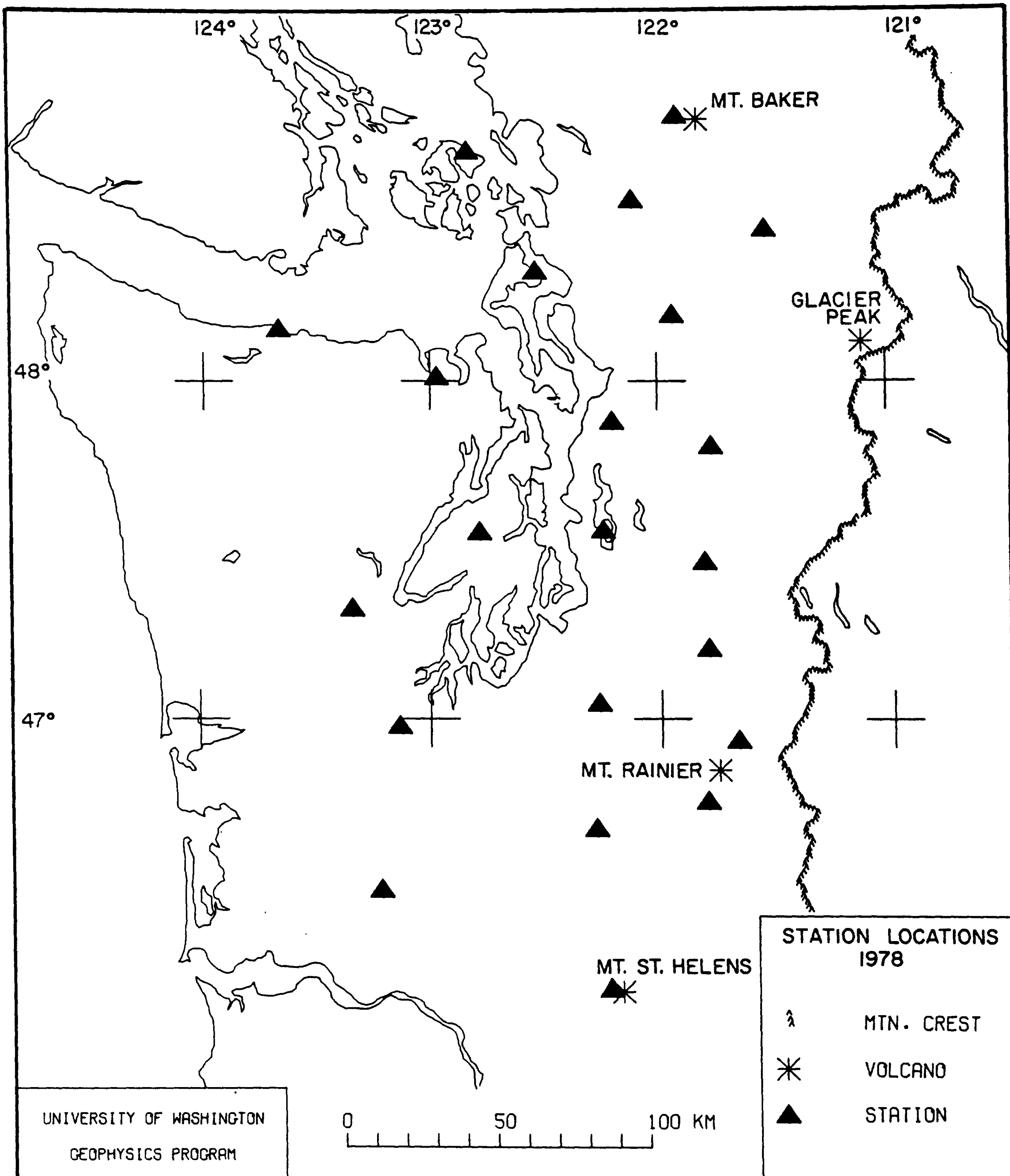

FIGURE 1.—Location map for stations operating in 1978.

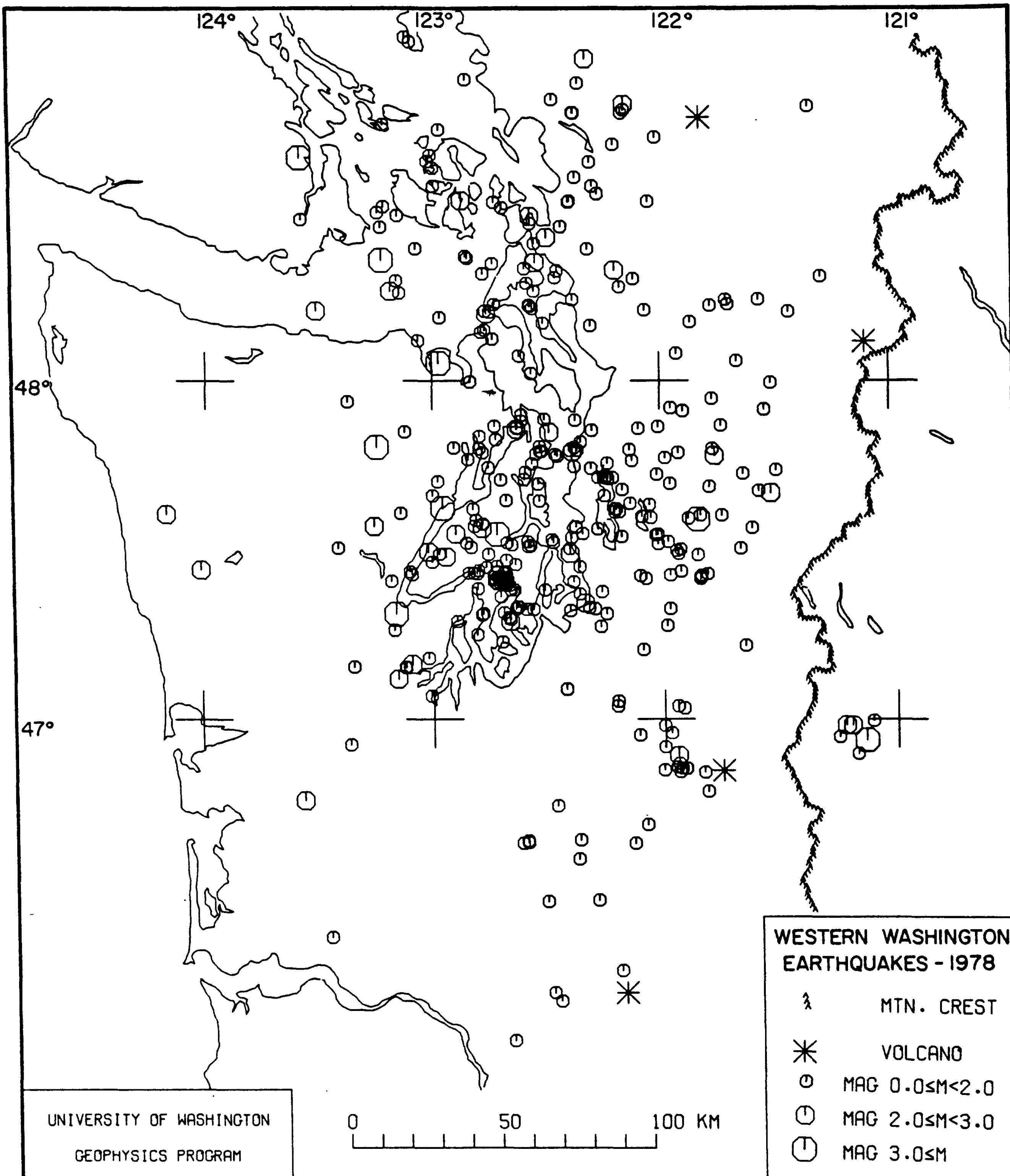

FIGURE 2.—Map showing epicenters for 1978 by magnitude.

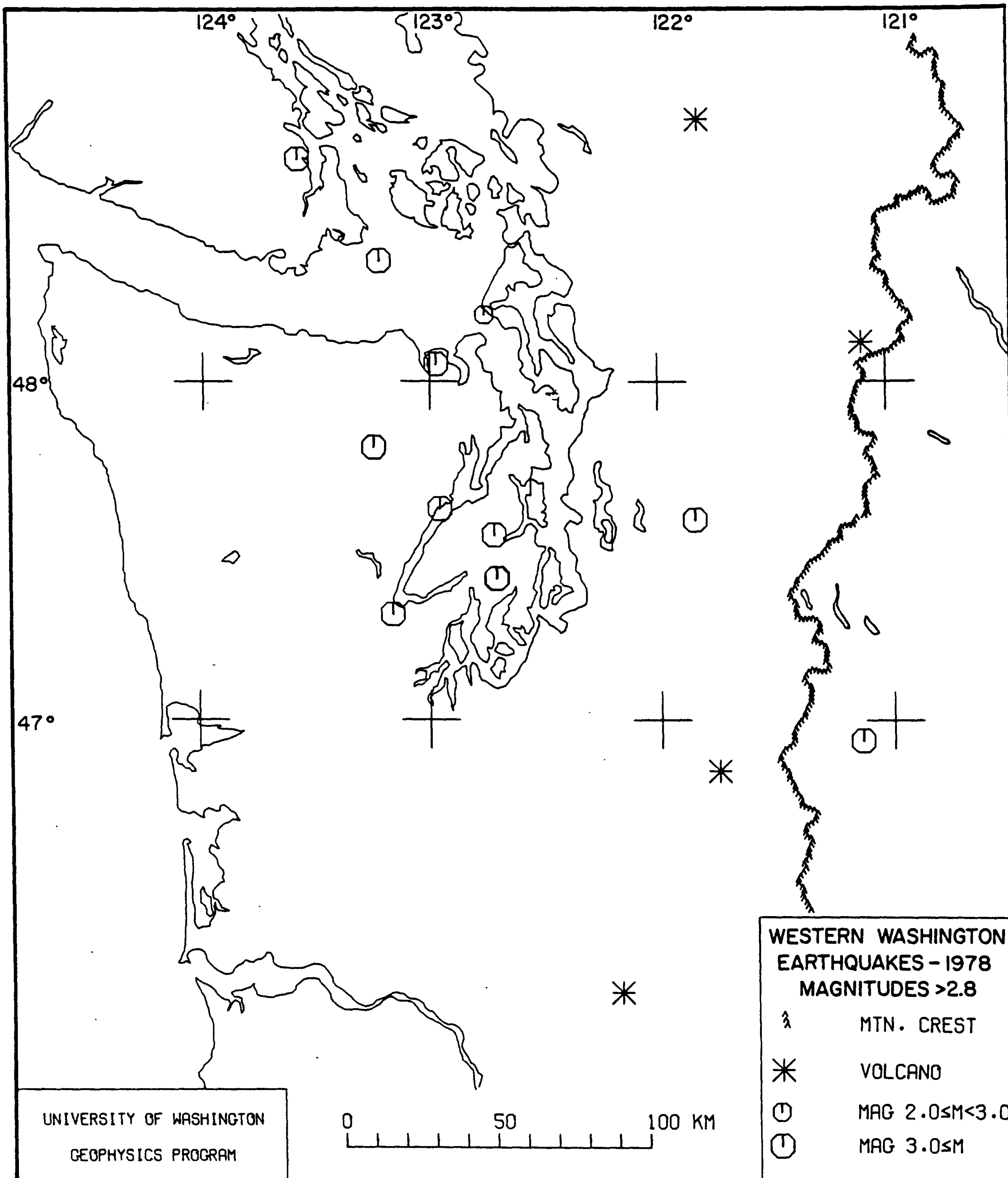

FIGURE 3.—Map showing epicenters for events greater than 2.8 magnitude.

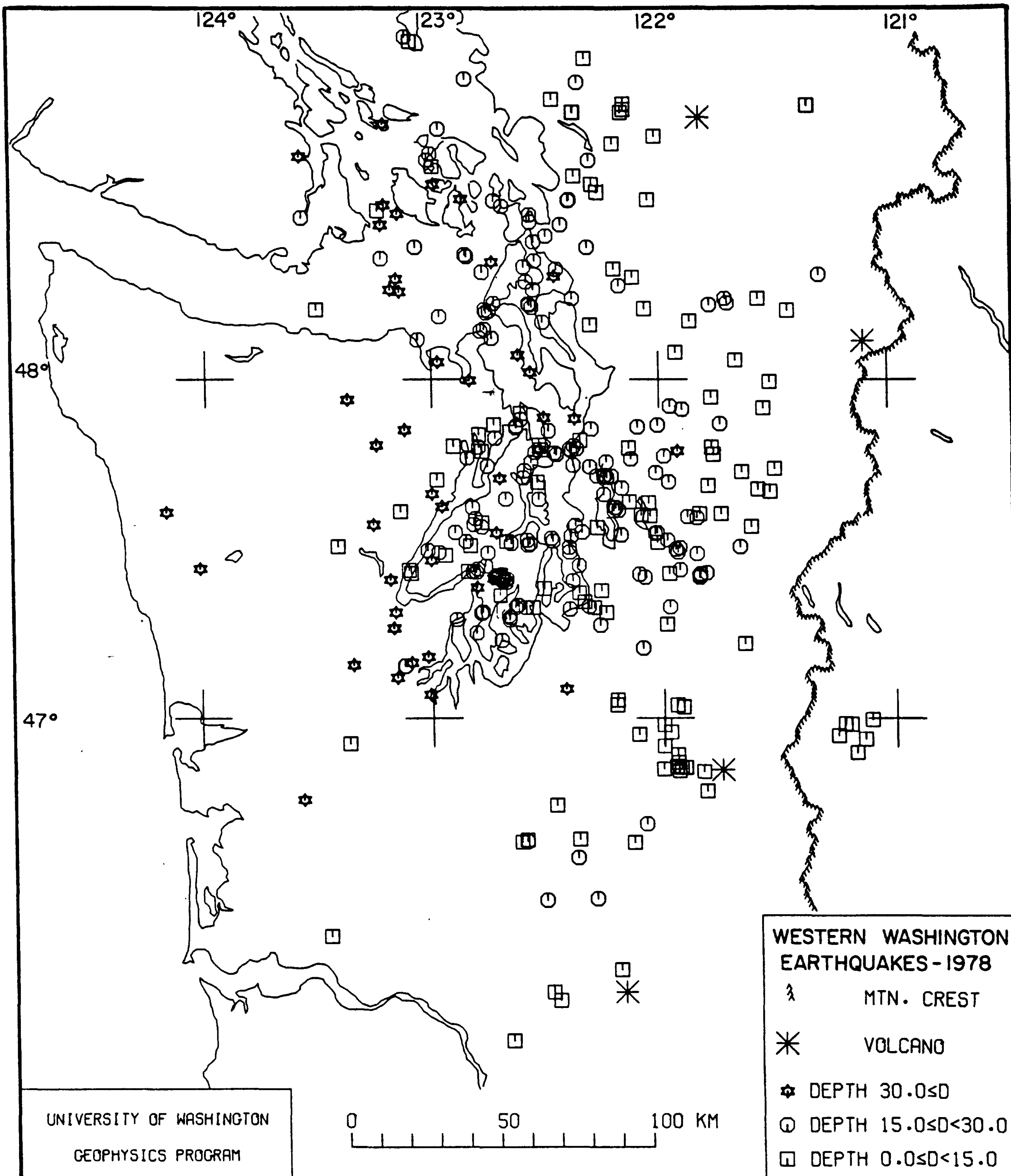

FIGURE 4.—Map showing epicenters for 1978 by depth (in kilometers).

