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INTRODUCTION AND SUMMARY

During the fiscal year 1978 the Eastern Washington seismic network has continued in operation in much the same configuration as the previous two years. Several minor changes have been made to improve its coverage and several new directions have been taken in routine data analysis and special projects. This report covers the results of our routine operations as well as several special research projects. The overall aim of this research is to provide a continuing data base of the seismicity of eastern Washington, to study the large scale structure and tectonic framework of the area, and to thereby address the genereal problem of earthquake hazards in eastern Washington.

This report is divided into several sections, each dealing with a specific research topic. Within several of the main sections there is a separate isolated section with its own page numbers and figures. These are individual papers written separately and either published separately or planned to be published separately but are included as part of this report since the work represented by them was partly or completely supported by this project.

Last year's annual technical report covered thoroughly the operation and data from the network since the University of Washington took it over in the summer of 1975. We refer the reader to that report for general operational descriptions and the catalog of earthquakes between July 1, 1975 and March 31, 1977. This year's report can be considered a continuation of last year's report updating some of the subjects in that report and introducing new topics that have begun this year. This report together with the quarterly technical reports provide a summary of the state of our research on the seismicity and seismic hazards in eastern Washington.

We first examine the operation of the regional network; changes and problems which involve the quality and quantity of basic data, the seismicity data obtained by the array, and how this year's seismicity differs from last year's. We also examine the seismicity of the state as a whole such that the relative level of activity in the Hanford area can be easily compared with other parts of the state. In the second section we look at earthquake magnitude calibration and attenuation of earthquake waves in eastern Washington. This is mostly a continuation of work begun last year but does include a paper presenting our work on state wide attenuation as revealed in intensity reports from larger earthquakes. The third section is on special detailed studies of localized seismicity. This section logically includes the Ph. D. dissertation by George Rothe on Wooded Island seismicity which is included as an addendum to this reprot. The fourth section is on our work using tilt meters and is the final report for this work. The last section discusses our initial work using digital recording for earthquakes in Washington. This section includes recordings in the Cascade Mountains, a brief recording of a small swarm in the Saddle Mountains and our testing of a down hole hydrophone system for use in deep bore holes.

I. OPERATIONS AND SEISMICITY

Array Operations. The routine operations of the network have gone very much as in the past several years. Minor changes have been made in some station locations and several new stations have been added. As mentioned in last year's report several new stations have been added in the Cascade Mountains including WTP, PLN, ETT, and RPW in the north. We feel these stations reduce our location threshold to less than magnitude 2.0 for events in the northern Cascades. In the south we added a local recording station at Goldendale (GLD) and moved the Hermiston station to a new and more sensitive location (IRG). A digital event recorder has been established near Ellensburg in the central Cascades and several temporary event recorders have been operated in this area from time to time. Problems with the event recorders have limited their usefulness to less than we had hoped. The quality of the data coming from them when they do work helps make up for the problems we have experienced. We hope that most of the problems have now been solved and we can continue obtaining high quality data from them. Table I gives the pertinent data about all the seismic stations that have been in the eastern Washington network. We include in this table the period for which the station has been operating.

Several problems have plagued the routine operation but none has been serious enough to cause significant degradation of the data. Electrical noise from new power lines required the relocation of the Wahluke (WAH) station about a kilometer to the east (WA2). Radio interference from a new weather station on Gable Butte continues to cause interference on several of the stations on that telemetry link. We have been trying to solve this problem for the past few months and have been given assurance that the radio in question will be fixed.

We are presently anticipating a minor extension of the network to cover areas which need monitoring in light of recent discussions with various concerned agencies. We feel that several permanent stations in the southern Cascades would improve the coverage in this part of the state. Because telephone telemetry channels come with eight slots available for seismic data, and they are quite expensive to lease for long distances, we have delayed moving in this direction until better recording facilities were available. With only a few spare channels available on our develecorders we have no place to record another telephone line full of data, and the cost of operating a phone line for only a few stations is discouraging our doing that. We anticipate receiving a new recording system in about six months which will have enough space for many more stations. When this new system is definitely on the way we plan to begin expanding with several new stations to broaden our coverage.