ter, an amplifier and a voltage-controlled oscillator, which converts the output voltage from each amplifier to a frequency modulated audio tone capable of being telemetered to the central recording laboratory at the University of Washington. The first report in this series (Crosson, 1974) contains a description of network instrumentation, background information, a glossary of terms, and a compilation of earthquake data for 1970, 1971, and 1972. In this report, we provide revised and updated information on instrumentation and analysis procedures. Table 1 of the second report (Crosson, 1975) shows the revised crustal velocity structure used in the determination of earthquake locations compiled since 1973. Details of the method used to determine this velocity structure can be found in a separate publication (Crosson, 1976a, 1976b). Station delays, which are also determined with the model, are reported in the second report and repeated here in table 1. This table provides a summary of network station information, including station coordinates, elevations, P-time corrections (P-delays), and installation dates. Stations added since the second report have provisional delays. Compilations of hypocenter locations for events recorded in 1974, 1975, 1976, and 1977 may be found in Crosson and Millard (1975), Crosson and Noson (1978a), Crosson and Noson (1978b), and Crosson and Noson (1979). Information for larger historic earthquakes in Washington State from 1840 to

TABLE 1.— *Summary of network station data*

List of NEIS abbreviated stations in western Washington

Sta. Name	LAT Deg	LAT Mn	LAT Sec	LON Deg	LON Mn	LON Sec	ELEV Km	P DEL Sec	INSTALL Date	MAG* 1 Hz	LOCATION
SPW	047	33	13.30	122	14	45.10	0.008	1.029	9/17/69	65000	SEWARD PARK
GMW	047	32	52.50	122	47	10.80	0.506	0.100	2/27/70	145000	GOLD MT
GSM	047	12	11.40	121	47	40.20	1.305	0.399	6/11/70	165000	GRASS MT
BLN	048	00	26.50	122	58	18.64	0.585	-.137	7/2/70	115000	BLYN MT
CPW	046	58	25.80	123	08	10.80	0.792	0.241	7/29/70	135000	CAPITOL PEAK
RMW	047	27	34.95	121	48	19.20	1.024	0.385	7/27/71	190000	RATTLESNAKE MT
JCW	048	11	36.60	121	55	46.20	0.616	-.033	2/18/71	120000	JIM CREEK
FMW	046	55	54.00	121	40	19.20	1.890	0.246	9/4/72	100000	MT FREMONT
BFW	046	29	12.00	123	12	53.40	0.902	0.113	10/25/72	150000	BAW FAW MT
SHW	046	11	33.00	122	14	12.00	1.423	0.319	10/25/72	45000	MT ST. HELENS
MCW	048	40	46.80	122	49	56.40	0.693	0.125	11/8/72	70000	MT CONSTIT
MBW	048	47	02.40	121	53	58.80	1.676	0.433	11/8/72		MT BAKER
STW	048	09	0.75	123	40	12.00	0.308	0.009	6/27/73		STRIPED PEAK
LON	046	45	00.00	121	48	36.00	0.853	0.011		60000	LONGMIRE
HTW	047	48	12.50	121	46	08.65	0.829	0.000#	6/11/75		HAYSTACK
LMW	046	40	04.80	122	17	28.80	1.195		6/30/75		LADD MT
SMW	047	19	10.20	123	20	30.00	0.840	0.200#	3/24/75		SOUTH MT
LYW	048	32	07.20	122	06	06.00	0.107		4/18/75		LYMAN
OHW	048	19	24.00	122	31	54.60	0.054	-.100#	5/27/75		OAK HARBOR
FTW	047	52	36.00	122	12	05.00	0.147		9/24/75		FAIRMONT
GHW	047	02	30.00	122	16	21.00	0.268		9/24/75		GARRISON HILL
RPW	048	26	54.00	121	30	49.00	0.850		12/1/77		ROCKPORT

Provisional station P delay
* Magnification at 1 Hz; not determined where blank

1965 was compiled by Rasmussen (1967).

Since no new stations were added to the network in 1978, the network configuration was essentially uniform throughout the year. Inevitable failure does occur in the operation of some stations, which affects the uniformity of station coverage. A station activity graph (fig. 5) shows the major gaps in station operation in order to indicate approximately where such failure may affect the data in this report.

The basic information for this series is contained in Appendix I. The Appendix listing is a direct copy of a machine listing. Appendix II lists corrected information for six earthquakes whose magnitudes were reported incorrectly in the compilation of hypocenters for 1977 (Crosson and Noson, 1979). These errors resulted from data entry. To assess the accuracy and consistency of past magnitude determinations, we are reviewing film records of earthquakes recorded from 1975 to the present.

EARTHQUAKE ANALYSIS PROCEDURE

A Geotech Develocorder with film speed of 15 mm/min records signals received onto sixteen millimeter film. The film is then scanned on a Develocorder viewer with a magnification of X 20. Events detected are classified into the following categories: teleseisms (greater than 1000 km distant), regionals (less than 1000 km, with an S wave to P wave time generally greater than 10.0 seconds) and local events (nominally within the network perimeter). Each 300 foot reel of film represents 96 hours of recording time during which, typically, a total of 30 or more events are detected. All events are classified and entered into a master catalog.

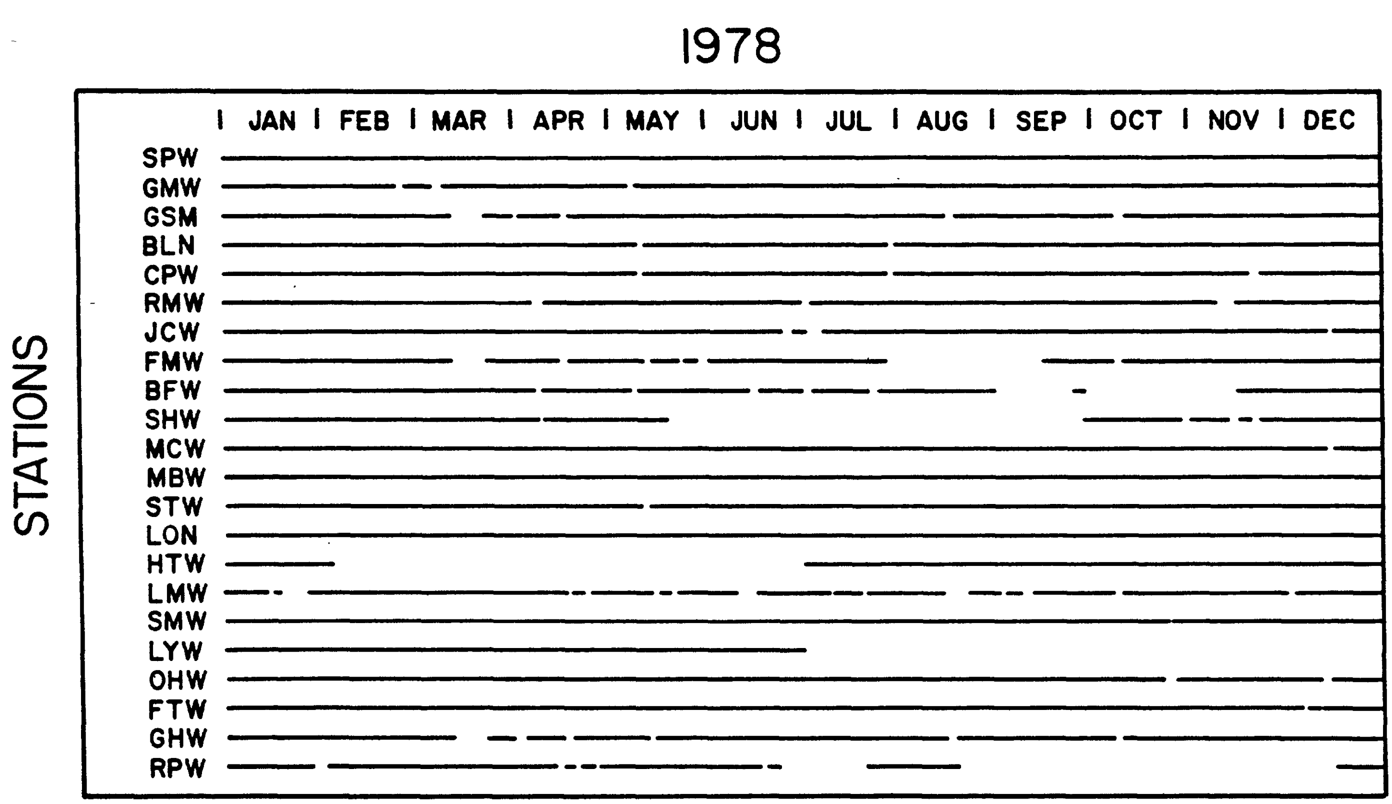

FIGURE 5.—Station activity graph.

Local earthquakes large enough to be well recorded on three or more stations are prepared for computer location runs. Usually, six or fewer local events will be successfully located during each four-day interval.

The location program, based on the standard nonlinear least squares inversion scheme of Geiger (1912), was especially written for use with data from the western Washington array. The accuracy of the locations determined with this program depends on the crustal model, station distribution and quality of the arrival time data. The main data set consists of P wave arrival times, coda lengths, and a weighting factor for each reading. S wave arrivals are used as supplementary data where necessary. Using the crustal model developed by Crosson (1976a, 1976b) and the current station distribution (fig. 1), hypocenter parameters are generated until the observed minus predicted arrival times (residuals) are a minimum. The quality of the data can then be estimated by examining the residuals for each event. Higher quality and quantity of data generally produces more reliable locations. The standard deviation (SD) of residuals for each earthquake is tabulated in the Appendix I. Although there are many possible indicators of solution quality, the standard deviation is an easily understood and useful one. An SD less than 0.1 second indicates a solution that fits the observed arrival-time data very well. A value greater than 0.5 usually indicates a poor solution. Events with an SD greater than 0.5 are usually removed from the data set. Earthquakes recorded on three or four stations theoretically always have an SD of zero. Since there is no measure of error, these events are removed unless they have very clear P-arrivals, locations within the perimeter of the network, and are recorded at stations distributed around the estimated hypocenter.

Explosions are removed from the data set wherever possible. Criteria useful in distinguishing explosions are: Shallow depths, positive P wave polarity, size, clustering, time of the day of occurrence, coda frequency, and of course, direct verification. When explosions occur in unusual locations and are nonrepetitive, positive identification is difficult. Suspected or possible explosions that are not subject to reasonable verification are indicated in the Appendix by a symbol ($). In particular, explosion contamination may be present in data recorded in the southern part of the network. All events from this area since 1970 are currently being reviewed.

Magnitudes of earthquakes are determined using a coda or signal duration technique. The method used is presented by Crosson (1972).

SIGNIFICANT EVENTS

During 1978, a total of 367 earthquakes were successfully located. Depending upon the location with respect to population centers and the depth of origin, most events with a magnitude greater than approximately 2.8 were felt. Ten of twelve 1978 events with magnitudes greater than 2.8 caused ground motion large enough to be detected by people living near the epicenter. These events are flagged in Appendix I by an asterisk (*). No structural damage was reported to have resulted from any of these earthquakes. Three events during the year had magnitudes greater than 4.0. The largest (m = 4.6) occurred on March 11, 1978 with an epicenter 4 km southwest of Port Orchard. Figures 2 and 4 show that this was an area of high seismicity during 1978 due to aftershock activity related to the event. Sixty-five earthquakes were located within a 10 km radius of the epicenter. A more detailed study of this earthquake is in preparation. A second felt event with a magnitude of 4.0 occurred in approximately the same location on March 31. Both of these events were felt widely in the Puget Sound area. A third earthquake (m = 4.0) occurred near Fall City on December 31. During 1978, six events were located within 10 km of this epicenter.

ACKNOWLEDGMENTS

The cooperation of many people and organizations is necessary to complete these reports. Although individual acknowledgment is impossible, we want to stress our appreciation to those involved. The contributions of the following merit special recognition. Laurens Engel provided major technical support and fulfilled the demanding task, often in adverse conditions, of network operation and maintenance. Access to lands and facilities for the purpose of station installation has been generously provided by the State Department of Natural Resources, U.S. Forest Service, State Parks Commission, Weyerhauser Company, U.S. Navy, U.S. National Park Service, and the City of Seattle Parks Department. The U.S. Geological Survey provided support for radio telemetering operations. Research support has been provided by the U.S. Geological Survey under contracts #14-08-0001-15896 and #14-08-0001-16723.

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APPENDIX I

CATALOG OF EARTHQUAKES (1978)

Earthquakes located with the western Washington seismograph network are listed chronologically in this Appendix. The columns are generally self-explanatory except the following features should be noted:

(a) The origin time listed is that calculated for the earthquake on the basis of multistation arrival times. It is given in Coordinated Universal Time (UTC), which is identical to Greenwich Civil Time, in hours (HR), minutes (MN), and seconds (SEC). To convert to Pacific Standard Time (PST), subtract eight hours.

(b) The epicenter location is given in north latitude (LAT N) and west longitude (LONG W) in degrees, minutes, and seconds.

(c) In most cases the depths, which are given in kilometers, are freely calculated by computer from the arrival-time data. In some instances, depths must be fixed arbitrarily to obtain epicenter solutions. Such depths are noted by an F (fixed) in the column immediately following the depth.

(d) The residual standard deviation (SD) is taken about the mean of the station first-arrival residuals. It is only meaningful as a general statistical measure of the goodness of the solution when 5 or more stations are used in the solution. Good solutions are normally characterized by SD values less than about 0.4.

(e) NO is the number of station observations used in calculating the earthquake location. Three observations at minimum are required and generally the greater the number of observations used, the better the solution quality.

(f) MAG is the local Richter magnitude as calculated using the coda length—magnitude relationship determined for western Washington. Where blank, data were insufficient or impossible to obtain for a reliable magnitude determination. Normally, the only earthquakes with undetermined magnitudes are those with very small magnitudes.

(g) SDMAG is the magnitude standard deviation. Where blank, either no magnitude was calculated or only one station observation was used to determine the magnitude.

(h) Felt earthquakes as determined by the University of Washington, various news and other agencies, are designated by a star (*) following the listing.

(i) Possible, but unverified, explosions are designated by a ($) following the listing.

APPENDIX I—Continued

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG	
JAN	2	10	49	28.9	47-59-39	121-30-54	5.9	0.0	4	1.1	.2	
	2	14	22	21.3	47-35-16	122- 8-13	4.4	.2	7	1.4	.3	
	4	17	51	44.7	45-48-53	122-34- 7	8.1	.3	5	1.7	.1	$
	5	15	9	4.3	47-34-13	123-15-36	44.5	.1	15	2.4	.2	
	7	4	14	25.4	47-47-35	122-23-47	21.4	.1	6	1.4	.5	
	9	16	38	16.5	47-32-23	122-10-36	24.2	.1	7	1.4	.3	
	10	16	47	58.4	48-55-59	122-18-23	.7	.2	7	2.7	.2	
	11	9	14	21.4	47-42-24	122-42-14	53.1	.2	20	2.0	.4	
	13	1	42	17.5	47-44-34	122-45-26	27.8	.0	5	1.0	.5	
	16	19	10	3.3	46-45-29	123-33-44	39.5	.3	19	2.6	.4	$
	18	10	33	31.4	47-15-30	121-59- 2	14.3	.2	6	1.3	.2	
	19	6	46	36.2	47-51-30	122- 5-52	22.3	.1	6	1.7	.1	
	22	16	47	13.8	47-29-12	122-45-36	16.5	.1	9	1.3	.4	
	23	9	14	59.9	47-45-37	122-27-13	15.2	.1	7	.7	.2	
	24	7	10	48.5	48-45-22	123-12-47	53.8	.1	7	1.3	.4	
	24	8	9	14.0	46- 9-48	122-28- 6	7.4	.1	9	1.5	.2	
	25	12	52	53.7	47-30- 6	121-55-16	21.7	.0	6	.8	.3	
	25	14	3	27.6	47-25-52	122-46-10	23.3	.1	6	1.0	.4	
	26	2	7	55.7	47-51-20	122-37-52	22.7	.2	19	2.3	.4	
	26	7	9	53.0	47- 7- 7	123- 9-25	47.6	.2	12	2.0	.2	
	27	13	56	24.4	47-25-27	121-49-55	18.7	.3	12	1.5	.4	
	29	13	14	38.2	47-25-29	124- 0-58	38.5	.2	18	2.8	.3	$
FEB	1	11	39	24.0	46-37-46	122- 8-30	2.7	.2	10	1.6	.1	
	3	12	9	30.4	47-31- 4	122- 1- 7	12.2	.1	7	1.3	.1	
	3	19	30	41.4	47- 3-11	122-12- 8	5.1	.2	13	1.6	.3	
	5	16	37	45.7	48-41-50	122-11-16	14.7	.2	9	1.4	.4	
	5	22	7	58.4	47-31-28	121-58-28	19.1	.2	14	1.9	.4	
	9	11	14	37.9	47-33-50	122-47-10	23.3	.2	17	2.0	.2	
	10	14	9	16.1	47-43-15	123-14-49	43.7	.2	20	3.1	.3	*
	11	5	3	43.9	46-13-22	121-46-17	16.6	.3	9	1.7	.3	
	11	6	12	13.2	47-27- 4	122-43-27	20.9	.1	5	.6	.5	
	12	10	16	11.7	48-21- 2	122-32-25	20.9	.3	15	2.2	.3	
	12	17	58	36.9	47-30-54	122-39-27	21.9	.1	6	1.2	.4	
	14	22	19	4.4	47-13-36	122-42- 6	17.5	.2	5	1.2	.1	
	15	10	42	6.5	47-39-40	123- 0- 5	47.0	.1	6	1.0	.3	
	22	18	52	40.4	48- 4-53	121-55-27	5.1	.4	7	1.1	.5	$
	23	4	46	42.7	47-35-45	122- 2-52	6.1	.3	6	1.0	.2	
	24	21	38	2.4	47-25-30	121-58- 3	5.2	.3	7	1.6	.3	
	26	14	0	34.4	47-42-48	122-12-49	20.5	.4	5	1.4	.3	
	26	21	48	18.6	47-29-20	122-24-10	18.6	.1	18	2.1	.3	
	27	6	9	23.7	48-13-26	122-34-10	17.5	.3	8	1.2	.4	
	27	7	12	28.2	46-35- 4	122-23- 5	20.4	.1	7	1.6	.4	
	27	10	28	53.4	48-12-49	122-33-21	16.5	.3	9	1.4	.2	
	27	11	47	12.8	47-47-22	122-23-14	16.7	.2	14	2.1	.3	
	27	16	47	26.9	48-13-13	122-33-56	16.7	.0	7	1.3	.1	
	28	3	46	11.4	47-35-27	124- 9-60	36.4	.2	7	2.0	.2	$
	28	10	10	21.4	47-54-55	121-32-40	.1	.2	6	1.6	.3	
MAR	2	5	41	27.9	48- 1-14	122-33-52	52.1	.0	6	1.5	.4	
	3	6	34	9.2	46-11-17	122-29-45	1.0F	.3	6	1.8	0.0	$
	3	8	58	53.8	47-51- 9	122-18- 0	20.3	.3	8	1.6	.3	
	3	10	42	25.9	46- 2-42	122-40-10	.7	.2	5	1.9	.1	$
	4	7	53	52.0	47-42-31	122-35-57	20.9	.2	13	1.8	.3	
	4	9	1	36.4	47-21-37	122-42-24	11.7	.1	4	.7	.1	
	4	13	59	51.0	47-22-52	122-38-44	25.5	.1	6	1.4	.3	
	5	18	13	36.1	48- 3- 6	122-58-22	56.5	.1	13	3.4	.2	*
	6	16	20	49.3	48- 4-20	122-37- 5	58.5	.2	6	1.5	.4	
	7	14	14	1.9	47-42-35	122-14- 2	19.6	.2	7	1.5	.3	
	11	1	13	29.8	46-47- 0	121-49-27	11.5	.2	7	1.4	.3	
	11	5	25	12.2	47-51-33	122-37-54	19.0	0.0	4	.9	.2	
	11	15	52	11.3	47-25- 4	122-42-31	24.6	.3	20	4.6	.1	*

APPENDIX I—Continued

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG	
MAR	11	16	31	9.9	47-25-11	122-40-44	24.6	.2	5	1.0	.4	
	11	16	37	31.9	48-23-25	122-18-25	15.2	.2	7	1.4	.3	
	11	16	49	.2	47-23-54	122-41-42	22.1	.1	5	.8	.5	
	11	18	6	17.6	47-24-24	122-41-35	23.9	.3	7	1.5	.3	
	11	19	40	48.6	47-24-25	122-42-13	23.2	.2	14	1.8	.1	
	11	21	18	40.8	47-24-31	122-42-10	22.9	.2	13	2.2	.1	
	12	1	22	14.5	47-24-44	122-41-57	23.0	.1	6	1.7	.3	
	12	5	41	48.3	47-25-16	122-42- 2	25.7	.1	7	1.5	.1	
	12	13	35	55.0	47-23-59	122-41-37	22.7	.1	9	1.4	.2	
	12	15	53	49.2	47-33-44	122-16-47	1.0F	.1	6	1.2	.4	$
	12	20	18	5.6	47-23-58	122-40-36	21.2	.0	5	.9	.4	
	15	17	53	28.3	47-18-46	122-41-34	7.2	.0	5	1.2	.3	
	17	11	38	47.6	47-26-19	122-48-11	21.7	.1	6	1.0	.3	
	17	19	13	33.7	47-23-49	122-40-41	21.3	.0	6	1.0	.2	
	19	5	50	45.5	47-30-13	122-24-14	18.4	.3	8	1.0	.3	
	19	15	53	13.3	47-24-16	122-41-39	22.0	.2	7	1.2	.3	
	20	13	21	8.0	48-34-31	122-59-23	48.7	.1	5	1.1	.2	
	20	14	7	34.1	47-24-33	122-40-33	24.0	.1	6	1.2	.2	
	20	23	58	12.5	47-23-38	122-40-13	20.5	.0	6	.9	.3	
	22	11	7	49.7	47-24-47	122-42-33	23.9	.2	10	1.4	.3	
	22	16	0	35.1	47-48- 8	122-22-43	16.5	.2	10	1.4	.4	
	23	23	41	39.6	47-47-55	122-47-48	20.0	.2	7	1.3	.5	
	25	6	26	32.7	47-24-13	122-42-43	24.0	.2	8	1.2	.5	
	26	5	15	37.9	48-20-49	122-43-50	51.9	.1	9	1.2	.2	
	26	6	51	4.1	47-30-18	121-39-33	18.9	.3	6	1.4	.1	
	26	11	3	5.4	47-51-54	122-43-41	9.8	0.0	4	.9	.6	
	27	4	48	11.1	48-24-24	122-32-35	24.9	.2	12	1.8	.4	
	27	8	51	26.9	46-55- 2	122- 0-16	8.0	.1	5	1.0	.5	
	27	13	28	6.0	47- 1-57	121-55- 5	12.7	.2	8	1.4	.4	
	28	8	14	26.5	47-24- 1	122-41-21	20.5	.0	5	1.1	.3	
	28	22	1	13.6	47-40-43	122-10-11	16.9	.2	6	1.1	.4	
	29	1	17	48.7	47-38-42	122-31-58	21.4	.1	7	.9	.1	
	29	3	51	3.1	48-31-56	122-51-56	57.9	.2	14	2.1	.3	
	29	12	16	38.5	48-11-52	122-45-31	23.6	.3	20	2.9	.3	*
	29	14	26	45.2	47-27-24	122-38-31	8.2	.1	5	1.2	.3	
	31	2	7	22.5	47-29-51	121-56-19	20.3	.2	11	1.3	.4	
	31	8	3	.1	47-24-57	122-42-48	23.8	.3	20	4.0	.1	*
APR	1	8	39	14.1	47-27-52	123- 0-22	43.6	.4	6	1.0	.4	
	1	9	37	48.6	48-19-58	122-35-21	22.0	.2	7	1.2	.4	
	2	22	18	34.6	47-32-51	122-54- 8	17.8	.3	20	2.2	.3	
	3	19	52	33.8	47-22-52	122-39-43	21.5	.2	6	1.2	.2	
	4	11	12	53.9	47-43-36	121-38-38	9.1	.2	9	1.5	.3	$
	6	6	8	32.4	47-25- 8	122-42-37	23.3	.2	12	1.8	.3	
	6	12	59	28.1	47-25-10	122-43-19	24.6	.2	9	1.8	.4	
	7	14	53	9.4	46-15-15	122-12-27	8.7	.2	9	1.5	.2	$
	8	20	36	22.6	48-43-11	121-59-59	2.7	.3	6	1.6	.3	$
	9	2	41	2.3	46-27-32	122-31- 9	20.2	.0	5	1.1	.3	
	9	15	46	35.6	47-40-32	121-34-31	7.4	.2	9	1.2	.4	
	10	19	43	26.7	46-57-31	121-58-30	6.6	.4	8	1.8	.3	
	14	11	59	56.9	48-47-57	122- 8-14	7.2	.3	7	1.9	.2	
	16	11	10	54.0	47-37-15	122-49-30	24.3	0.0	4	.7	.3	
	17	15	30	3.7	47-25-48	122-41-45	22.5	.1	5	.9	.3	
	18	10	33	51.1	47-23-44	122-40-56	19.4	.2	6	1.0	.3	
	19	3	32	37.8	47-25- 2	122-41-55	23.7	.1	6	1.2	.5	
	19	4	11	13.3	47-29-19	121-55-49	20.9	.2	6	1.1	.5	
	19	10	51	39.9	47-25-12	122-42-34	24.3	.2	10	1.3	.3	
	19	18	50	5.9	47-48- 6	122-54-26	6.6	.1	5	1.1	.4	
	20	23	41	33.8	48-31-39	122-43-15	26.9	.2	9	1.0	.4	
	22	7	42	.1	46-53-51	121-10-33	10.1	.1	6	1.6	.5	
	24	23	47	28.6	48-30-41	122-41- 8	20.3	.3	8	1.1	.3	

APPENDIX I—Continued

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG	
APR	25	8	46	49.0	47-53- 6	122-30-29	53.0	.2	13	1.5	.4	
	25	9	52	31.7	47-17-13	122-40- 1	23.6	.2	18	2.2	.4	
	25	15	28	59.0	48-47-27	122-21-54	2.3	.1	6	1.4	.3	$
	25	19	6	32.6	48-47-23	122-21-41	3.6	.2	6	1.3	.2	
	26	12	26	20.5	47-24-46	122-42-24	23.6	.1	8	1.2	.4	
	26	15	49	53.2	47-17-56	122-40-14	29.3	.2	8	1.2	.3	
	26	21	50	10.3	47-24-34	122-41-55	22.0	.1	6	.9	.1	
	26	22	0	18.6	48-38-51	123- 1- 1	15.9	.2	8	1.4	.3	
	27	2	14	51.8	47-17-38	122-39-53	23.3	.3	13	1.8	.4	
	28	9	6	40.4	47-25-22	122-42- 3	23.9	.1	9	1.1	.2	
	30	0	57	50.4	47-22-52	122-30-46	11.1	.4	6	.7	.3	
	30	19	16	9.4	48-31-54	122- 2-10	1.7	.3	6	1.7	.3	
MAY	1	0	20	55.4	47-52- 7	121-44- 7	20.9	.1	5	1.1	.3	
	1	20	46	14.1	47-24-50	122-42-22	22.1	.2	15	1.7	.2	
	2	13	28	27.7	47-24-22	122-41-10	22.2	.1	6	.5	.4	
	2	16	34	7.3	47-25-51	122-49-26	23.3	.3	16	1.9	.2	
	5	3	58	28.5	47-19-29	122-38-24	26.1	.2	11	1.6	.3	
	5	5	29	47.5	48-29-12	122-33-42	17.4	.4	19	2.3	.4	
	5	21	18	58.7	47-45-42	121-45-60	4.6	.3	18	2.3	.3	
	6	2	1	2.4	47-43-46	122-35-42	16.3	.1	5	.5	.4	
	6	9	44	50.4	47-32-11	122-23-42	19.3	.1	6	.6	.4	
	6	11	18	45.2	47-24-31	122-41-38	21.7	.1	5	.6	.4	
	7	5	23	44.9	47-19-50	122-37-59	22.3	.2	8	.7	.3	
	9	8	32	52.1	47-13- 2	121-38-53	1.0F	.3	5	1.2	.2	
	9	18	22	2.6	47-25-20	122-41-25	25.8	.1	12	2.0	.3	
	10	2	29	45.1	47- 9-42	123- 5-42	43.3	.3	19	2.7	.3	
	10	15	0	10.1	47-24-45	122-43-42	23.5	.2	10	1.5	.4	
	10	17	19	36.3	47- 2-19	122-12-20	5.5	.2	5	1.3	.4	$
	11	18	50	20.5	48-27-56	122-33-40	20.6	.3	10	1.4	.4	
	12	8	48	5.5	47-48-18	122-31-48	3.6	.1	5	.7	.5	
	13	11	59	18.5	47-38- 4	122- 3-11	13.8	.3	18	1.8	.4	
	14	4	1	11.1	47-46-19	121-58-57	27.6	.1	9	1.1	.2	
	15	19	21	50.9	47-24-14	122-41-34	20.5	.2	6	1.1	.4	
	16	14	52	6.0	47-54-36	121-54- 2	15.5	.2	14	1.8	.4	
	17	4	43	36.3	48-48-54	122- 8-11	4.8	.3	11	2.5	.2	
	18	18	50	19.9	47-53-53	122-36-33	7.4	.2	11	1.1	.3	
	20	14	6	15.0	48-19-39	122-11-25	7.4	.3	18	2.5	.3	
	21	9	41	53.9	48-53-18	122-50-33	15.8	.1	6	1.3	.5	
	24	14	2	4.7	48-39-56	123- 0- 9	19.1	.0	5	1.0	.4	
	24	19	55	58.5	48-12-11	122-44-42	21.0	0.0	4	.8	.2	
	24	22	38	30.1	47-35-56	122- 5-13	13.3	0.0	6	.7	.4	
	24	23	16	37.8	47-31-15	122-40-41	3.4	.2	5	1.1	.4	$
	25	3	43	38.8	47-56-50	121-46-19	11.1	.1	5	1.2	.3	
	26	8	47	51.4	48- 9-42	122-17-55	12.1	.2	9	1.0	.4	
	26	10	54	38.2	47-30-23	123-25- 3	6.6	0.0	4	.6	.1	
	26	15	46	55.2	48-19- 2	122-46-28	20.2	.4	11	1.5	.6	
	27	23	11	25.4	47-24-40	122-44- 6	39.2	.1	6	.8	.2	
	29	23	28	48.5	47-25-53	122-50-45	8.6	.3	5	1.0	.3	
	31	0	38	24.2	47-44-15	121-30- 2	11.6	.2	5	.9	.3	$
JUN	1	3	52	26.0	47-14-54	122-48-40	18.7	.1	6	.6	0.0	
	2	3	51	38.1	47-17-18	122-53-51	19.4	.2	8	1.2	.3	
	2	5	16	4.2	47-34-37	122-47- 0	14.7	.1	5	.8	.5	
	3	8	52	13.5	47-34-15	122-49-11	16.5	.2	6	.9	.5	
	3	12	12	37.9	47-32-39	122- 1-39	17.9	.1	11	1.1	.3	
	4	2	32	22.5	47- 4- 6	123- 0-42	39.9	.4	7	.7	.1	
	4	6	57	50.1	48-10-12	122-30-31	28.8	.1	8	.8	.3	
	4	8	37	16.9	47-24-44	122-42-31	23.2	.1	10	.8	.4	
	4	14	4	3.7	47-24- 3	122-40-52	20.7	.2	6	.7	.4	
	4	20	33	41.9	48-31-51	122-23- 5	15.3	.1	7	1.5	.4	
	5	3	44	24.9	48-31-44	122-23-21	16.8	0.0	4	.8	.1	