Seismicity. Before discussing the seismicity of eastern Washington an overview of the seismicity of the entire state is useful. Since 1969 at least small seismic networks have been operating in both eastern and western Washington. At first there were less than a dozen stations in each local array but both arrays grew at about the same rate until there are over 50 stations in the entire state for which we now get seismic data. During the past eight years the location threshold of each array has improved until now most earthquakes in the state larger than magnitude 2.0 are located. In some areas the location threshold is less than magnitude 1.0 and occasionally earthquakes with a magnitude less than zero are locatable.

To remove the obvious bias which exists when all located earthquakes are plotted on one map due to the variable density of seismic stations, we limit the epicenters plotted in Figure I-1 to well located events larger than M_L = 2.5. This map represents a uniform cutoff by magnitude and should be little biased by station configuration. We feel that it represents the general seismicity of the state. Note that the majority of the activity is in the Puget Sound area where, of course, most of the felt and damaging earthquakes have occurred. (See Figure 1 in the paper in section II). There is also a group of events in the southern Lake Chelan area where likewise there have been numerous felt earthquakes. The central Columbia basin (Hanford area) has a scattering of events mostly in the Saddle Mountains area. The Cascade Mountains is relatively quiet with the exception of a group of earthquakes in the Cle Elum area most of which occurred in the last year and a half.

The seismicity of eastern Washington has been discussed in some detail in previous reports. We will now only deal with those aspects of the seismicity which are new in this reporting period. First we discuss a missing set of data from the first part of 1975.

First half of 1975. The U.S. Geological Survey operated the network from its beginning in 1969 to July, 1975 and they must be contacted for the catalog from the beginning until December 31, 1974. The first 6 months of 1975 were recorded by the U.S.G.S. but the University of Washington has been responsible for locating the earthquakes during that period. Because of problems interpreting the data we have not reported final locations for this period as of yet. The data from this period has now been reinterpreted and new locations and magnitudes computed. Table II is a catalog of the earthquakes during the first half of 1975 and should be included with the catalog reported in last year's annual report. Figure I-2 is an epicentral plot of the data for this period. Note that most of the earthquakes are in the Wooded Island area. This corresponds to the first part of a large swarm that occurred there during the summer of 1975. More than 70 earthquakes are located in the black blob just to the west of the station lable "I". Because of resolution problems with the map plotting routine these events appear to be quite a bit to the west of the river when, in fact, they are located almost under it. A special study using the U. of W. portale array was run on this swarm which is covered in another part of this report. There were two felt earthquakes during this period: a M_L = 3.1 on June 15, 1975 near the Tri-cities and a M_L = 3.8 in the Horse Heaven Hills on June 28, 1975.

Quarterly Technical Report 78-B. The technical report for the second quarter of 1978 is being included in this annual report since the reporting periods come out at the same time. The details of special research and operations are covered in other parts of this report. In this section we describe the seismicity for the past three months, give the epicenter plot Figure I-3 and catalog Table III for this period. The stations that have been operating this quarter can be determined from Table I.

The earthquake activity during this quarter is dramatically higher than during the past few years. The activity began last quarter with a swarm in the Corfu area just north of the Saddle Mountains. (See technical report 78-A) This activity has continued into this quarter and spread to other swarms. Over 50 earthquakes have been located in 4 distinct swarms along the north flank of the Saddle Mountains. One of these is only about 4 km. from the swarm that started last quarter. Over 100 other earthquakes in this area were detected but were too small to be located (less than $M_L = 0.5$). Each swarm is characterized by several bursts of activity in which 10 or more events will occur in a day and then there will be several days of quiet. We have begun studying these swarms using digital event recorders to improve the quality of the records. A preliminary discussion of this work is covered in another part of this report.

In addition to the Saddle Mountain swarms, activity continues as normal in the Lake Chelan area including one shallow earthquake with a magnitude of $M_L = 3.3$ just north of Entiat. This event should have been felt, but we are aware of no felt reports. There were also two earthquakes larger than magnitude 3.0 in the Cle Elum area. On June 26 a $M_L = 3.7$ event occurred near the Naches River south of Cle Elum. This event was lightly felt in the town of Naches, and is covered in more detail later in this report.