APPENDIX I—Continued

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG	
JUN	7	15	15	14.2	47-23-22	122- 5-50	15.3	.2	10	.9	.1	
	8	1	8	8.3	47-24-53	122-42- 3	22.6	.1	6	.8	.1	
	10	10	46	43.2	47-24-55	122-42-54	23.7	.1	9	1.1	.3	
	10	21	25	13.6	47-15-46	123-10-19	42.9	.3	13	1.9	.3	
	11	1	34	5.3	48-27-22	123-13-32	48.7	.1	7	1.5	.3	
	11	1	41	35.4	47-47-14	121-55-27	30.3	.1	5	1.1	.3	
	11	2	43	57.3	46-58-54	121-11-48	1.0F	.3	14	2.2	.4	
	11	2	49	11.0	47-47-56	121-46-28	9.2	.3	6	1.5	.2	
	11	3	18	47.9	47-36-10	121-49-53	6.7	.3	5	.9	0.0	
	11	15	55	8.1	46-38-15	122-36- 6	2.0	.2	11	1.5	0.0	
	12	15	57	32.9	46-58-60	121-13-22	1.0F	.3	9	2.2	.3	
	14	5	54	44.5	47-23- 4	122-48-24	31.5	0.0	4	.8	.3	
	16	3	3	31.0	47-19-31	121-58-11	22.3	.2	12	1.3	.3	
	18	0	53	4.3	48-25-27	122-29-19	28.2	.4	16	2.2	.3	
	20	8	45	24.8	47-45-52	122-27-44	21.2	.1	8	.8	.3	
	20	14	40	20.8	47-32-46	122-43-15	49.6	.2	16	3.3	.2	
	21	3	34	2.1	47-19-26	122-35-44	15.2	.3	6	.4	.2	
	22	5	49	16.0	48- 8-34	122-46-57	27.6	.1	5	.8	.4	
	22	7	51	27.1	47-24-43	122-42-19	22.2	.2	7	.9	.2	
	23	6	27	6.5	47-34- 3	122-22-30	23.4	.1	8	.9	.5	
	25	8	58	2.1	47-26-57	122-21-39	27.0	.2	7	1.0	.3	
	26	11	55	12.7	47-25-42	121-48-20	20.7	.2	8	1.1	.4	
	27	2	19	.3	46-56-15	121- 8-13	3.1	.2	14	3.4	.3	*
	27	13	48	36.4	48-14-22	122-22-37	23.2	.2	8	1.2	.2	
	28	13	20	8.7	47-31-28	122-35-12	23.0	.1	6	.8	.2	
	29	18	50	6.5	46-55-53	121-15-14	10.0F	.2	6	1.7	.2	$
JUL	1	3	55	16.6	48-28-41	123-34-43	16.1	0.0	4	.9	0.0	
	2	2	34	36.7	46-41- 7	122- 5-13	17.7	.2	9	1.6	.2	
	2	17	28	32.5	47-43-24	122- 1-10	22.8	.1	6	1.0	.3	
	3	14	35	15.5	47-42-48	122-14-53	21.6	.1	9	1.0	.2	
	4	13	27	54.4	47-26-10	121-55-14	25.3	.2	7	.8	.3	
	5	6	10	37.6	47-55- 9	121-57-12	20.0	.4	13	1.6	.3	
	7	0	5	53.0	48-30-55	123-12-44	32.7	.2	8	1.5	.4	
	8	3	47	46.3	46-51-10	121-54-51	9.6	.3	10	1.5	.4	
	8	11	1	50.5	47-19-52	122-37-41	22.2	.0	6	.9	.3	
	8	11	55	56.4	46-52- 3	121-56-43	4.7	.2	10	1.6	.3	
	8	15	54	50.1	47-45-60	122-32-48	19.3	.0	5	.4	.4	
	8	19	50	.9	46-51- 8	121-54-56	9.5	.4	10	1.3	.4	
	8	21	53	2.5	47-37-18	122-12- 8	25.1	.1	8	1.0	.5	
	9	6	12	43.1	47-24-51	122- 4-28	18.0	.2	14	1.4	.3	
	9	17	20	8.7	47-45-50	122- 7-41	20.6	.2	7	1.1	.1	
	13	5	25	43.8	48-29-53	123-14-22	9.1	.2	5	.9	.3	
	14	5	3	41.4	48-33-45	122-17-38	20.5	.2	9	1.5	.4	
	14	7	44	7.2	47-37-16	122-12- 7	27.6	.1	8	1.1	.4	
	15	2	57	1.2	47-37-16	122-11-49	25.2	.0	7	.9	.4	
	15	17	38	56.4	48-12-23	121-25-40	9.5	.2	5	1.5	.1	
	19	3	42	23.7	47-36-49	122-11- 5	26.3	.1	6	.7	.2	
	19	13	17	9.7	46-53-48	122- 0-10	11.4	.4	8	1.4	.2	
	19	14	11	58.3	48-18-11	122- 6-30	12.7	0.0	4	.8	.5	
	20	3	20	3.1	47-45-19	122-14- 9	20.9	.2	6	.9	.2	
	21	8	38	31.0	47- 9- 8	123- 7-19	17.4	.1	10	1.3	.1	
	21	8	38	51.9	47- 9-10	123- 7-34	16.9	.1	7	1.3	.3	
	21	18	40	15.7	48- 3-35	121-39-38	7.3	.2	5	1.2	.1	$
	22	0	1	18.1	48-44-23	122-57-50	20.5	.1	6	1.2	.3	
	23	5	47	45.7	48- 7-21	122-44- 1	27.7	.2	14	1.9	.3	
	23	19	14	56.1	46-50-53	122- 0-36	3.2	.3	13	1.6	.4	
	25	12	22	24.0	48-18-43	121-17- 5	16.8	.3	6	1.4	.4	
	28	4	56	54.4	46-21-10	123-26-53	13.3	.0	5	1.5	.1	
	29	5	13	34.3	47-52-47	122-36-39	17.2	.2	11	1.5	.3	
	29	6	42	41.8	48-49-45	122-27-19	1.5	.3	7	1.3	.2	

APPENDIX I—Continued

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG	
JUL	29	7	56	31.9	47-24-28	123-11- 8	40.9	.3	9	1.2	.3	
	30	6	12	1.0	47- 9-18	123-20-56	31.6	0.0	4	.8	.1	
AUG	2	18	6	53.9	47-29- 5	121-50-48	20.7	.2	11	1.5	.3	
	4	11	58	50.1	46-38- 0	122-36- 3	15.3	.1	10	1.6	.3	
	4	13	15	23.6	46-37-51	122-37-24	8.5	.3	9	.9	.2	
	5	22	19	59.2	47-47-13	122-46-56	8.9	.1	4	.6	.5	
	6	13	5	23.2	48-27-24	122-25-28	16.2	.2	11	1.4	.4	
	7	20	37	3.5	48-14-30	121-42- 8	17.1	.4	7	1.7	.5	
	8	16	19	6.1	48-12-36	122- 3-30	13.8	0.0	4	1.0	.2	
	9	1	49	6.5	47-44-44	122-22-51	20.7	.3	5	.8	.1	
	10	22	51	57.4	47-32-46	122- 1- 6	18.4	.1	10	1.1	.4	
	11	22	54	15.1	47-25-10	122-43- 5	23.3	.2	11	1.0	.3	
	11	22	55	5.9	47-25- 1	122-42-51	23.6	.2	14	1.6	.4	
	13	6	46	30.7	47-31-48	122-28-49	19.2	.1	15	1.7	.4	
	17	7	5	9.0	47-40- 8	121-31-23	8.7	.3	15	2.3	.2	
	17	14	58	24.8	47-47-46	122- 8-16	1.0F	.5	6	1.1	.4	
	19	1	51	18.3	48-39-34	123-35-15	53.9	.2	17	3.9	.2	*
	19	11	25	8.2	48-37-41	122-59-34	14.6	.2	7	1.2	.5	
	23	10	37	18.5	48-21-29	123-13-24	20.9	.4	17	3.6	.2	
	24	0	20	15.9	47-47-28	122-31-20	5.2	.1	5	.8	.2	
	26	10	11	59.4	48-48-39	121-19-10	1.3	.2	8	1.9	.2	
	26	17	39	42.9	48- 8-56	122-46- 3	25.5	.2	10	1.3	.2	
	27	0	59	28.6	47-45-15	122-33-53	21.6	.2	9	1.2	.3	
	28	2	17	11.3	47-37-26	122-57-30	46.9	.3	17	3.2	.4	
	28	2	51	10.8	48-17-21	122-34-44	23.6	.2	7	.7	.5	
	29	3	38	44.8	47-55-18	123-22-24	38.2	.2	5	1.2	.3	
	29	14	20	40.1	47-25-35	123- 5-38	5.9	.1	5	.9	.2	
	29	22	23	24.9	48-13-41	121-41-35	17.4	.2	6	1.4	.4	
	31	2	46	8.3	47-26- 8	123- 6-13	6.5	.1	8	1.6	.2	
	31	10	0	37.2	47-47-39	122-21-56	26.6	.1	8	1.4	.2	
SEP	3	5	45	.4	47-50-48	122-29-16	22.3	.1	14	2.1	.4	
	5	9	16	25.2	47-29-17	122-58-25	17.0	.2	6	.8	.3	
	5	13	17	46.8	47-35-17	122-48-45	20.3	.2	5	1.0	.2	
	6	8	51	40.7	47-25-10	122-42-47	23.4	.2	13	1.9	.4	
	8	5	57	32.6	47-41-44	122-32-16	5.9	0.0	4	.6	.2	
	9	1	48	11.1	48-29-22	123- 9- 3	36.8	.4	5	1.2	0.0	
	9	8	36	56.9	46-13-32	122-43-24	24.0	.2	9	1.4	.4	
	10	15	5	12.8	48-14-29	121-33-26	2.4	.0	5	1.2	.4	
	11	20	53	34.1	49- 0- 2	123- 5-23	14.6	.4	9	1.8	.1	
	12	22	3	10.7	47-35-14	121-44-17	8.3	.4	7	1.6	.4	
	14	1	31	4.1	47-35-35	123- 8-29	6.0	0.0	4	.6	.2	
	14	3	13	27.1	46-50-26	121-50-13	5.0	.1	5	.9	.2	
	15	16	49	26.8	47-20-29	122-20-19	14.2	.1	13	2.2	.2	
	16	15	11	23.8	47-19-39	122-19-14	17.3	.1	6	.8	.1	
	17	2	32	.6	48-52-41	122-20-26	21.0	.2	6	1.4	.4	
	18	15	52	11.8	47-25- 6	121-50-11	20.0	.1	6	1.0	.1	
	20	23	51	1.8	47-19-25	122-33-48	8.5	.2	12	1.4	.3	
	21	3	22	3.2	47-51-39	122-37-46	20.5	.1	5	.5	.3	
	21	3	36	15.1	47-30-29	122-50- 8	11.6	.2	5	1.0	.1	
	23	23	2	47.3	47-24-18	122-41-55	21.8	.1	6	.7	.2	
	24	19	57	32.8	47-42- 9	122-58-46	2.7	.2	5	.7	.1	$
	26	17	34	52.8	48-12-27	123-30-43	1.0F	.3	5	2.0	.2	
	27	12	34	18.5	48-15-57	123-11- 1	42.9	.2	15	2.2	.2	
	28	0	34	9.9	48-10-27	121-51-37	2.2	.1	4	1.1	.4	$
	29	9	27	55.8	47-42-50	122-16-38	21.3	.2	11	.7	.5	
	29	18	48	29.5	47-18-39	122-46-60	19.9	.2	7	.4	.2	
	29	18	52	14.4	47-15-26	122-47-24	21.8	.2	7	.7	.5	
	30	5	27	47.7	48- 7- 4	123- 3-41	27.3	.3	7	.8	.3	
	30	19	4	9.9	47-47-27	122-31-43	46.2	.2	6	.6	.2	
OCT	2	13	25	57.7	47-33-48	122-40-46	23.3	.0	5	.6	.5	

APPENDIX I—Continued

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG	
OCT	2	14	42	54.2	48-34-33	122-16-60	6.5	.3	6	1.0	.3	
	5	6	5	3.4	47-19-28	122-17-47	6.9	.1	5	.8	.4	
	6	4	55	42.5	47-39-34	122-14-57	27.1	.1	10	1.4	.2	
	6	8	55	46.5	47-22-30	122-15-54	2.7	.4	7	1.0	.3	
	6	17	54	34.0	47-41-47	121-57-50	21.5	.2	6	1.0	.3	
	8	10	26	34.5	47-31-15	122-51-18	22.7	.2	6	.5	.4	
	8	15	5	38.8	47-22- 6	122-21-41	12.1	.1	4	.7	.1	
	8	16	15	43.7	47-52-56	122-22-20	32.5	.3	12	1.4	.4	
	9	17	28	43.8	46-50-32	121-56-34	7.3	.4	9	1.5	.3	
	13	13	14	.9	48-35- 5	122-21-36	10.0F	.3	4	1.4	.4	
	14	9	16	33.4	47-45- 1	122-50-45	22.7	.0	5	1.3	.2	
	14	14	46	.7	47-12-13	122- 5-22	19.9	.2	7	1.3	.3	
	15	9	45	.1	47-24-51	121-50-14	20.7	.1	5	1.0	.4	
	16	13	33	55.5	46-57- 6	122- 6-45	4.3	.3	10	1.9	.3	
	16	20	13	36.0	47-19- 9	122-24-14	22.8	.2	10	1.6	.4	
	16	20	22	35.8	48-19-33	122-26-42	20.2	.2	8	1.3	.4	
	17	6	13	26.3	48-17-50	123- 9-29	41.7	.1	6	.8	.3	
	17	7	51	43.6	47-13-34	122-14-46	8.3	.2	14	1.6	.4	
	17	8	16	17.9	47-59-46	122-50- 2	50.1	.1	12	1.3	.3	
	17	19	24	51.6	47-50-59	123- 7-18	47.1	.1	6	1.0	.5	
	18	12	57	59.1	46-51-23	121-57-14	11.9	.2	7	1.1	.3	
	19	2	8	45.6	48-23-28	123- 4-14	20.3	.1	8	1.1	.3	
	19	13	1	7.8	47-34- 0	121-36-28	6.6	.2	5	.7	.2	
	22	16	25	18.5	47-32-54	122-20-47	22.7	.2	9	1.0	.4	
	25	11	6	15.8	46-27-46	122-18-10	23.5	.3	7	.9	0.0	
	26	5	28	13.4	48-11-10	122-57-55	23.7	.3	8	1.1	.3	
	26	13	30	17.3	48-47-25	122- 8-58	12.2	.2	5	1.4	.2	$
	27	12	39	50.2	46-51-10	121-55-59	3.6	.3	10	1.1	.5	
	27	13	16	34.5	47-24-16	122-23-20	17.5	.1	11	1.2	.1	
	28	15	25	18.9	47-51-49	122- 0-29	17.1	.0	5	1.4	.3	
NOV	2	1	59	39.1	47-49-33	122-43-22	22.0	.1	7	.8	.3	
	2	3	59	46.3	48-12-21	122-45-50	25.5	.2	11	1.9	.4	
	2	21	31	18.6	48-15-42	122-10-10	17.6	.1	6	1.5	.5	
	6	19	51	56.4	46-44-27	122-28-23	8.0	.2	11	1.9	.1	
	8	18	52	.9	47-30-37	122-35- 1	25.5	.2	8	1.2	.3	
	9	3	59	51.5	47-10-46	123- 1-24	31.7	.1	6	1.1	.2	
	12	0	27	56.4	47- 2-17	121-56-39	3.0	0.0	5	1.1	0.0	$
	12	20	23	59.0	48-33-12	122-15-38	.8	.3	5	1.1	.1	$
	14	10	10	10.2	47-42-56	122-14-29	23.7	.2	9	1.2	.4	
	15	5	27	41.2	47-31-18	122-28-26	17.9	.1	8	1.2	.2	
	17	15	55	30.8	48-18-19	122-27-16	52.5	.2	5	1.1	.2	
	21	3	29	16.8	46-53-28	121-56-51	11.4	.3	10	2.0	.2	
	21	5	21	17.3	47-28-47	122-56-42	14.1	.2	11	2.0	.1	
	24	17	53	31.0	46-59-44	121- 6-19	3.5	.3	11	1.9	.1	
	25	6	18	28.2	47-24-36	122-41-51	21.9	.2	6	1.0	.3	
	25	9	20	26.1	47-41-13	121-47-31	7.8	0.0	5	1.3	.4	
	28	12	47	58.6	47-50- 7	122-47-43	5.5	.2	6	.9	.4	
	29	2	16	1.8	49- 0-53	123- 6-46	13.0	.1	8	1.5	.2	
	30	11	24	37.9	47- 5-13	122-25-27	43.7	.4	9	1.2	.4	
DEC	1	1	35	15.9	47-30-49	122-34-26	25.6	.1	11	1.5	.4	
	1	7	42	42.7	47-23- 9	122-40-54	31.0	0.0	4	.4	.2	
	3	9	12	29.1	47-29-40	123- 1-18	15.6	.3	17	2.5	.2	
	3	13	52	48.9	47-44-26	122-18-26	25.4	.2	6	1.7	.1	
	6	0	42	27.6	47-24-38	122-41-60	23.9	.0	6	1.2	.3	
	6	5	33	44.2	47-16-19	122-16-22	18.3	.3	7	.7	.4	
	9	22	9	58.9	48-15-36	123- 8-34	48.6	.3	8	1.6	.2	
	13	4	5	27.4	47-49- 6	122-20-60	7.6	.1	7	1.0	.3	
	13	20	59	11.3	47-25-46	122-48-35	24.6	.1	9	1.3	.4	
	14	1	59	10.5	47-35-44	122-12-21	25.2	0.0	4	.9	.1	
	18	1	52	23.6	48-21-46	122-50-33	19.3	.4	8	1.6	.4	

APPENDIX I—Continued

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG	
DEC	18	12	19	38.4	46-55-28	123-21-53	10.0F	.4	4	1.4	.3	
	18	14	56	46.4	48-22- 5	122-50-60	18.3	.2	6	1.4	.2	
	23	7	59	19.5	46-38-22	122-22-39	10.6	.2	11	1.6	.3	
	28	12	18	58.3	47-18-36	123- 9-49	42.0	.3	19	3.4	.2	*
	29	8	41	34.4	48-15-57	122-32-49	23.8	.1	6	1.[illegible]	.4	
	31	3	23	40.6	47-35-25	121-50-39	19.9	.2	20	4.0	.3	*
	31	3	30	34.4	47-35-37	121-53- 5	18.8	.1	6	1.4	.4	

APPENDIX II

CATALOG OF EARTHQUAKES (1977)

Corrected Values

	DY	HR	MN	SEC	LAT N	LONG W	DEPTH	SD	NO	MAG	SDMAG
FEB	11	14	23	55.6	46- 5-44	122-43-53	2.2	.2	9	1.8	.2
AUG	6	9	13	28.2	46-10-25	122-11-48	6.6	.3	9	1.4	.1
	27	16	3	12.9	46-18-60	121-57-25	2.5	.2	6	1.3	.6
OCT	7	6	22	57.9	45-56-56	122-15-17	1.0F	.4	7	1.6	.2
	12	5	24	25.1	46-15- 4	122- 6-41	7.0	.1	6	1.0	.1
	15	4	24	7.2	48-14-35	123-47-43	49.3	.2	13	3.2	.1
NOV	13	14	58	39.3	46-45-58	122- 3- 5	2.1	.2	10	1.5	.3

APPENDIX D

The Magnitude 4.6 south Puget Sound earthquake of Mar. 11, 1978

THE MAGNITUDE 4.6
SOUTH PUGET SOUND EARTHQUAKE OF MARCH 11, 1978:
MAIN SHOCK AND AFTERSHOCKS

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On March 11, 1978, a magnitude 4.6 earthquake occurred 35 km southwest of Seattle at a depth of about 24 km beneath the Kitsap Peninsula, in the south-central Puget Sound basin (we define the Puget Sound basin to extend approximately from Olympia on the south to Port Townsend on the north and from Seattle on the east to the Hood Canal on the west). The earthquake was felt widely over the south-central basin but there were no reports of significant property damage. In the nine months following the March 11 earthquake, 44 aftershocks occurred in the immediate vicinity of the main shock. Only two of them had magnitudes greater than 2. The rate of aftershock occurrence decayed with time in approximately a 1/t fashion (Figure 1).

This sequence of earthquakes is noteworthy for two reasons. The main shock is the largest earthquake recorded in the south-central basin since 1970. It is also the first well-defined example of a classical main shock-aftershock sequence observed in the Puget Sound basin since the western Washington regional seismographic network began operation in 1970.

Epicenters for the years 1970-1977 in the region adjoining the immediate area of the 1978 sequence are shown in Figure 2. The distribution is generally diffuse, with only a few distinct areas of clustering. The hypocenter region of the March 11 earthquake had only a moderate amount of seismicity during the years 1970-1977.

We first located the earthquakes in this sequence with the velocity model and station corrections developed by Crosson (1976). The locations resulting from this initial analysis are summarized in Figures 3 and 4. Figure 3 is an epicenter map which suggests a fault plane striking N45°W. Figure 4a is a projection of the hypocenters onto a vertical plane striking N45°E. The alignment of hypocenters in this cross section supports the idea of a nearly vertical fault plane striking N45°W. Figure 4b is a projection of the hypocenters onto a vertical plane striking N45°W, at right angles to the plane of Figure 4a. This cross section indicates that the distribution of hypocenters dips to the northwest.

We constructed first motion projections for the main shock using both a constant gradient velocity model and the layered model used to locate the earthquakes. Polarity readings from the USGS network in the vicinity of Mount Hood were helpful in providing some additional constraint on the focal mechanism. The mechanisms obtained from the two different models are essentially identical, with conjugate fault planes striking N18°W and N78°E and dipping, respectively, 80° to the east and 60° to the south (Figure 5). Very similar focal mechanisms were obtained for the largest aftershock (M=4.0) and a composite of three smaller aftershocks. Thus, there is a discrepancy in orientation between the fault plane determined by the first motion projections and the fault plane suggested by epicentral and hypocentral alignments. This discrepancy may be due to several causes. The locations and/or fault planes may be influenced by the lateral heterogeneities which we know exist in the crust of this region. Another possibility is that poor location control in certain spatial directions may be influencing the locations and also indirectly influencing the focal mechanisms determined.

In an attempt to evaluate these effects we carried the analysis further by calculating error ellipsoids (Flinn, 1965) for each location to reveal directions in space along which relatively poor location control exists.

Figure 6 is a lower hemisphere stereographic plot of the three axes of each error ellipsoid. Twenty five (53%) of the earthquakes have error ellipsoids whose major axis to minor axis ratio is 3:1 or greater and whose intermediate to minor axis ratio stands as 1.5:1 or less. No ellipsoid had a major to minor axis ratio of less than 2:1. The axis orientations of these 25 ellipsoids are plotted in Figure 7. All the major axes in this group have plunges of 60° or greater. This reflects the fact that, in general, depth is the most poorly controlled hypocenter coordinate. The orientation of the minor and intermediate axes are seen to be rather evenly distributed in azimuth compared to the orientations of the major axes. The majority of minor and intermediate axes have plunges of less than 20°. Thus, the majority of the earthquakes have error ellipsoids which are considerably elongated, with their axis of elongation plunging steeply to the northwest and north-northwest. The lengths of the major axes range from about 1 km to 2.4 km. These probably represent lower limits on the true errors and in any event should be interpreted only in relative terms. The major axis errors are a significant fraction of the apparent spatial extent of the sequence. The results of this error analysis indicate that there is a true lack of control of hypocenters along the major axis directions indicated in Figure 7. The approximate direction of hypocenter alignment (as determined from Figures 3 and 4b) is also indicated in Figure 7 by the the solid square. We believe this direction is close enough to the average direction of elongation of the error ellipsoids that the hypocenter alignment could be at least partially the result of the relatively poor control of hypocenters parallel to that elongation.

In an effort to reduce the error of relative location, with the hope that we might be able to detect a spatial structure which was less likely to be a product of location error, we relocated the earthquakes using the master event technique (Evernden, 1969), as applied to tightly grouped local earthquake sequences. Residuals from a single well-located earthquake were used in the location procedure as station corrections. The main shock of March 11 was used as the master event. Figure 8 is an epicenter map of the solutions obtained with the master event technique. Comparison with Figure 3 shows that the epicenters have generally become more tightly grouped, suggesting that the source area is smaller than previously indicated. There is an apparent alignment of epicenters trending NNW, much closer to the NNW nodal plane of Figure 5. Figures 9a and 9b are projections of the master event hypocenters onto vertical planes striking N70°E and N20°W, respectively. Comparison of Figures 4a and 9a show that the vertical alignment of hypocenters is preserved. Comparison of Figures 4b and 9b also show that the distribution of hypocenters still seems to plunge in a linear alignment. A near-vertical fault plane trending north-northwest appears to be favored although the evidence is somewhat ambiguous, due to the small aftershock volume. Focal mechanisms for the master event locations, which are essentially identical to the initial mechanisms, are in accord with this conclusion. The identical nature of the initial and master event mechanisms is not suprising in light of the fact that the locations of most of the earthquakes were not changed by more than a kilometer or two.

We proceeded to calculate error ellipsoids for the master event solutions and plotted the three axes of each ellipsoid on a stereo net (Figure 10). Twenty two (49%) of the master event ellipsoids were significantly elongated, with major to minor axis ratios of 3:1 or greater and intermediate to minor axis ratios of 1.5:1 or less. As was the case with the initial solutions, no ellipsoid had a major to minor axis ratio of less than 2:1. The axes of these 22 ellipsoids are plotted on Figure 11. Once again, these ellipsoids have directions of elongation that plunge steeply (60° or greater) to the northwest and north-northwest. The other two axes of the ellipsoids are again distributed relatively evenly in azimuth with most plunging less than 20°. For the most part, the length of the major axes lie between .75 km and 1.5 km. These lengths should again be interpreted in relative terms. The approximate axis of hypocenter alignment (as determined from Figures 8 and 9b) is plotted as a solid square on Figure 11.

The alignment of epicenters and hypocenters obtained with the master event technique may well be a real feature of the spatial distribution of this sequence of earthquakes. Unfortunately, clear resolution of the problem for this case is not possible in view of the small source region and the fact that the alignment that does exist is close to but not exactly in the direction of poorest location control. It is difficult to determine how different the alignment and location control bias must be before alignment may be regarded as a real feature of the distribution. However the focal mechanism evidence, when combined with the spatial alignment provides a stronger indication of the true fault orientation than either does alone. It is clear that both error ellipse calculation and master event locations are extremely valuable when evaluating the spatial distribution of tightly clustered hypocenters.

There is no geologic evidence for any through-going fault in this region along which these earthquakes might have occurred. This is not suprising in view of their depth and the glacial overburden which obscures the basement structure in this region. If the spatial arrangement of hypocenters is real, the area of fault surface involved is approximately 12-15 km2 (roughly $2.5 \times 5 km^2$). For either choice of conjugate fault planes the dominant component of motion is strike slip. The axis of maximum compression (P) has an azimuth of 32° and a plunge of 14° to the northeast. Other shallow earthquakes (depth less than 30 km) in the Puget Sound region seem also to result from a roughly north-south compression of the crust (Crosson, 1972).

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Evernden, J.F. (1969). Identification of earthquakes and explosions by use of teleseismic data, J. Geophys. Res. 74, 3828-3856.

Flinn, E.A. (1965). Confidence regions and error determinations for seismic event location, Rev. Geophys. 3, 157-185.

CAPTIONS FOR FIGURES

Figure 1: Distribution of south Puget Sound sequence in time.

Figure 2: Epicenters in south Puget Sound for the years 1970-1977 (box contains area of 1978 sequence).

Figure 3: Map of initial epicenters of 1978 sequence.

Figure 4a: Projection of initial hypocenters onto a vertical plane striking N45°E.

Figure 4b: Projection of initial hypocenters onto a vertical plane striking N45°W.

Figure 5: Fault plane solutions for main shock using both linear and layered velocity models for the focal sphere projections (open circles = dilatation, closed circle = compression, P = axis of maximum compression, T = axis of maximum tension).

Figure 6: Lower hemisphere stereographic plot of the three principle axes of the error ellipsoids of all the initial hypocenter solutions. Solid square denotes direction of hypocenter alignment as determined from Figures 3 and 4b. All other solid figures denote two or more axes with essentially identical orientations.

Figure 7: Same as Figure 6 except that only initial ellipsoids with major to minor axis ratios of 3:1 or greater and intermediate to minor axis ratios of 1.5:1 or less are plotted. Symbols as in Figure 6.

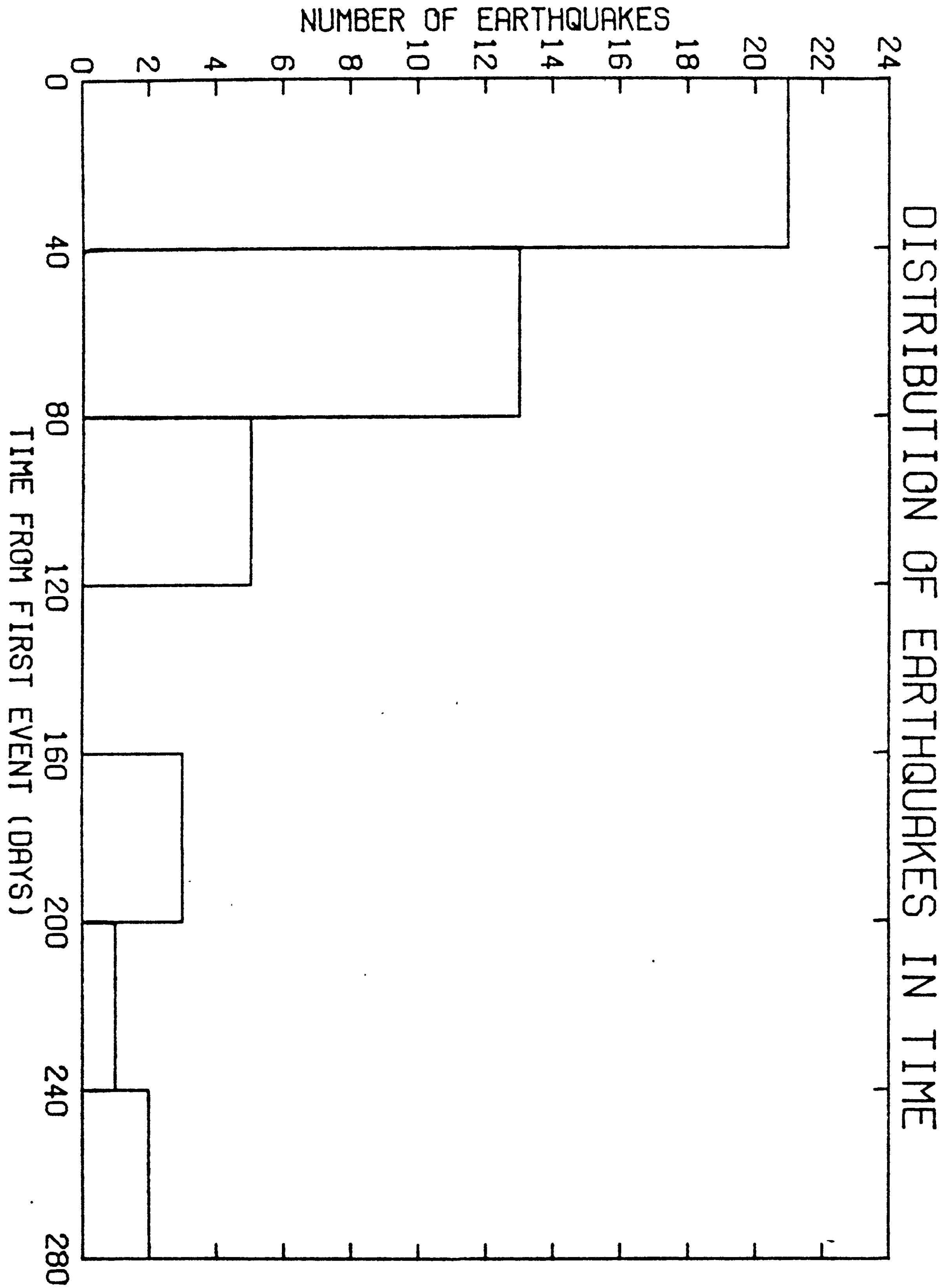
Figure 8: Map of master event epicenters.