Figure I-4 shows an epicenter plot for all of fiscal 1978. The areas of outstanding seismicity are those just mentioned above, namely the Saddle Mountain swarms, the Lake Chelan-Entiat group and Cle Elum group which includes two felt earthquakes and their related shocks or aftershocks. This year's activity is greater than that of last year both in number of earthquakes and the size. We feel that rather than this year being unusually active, last year was unusually quiet. The activity near Cle Elum is unusual, however. While our location ability in this area has improved with the addition of several stations we do not think the new activity in this area is solely due to this effect. Even without the new stations we would have located most of these earthquakes; certainly the felt ones would have been known about. The new stations in this area simply improve the accuracy of our locations.

TABLE I. Eastern Washington Seismograph Stations

Station	Lat (N)	Long (W)	Elevation (M)	South Delay	North Delay	Operating Period
MDW	46 36.80	119 45.65	330	.00	.53	7/75-
SYR	46 51.78	119 37.07	260	.00	.47	7/75-
OTH	46 44.34	119 12.99	260	.00	.39	7/75-
WAH	46 45.12	119 34.68	230	.00	.55	7/75-5/78
WA2	46 45.40	119 33.76	230	.00	.55	5/78-
CRF	46 49.51	119 23. 09	260	.00	.47	7/75-
GBL	46 35.86	119 27.59	360	.00	.57	7/75-
ETP	46 27.89	119 3.54	250	.00	.30	7/75-
BDG	46 14.08	119 19.05	410	.00	.48	7/75-
EUK	46 23.75	118 33.72	400	-.10	.26	7/75-
PRO	46 12.76	119 41.15	600	.00	.54	7/75-
RSW	46 23.47	119 35.32	1130	.00	.62	7/75-
PEN	45 36.72	118 45.77	460	-.15	.18	7/75-
WGW	46 2.68	118 55.96	160	.00	.35	7/75-
WIW	46 25.93	119 17.29	130	.00	.55	7/75-
HER	45 50.14	119 22.85	190	.00	.47	7/75-11/77
IRG	45 53.15	119 29.92	200	.00	.47	11/77-
MFW	45 54.18	118 24.35	430	-.15	.18	7/75-
OMK	48 28.82	119 33.65	450	-.12	.23	7/75-
DYH	47 57.63	119 46.16	900	-.20	.07	7/75-
WBW	48 1.07	119 8.23	910	-.22	.11	7/75-
SAW	47 42.10	119 24.06	800	-.25	.06	7/75-
CBW	47 48.42	120 1.96	1290	-.30	.00	7/75-
FPW	47 58.00	120 12.77	360	-.30	.00	7/75-
PLN	47 47.08	120 37.97	670	.00	.00	6/77-
ETT	47 39.30	120 17.60	930	.00	.09	6/77-
WEN	47 31.77	120 11.65	1140	-.30	.00	7/75-
EPH	47 21.13	119 35.77	500	-.14	.20	7/75-
ODS	47 18.40	118 44.70	610	-.20	.11	7/75-
DAV	47 38.30	118 13.56	780	-.20	.11	7/75-
WRD	46 58.19	119 8.60	410	-.05	.35	7/75-
WAT	47 41.92	119 57.25	900	-.25	.04	11/76-
ENT	47 40.73	120 13.80	860	-.24	.07	11/76-6/77
VTG	46 57.48	119 59.24	210	.00	.28	7/75-
COL	48 35.60	117 52.92	810	.00	.00	7/75-4/77
NEW	48 15.83	117 7.22	830	.00	.00	5/77-
FMC	45 37.47	120 1.70	300	-.20	.00	1/77-
RPK	45 45.70	120 13.83	330	-.20	.00	1/77-
ALD	45 49.17	120 4.00	290	-.20	.00	1/77-
RPW	48 26.90	121 30.82	850	-.20	.00	8/77-
GLD	45 50.33	120 48.85	700	.00	.00	11/77-
EBW	47 00.25	120 40.47	830	.00	.00	12/77-

II MAGNITUDE-ATTENUATION STUDIES

Over the past several years we have been studying the regional attenuation properties in Eastern Washington and how these might affect the calculation of local magnitude. This is also an appropriate study for the estimation of future strong ground motion. During this year three separate studies have continued related to this general topic. First we are continuing to use a Standard Wood-Anderson seismograph for calibrating our local coda length magnitude relation. Second we have completed the Lake Chelan area attenuation (Q) study and include as part of this report a master's thesis on this subject. We have also studied state wide attenuation patterns using intensity data from large historic earthquakes. This study is included in this report as a preprint for a paper we will be submitting for formal publication in the near future.