Figure 9a: Projection of master event hypocenters onto a vertical plane striking N70°E.

Figure 9b: Projection of master event hypocenters onto a vertical plane striking N20°W.

Figure 10: Lower hemisphere stereographic plot of the three principle axes of the error ellipsoids of all the master event hypocenter solutions. Solid square denotes direction of hypocenter alignment as determined from Figures 8 and 9b. Other symbols as in Figure 6.

Figure 11: Same as Figure 10 except that only master event ellipsoids with major to minor axis ratios of 3:1 or greater and intermediate to minor axis ratios of 1.5:1 or less are plotted. Solid square as in Figure 10. Other symbols as in Figure 6.



DISTRIBUTION OF EARTHQUAKES IN TIME
NUMBER OF EARTHQUAKES
0
2
4
6
8
10
12
14
16
18
20
22
24
TIME FROM FIRST EVENT (DAYS)
0
40
80
120
160
200
240
280

FIGURE 1

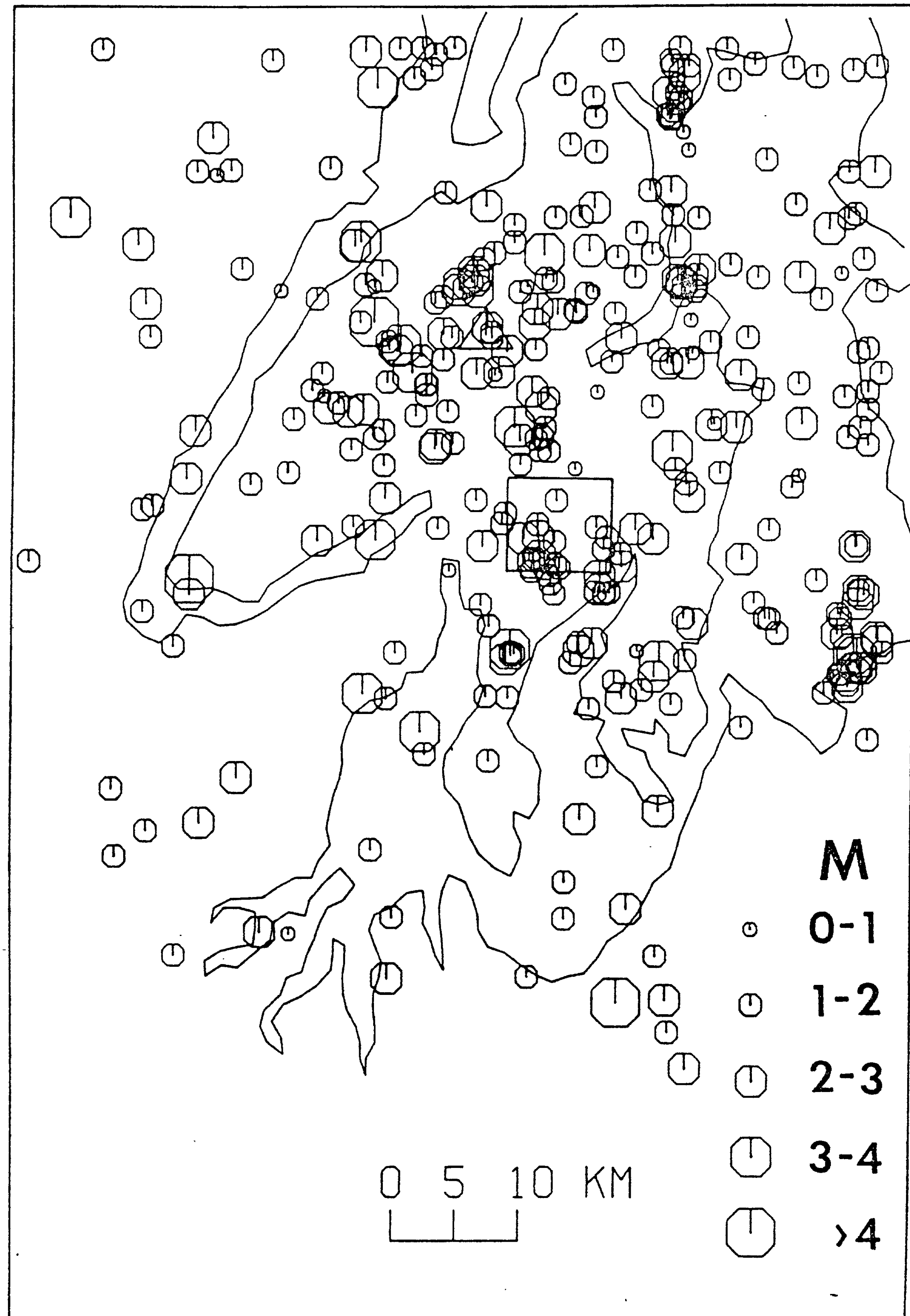


FIGURE 2

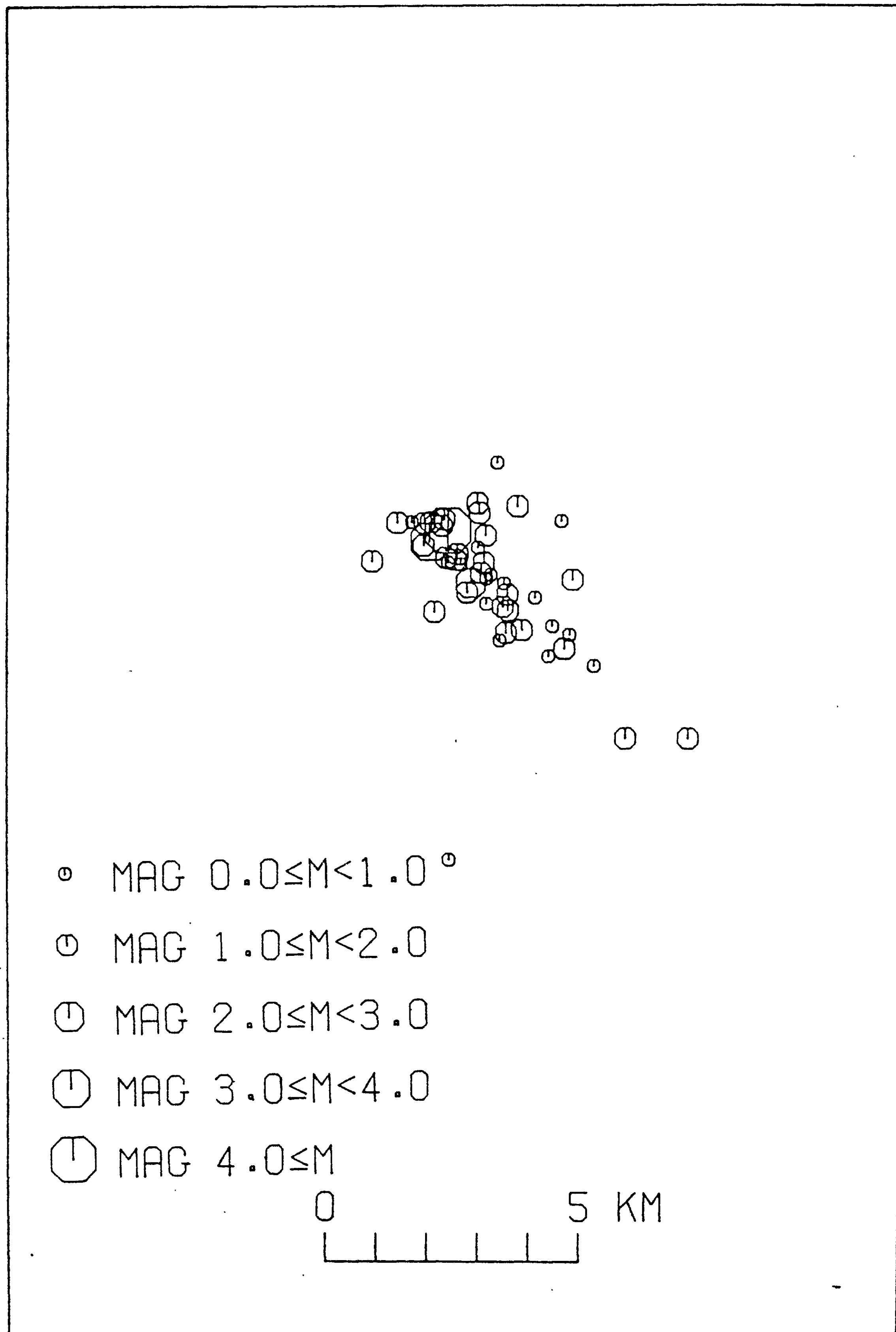


FIGURE 3

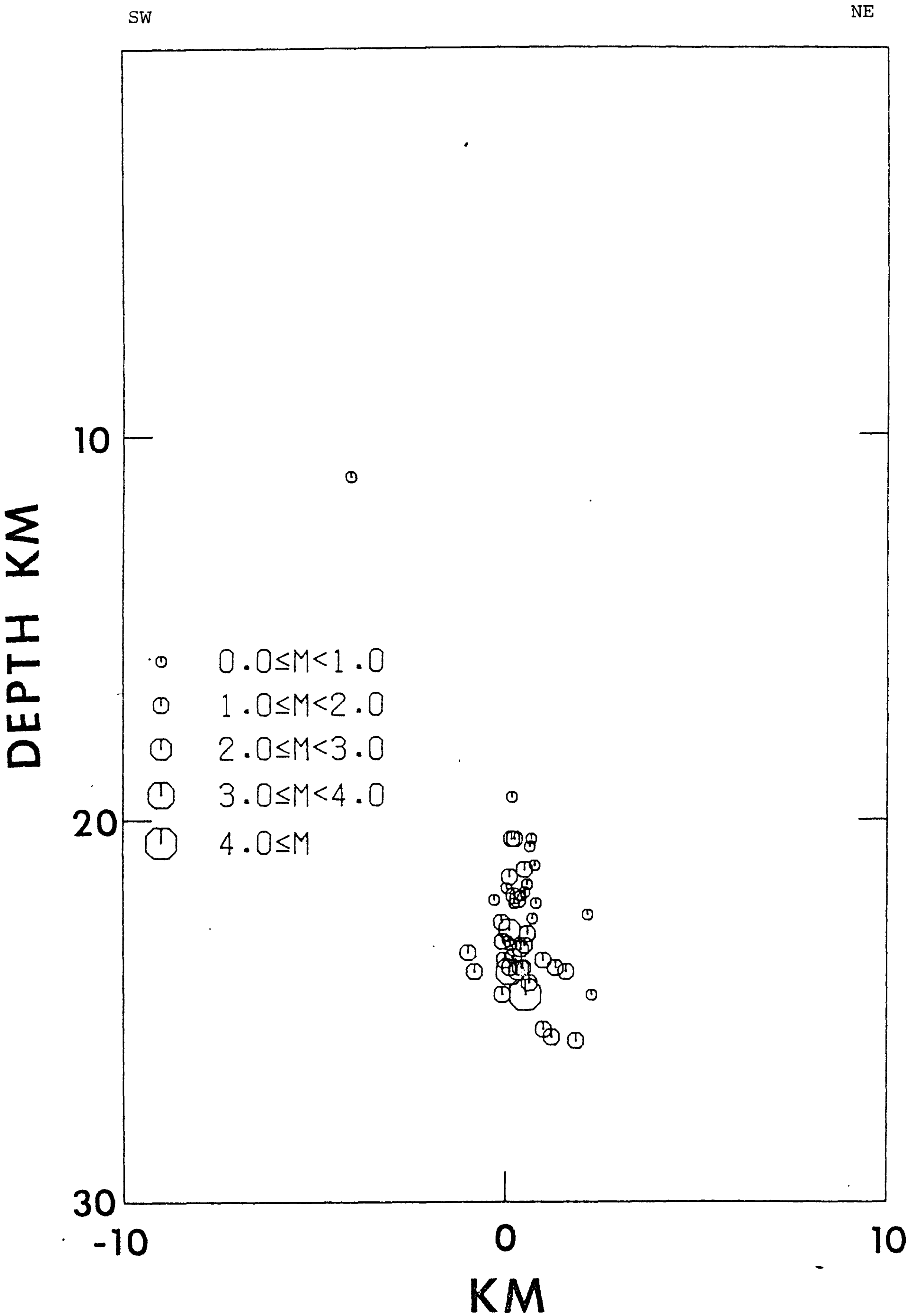


FIGURE 4A

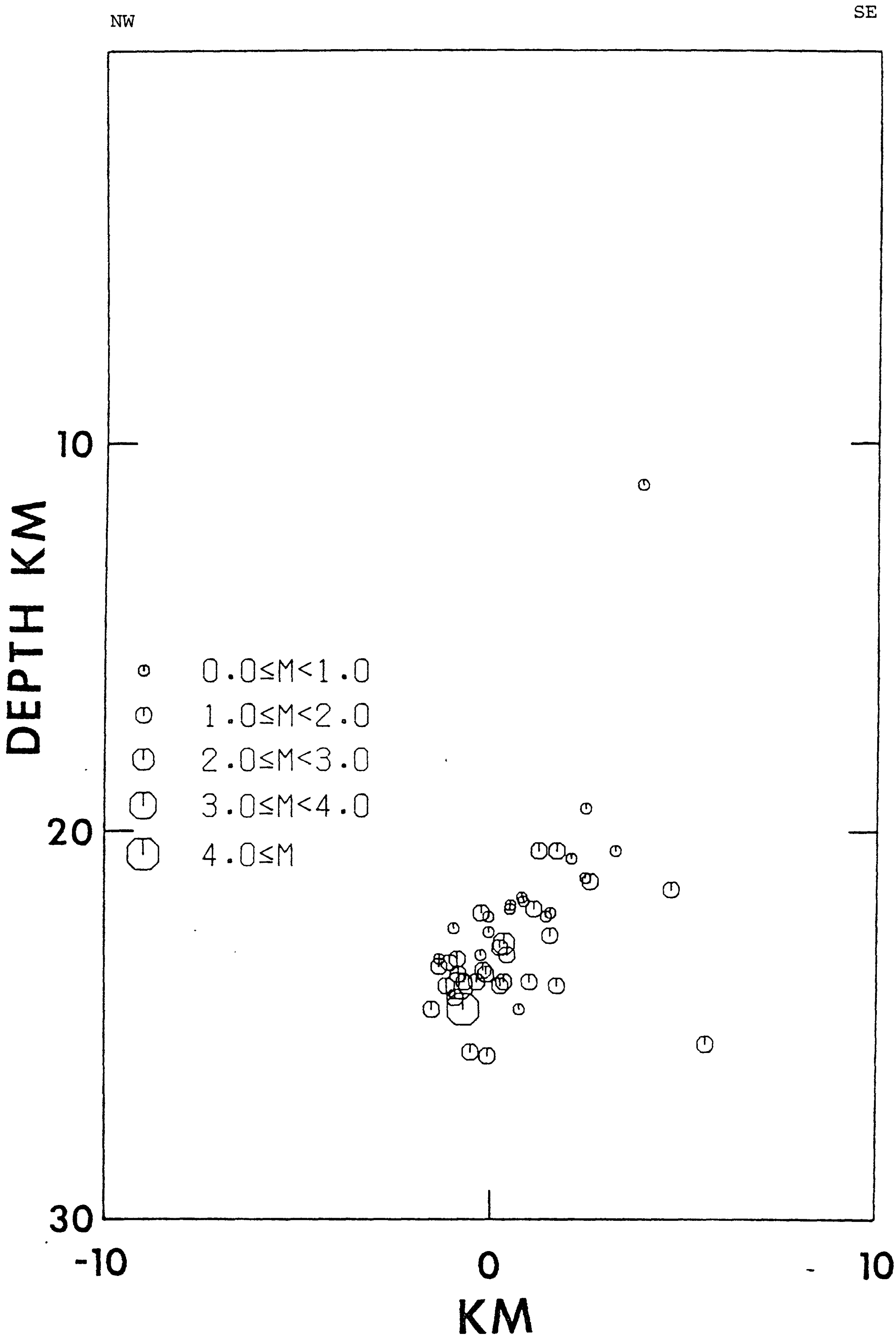


FIGURE 4B

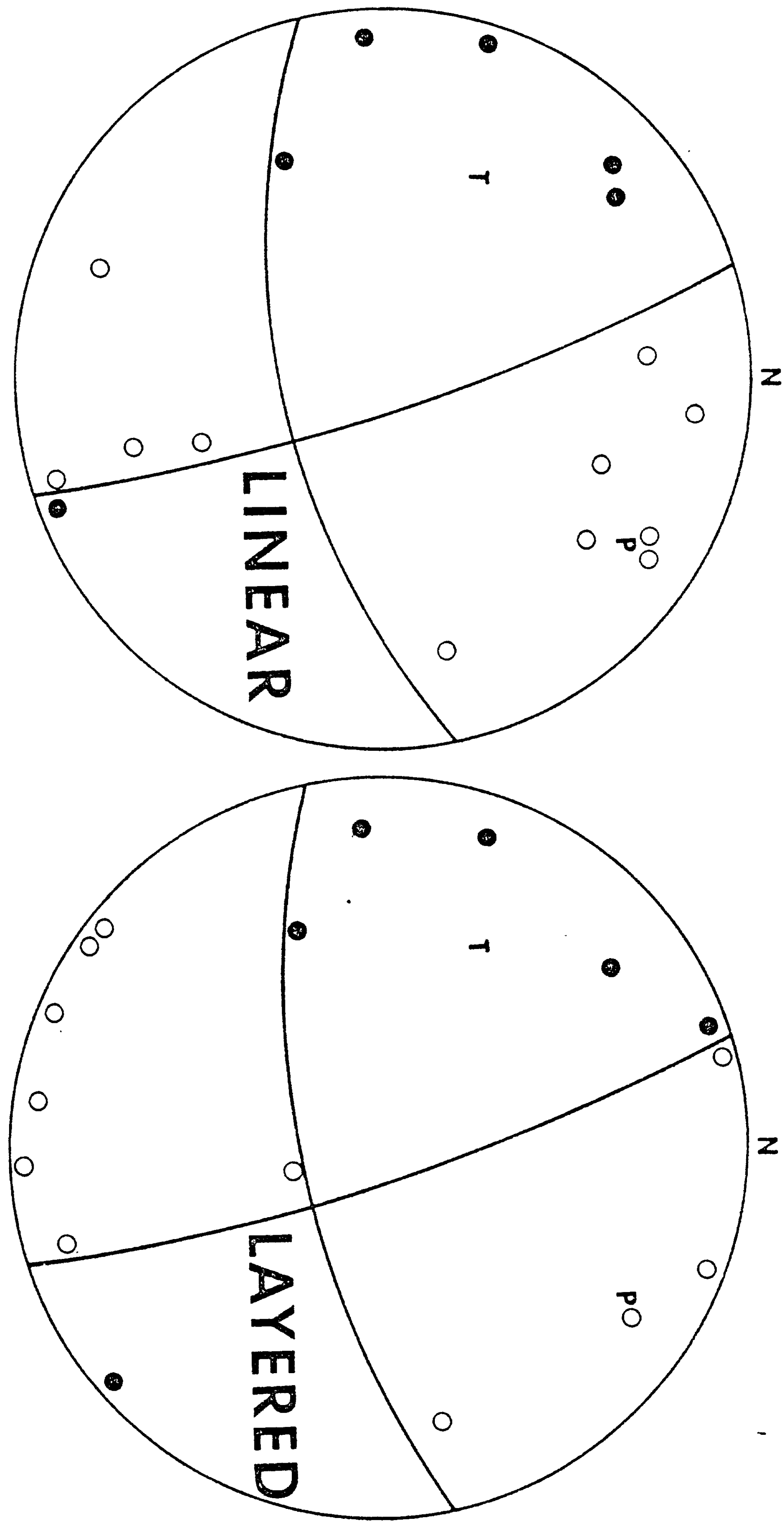


FIGURE 5

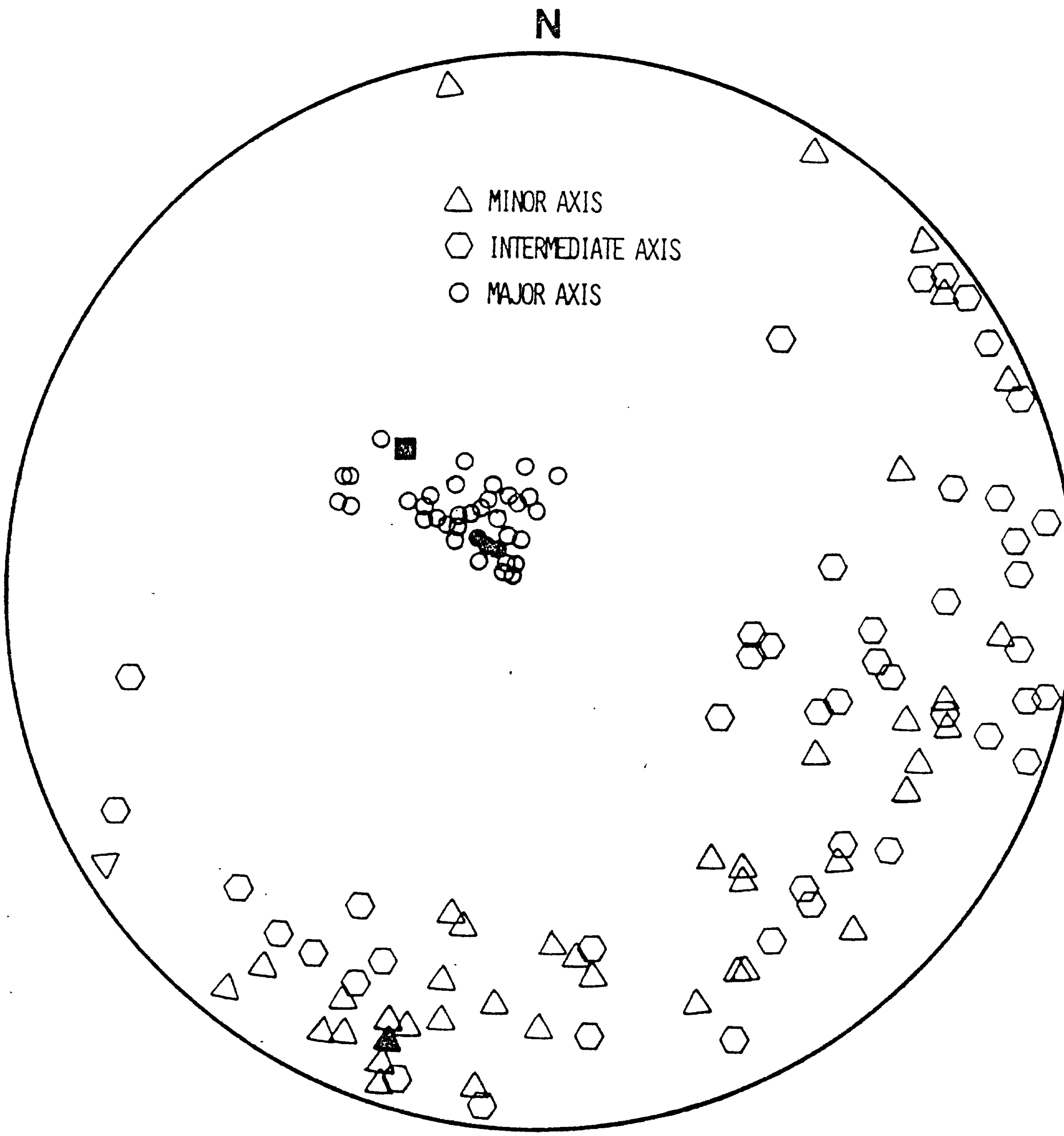


FIGURE 6

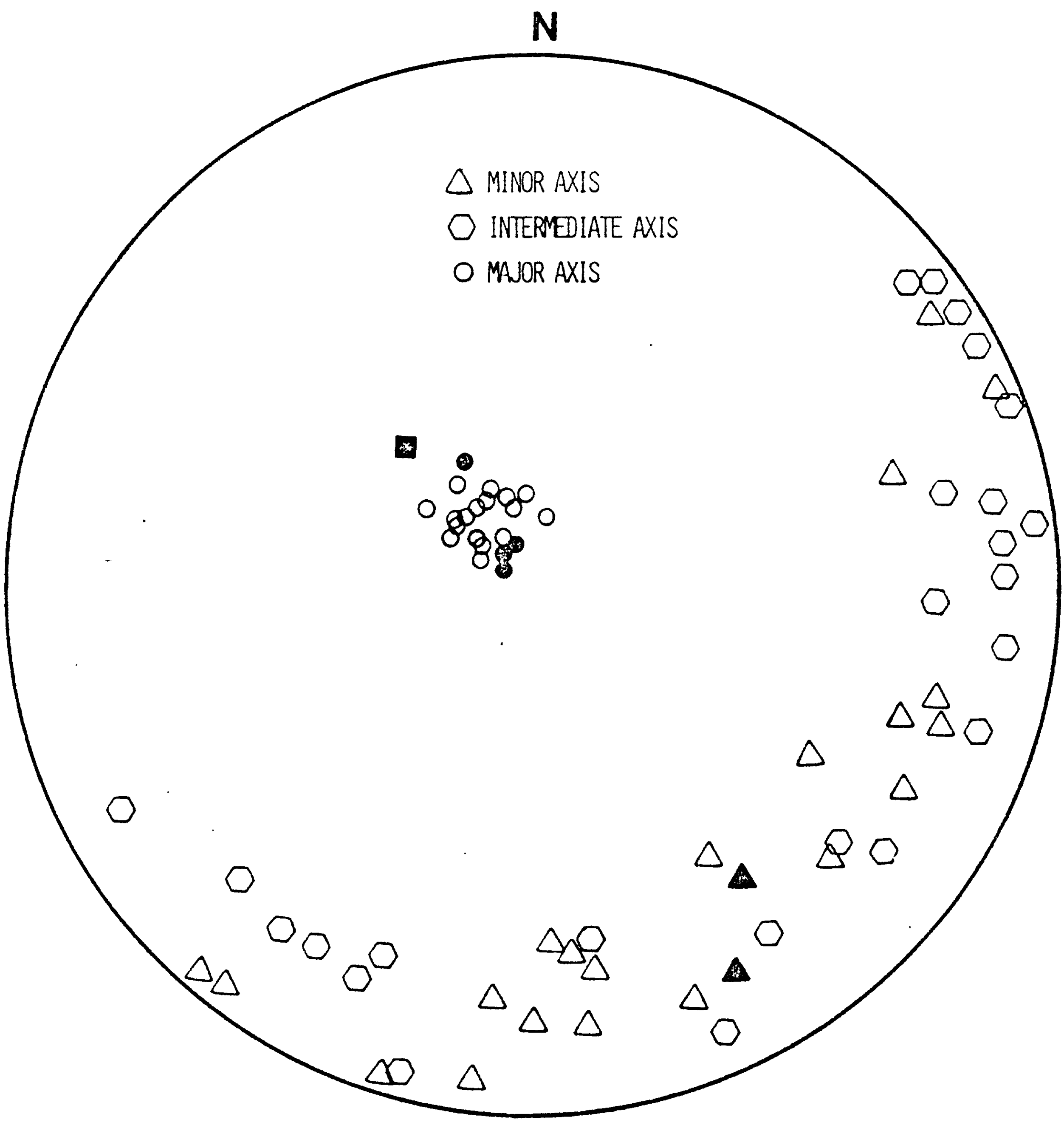


FIGURE 7

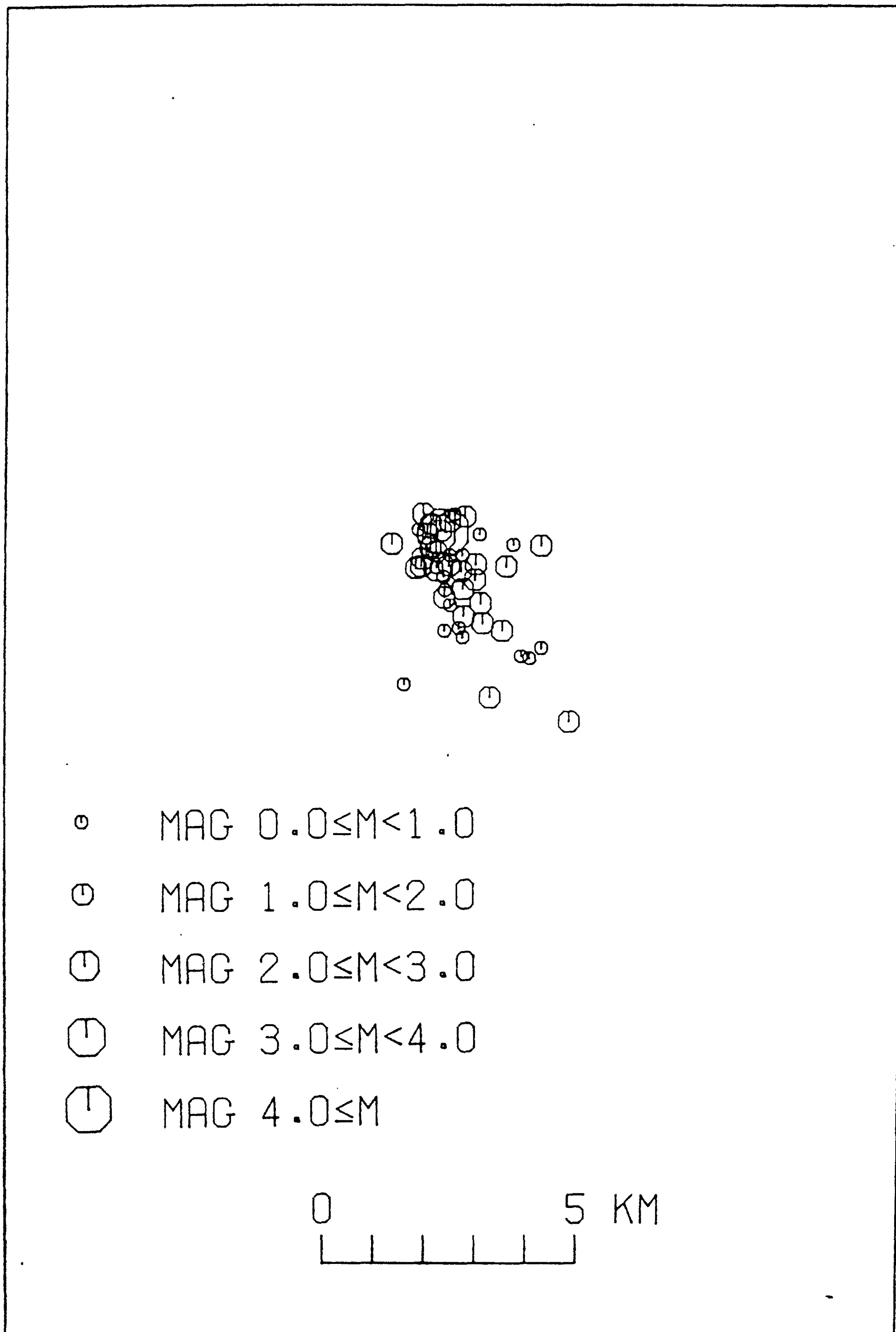


FIGURE 8

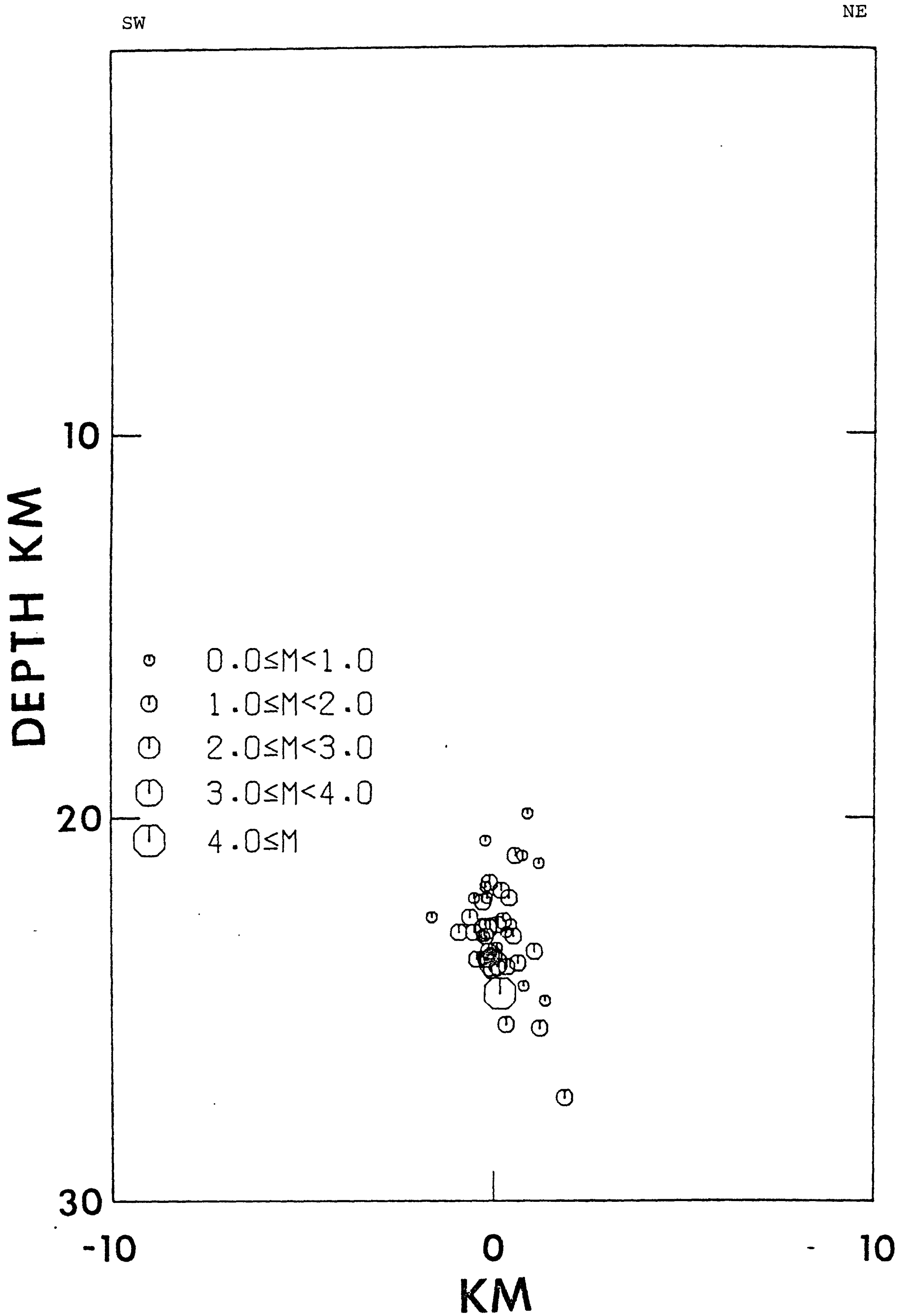


FIGURE 9A

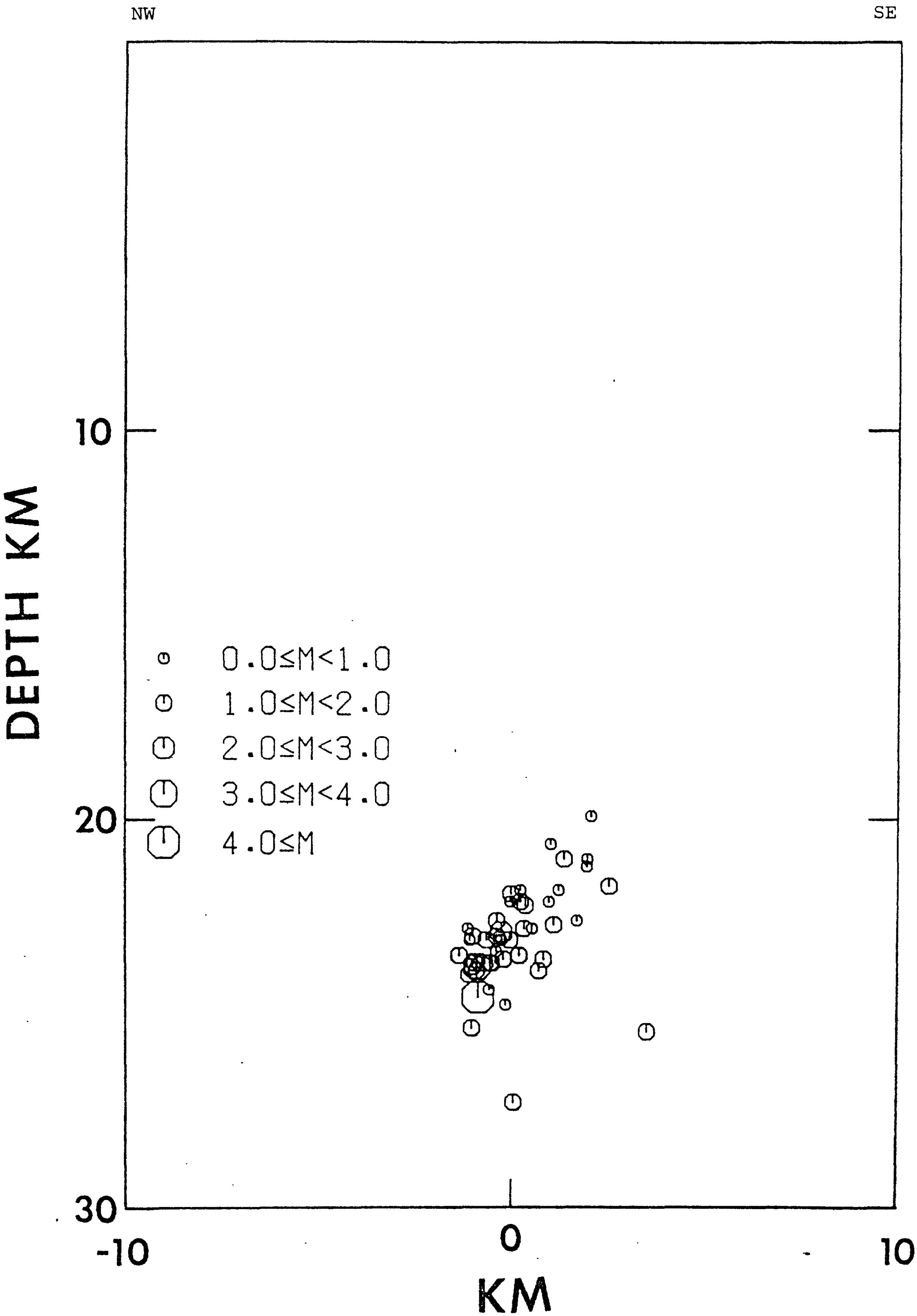


FIGURE 9B

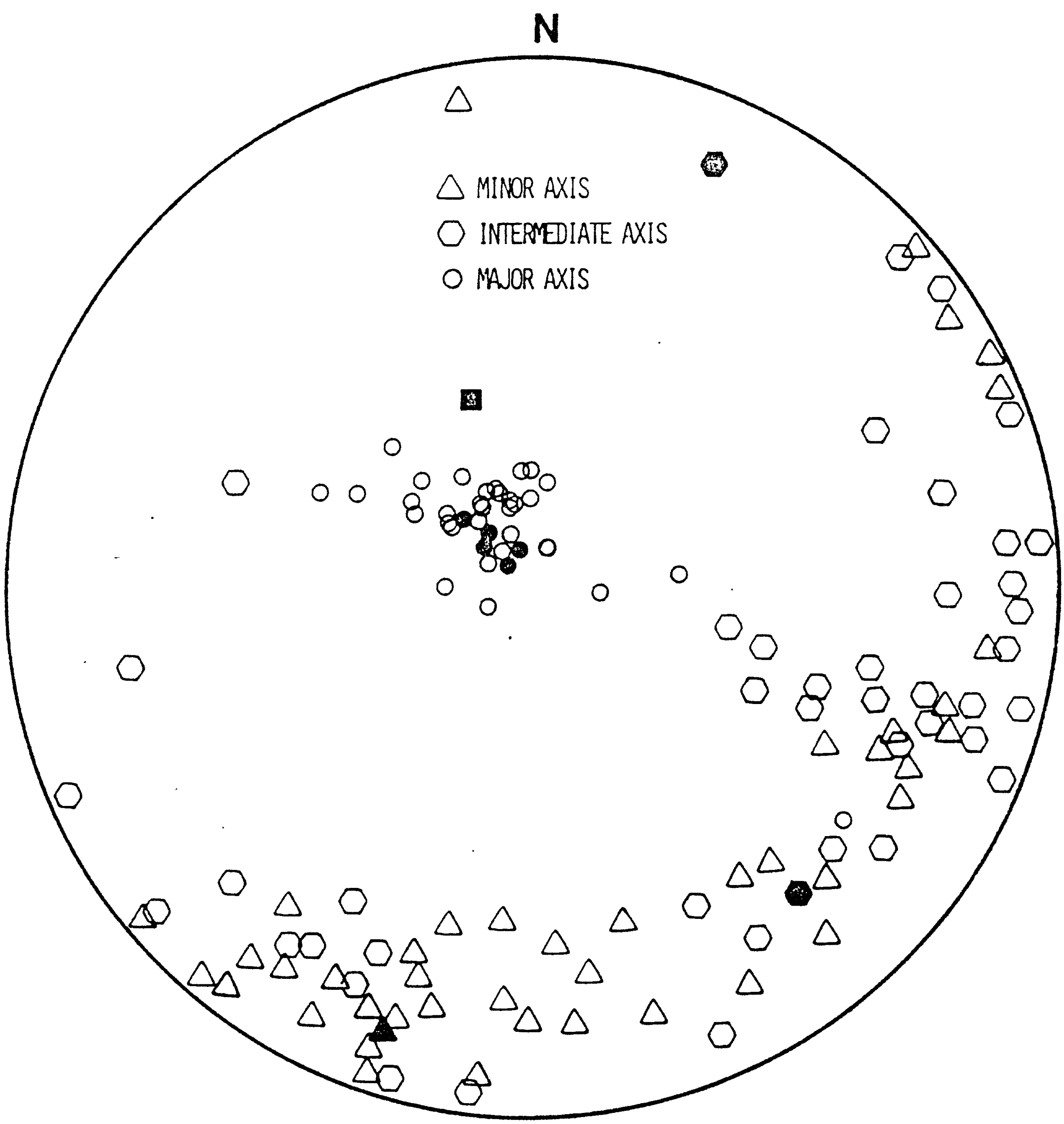


FIGURE 10

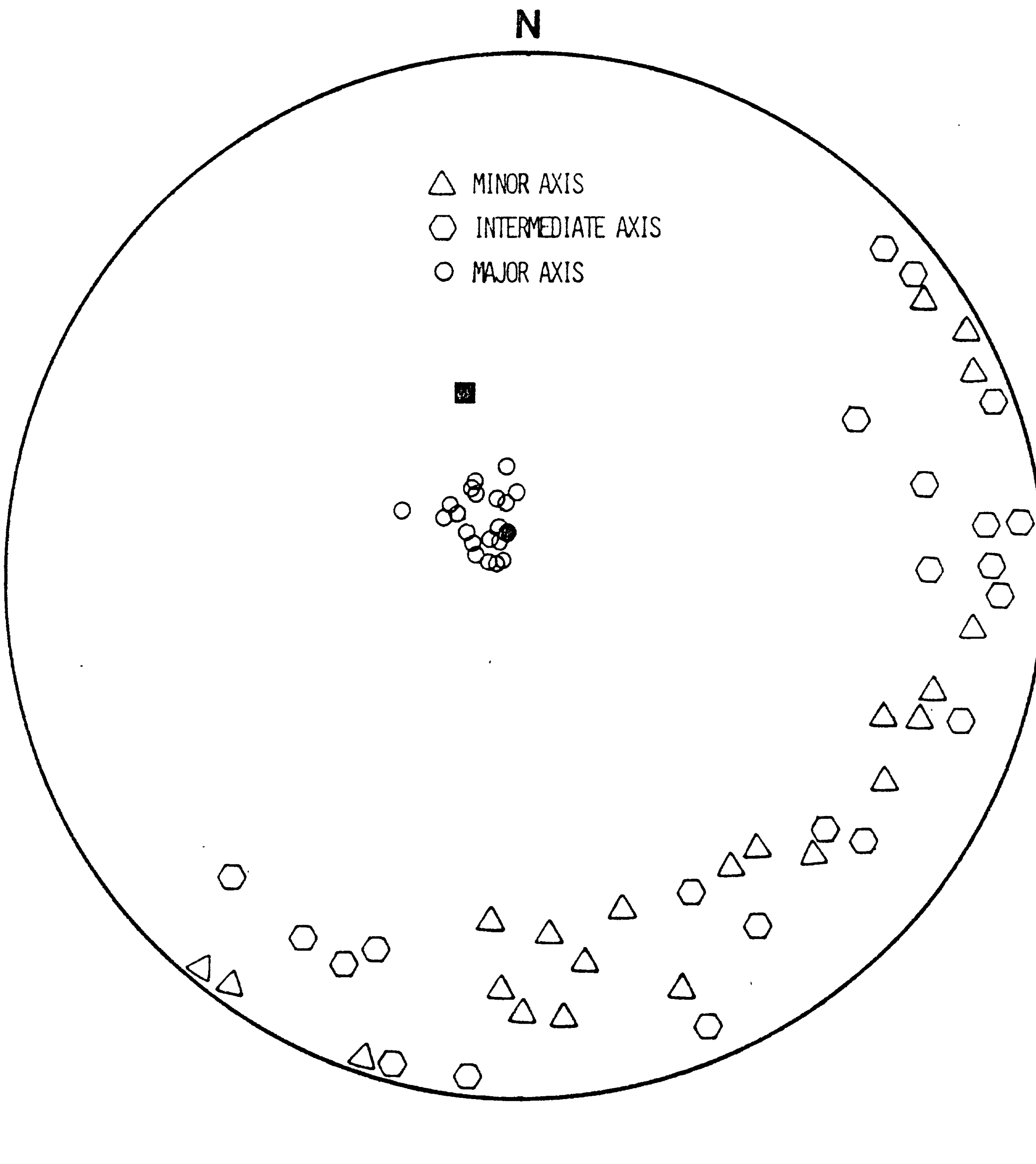


FIGURE 11

APPENDIX E

Reports and Publications

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