Wood-Anderson-Coda Length Magnitude Study. During 1977 we located our Wood-Anderson instruments at Entiat, Washington, 47° 40' 17" N, 120° 13' 24" W. We recorded twelve local earthquakes, at Entiat, large enough for a Richter magnitude to be computed. All but two shocks occurred less than 15 kilometers from our station location, creating a problem in computing a magnitude. The problem being that near earthquakes have a large variation in their radiation pattern for any given radius, depending on direction.

We are currently recording our two Wood-Anderson seismometers at Richland, Washington, 46° 20' 50" N, 119° 16' 28" W, and will continue recording through 1978. We are presently picking the Richland records, but the results appear disappointing because of the few recorded earthquakes.

In March, 1978, a trip was made to Newport, Washington in order to pick all the Newport Wood-Anderson seismograms recording local earthquakes in Eastern Washington since July, 1975. Forty-four local shocks were found for magnitude determination. All the Newport data has been converted to Richter magnitude.

We are presently rescanning the coda-lengths from our Eastern Washington seismograph networks for the forty-four earthquakes that were picked from the Newport Wood-Anderson records, if a coda length magnitude was computed using less than five coda-lengths. This is being done because it was found that coda length can vary from station to station, for the same earthquake, up to about 60%.

No conclusions will be drawn until all the data has been analyzed. Table IV shows the preliminarydata comparison between coda-length magnitude and Wood-Anderson magnitude.

TABLE IV

Earthquakes recorded by Wood-Anderson instruments installed at Entiat, Washington and their comparison with Newport, Washington Wood-Anderson magnitude, also previously reported coda-length magnitude and rescanned coda-length magnitude.

Date	Time	distance	Magnitude and	Stations	Magnitude and	Stations	Magnitude	Magnitude
(GMT)	(GMT)	A	B	C	D	E	F	G
3/7/77	04:45:11	95	2.3	4	2.5	14	2.7	--
3/9/77	10:44:54	8	2.0	6	2.0	13	2.8	--
4/8/77	21:53:42	8	1.9	6	2.0	12	2.6	--
5/7/77	15:13:32	14	2.1	5	2.1	12	1.9	1.7
5/9/77	23:50:44	9	2.0	3	2.0	4	2.5	--
5/12/77	09:48:15	10	1.6	3	1.5	4	2.0	--
5/17/77	04:14:08	9	1.5	5	1.5	9	1.5	--
6/11/77	16:24:32	7	1.7	4	1.6	8	2.1	--

TABLE IV (cont.)

Date	Time	A	B	C	D	E	F	G
7/13/77	07:15:06	90	3.8	1	3.8	10	3.1	3.5
8/29/77	12:40:39	10	2.8	1	2.5	12	3.0	3.2
10/9/77	01:16:47	5	1.6	8	1.6	8	1.3	--
10/22/77	14:18:43	8	1.7	7	1.6	10	2.0	--

A: Hypocentral distance from Entiat, Washington in kilometers

B: Previously reported coda-length magnitude

C: Number of stations used in previously reported coda-length magnitude

D: Rescanned and recomputed coda-length magnitude

E: Number of stations used to recompute coda-length magnitude

F: Magnitude computed from Wood-Anderson instruments at Entiat, Washington

G: Magnitude computed from Wood-Anderson instruments at Newport, Washington

Coda-length magnitude formula: $M = -2.46 + 2.82 (\log_{10}(\text{coda-length in seconds}))$
The coda-length is the time interval between the first arrival of the earthquake signal until the earthquake signal is reduced to twice the station's background signal.

Northeast Washington attenuation study. During the past two years we have been involved in studying the attenuation of seismic waves as revealed by the Q structure. A master's thesis has been completed using data from the Lake Chelan area. A summary of this work is included here and the complete thesis is included in this report as an addendum.

Earthquakes occurring in the Lake Chelan region were monitored by the seismic array of the Geophysics Program, University of Washington. The signals were recorded on FM magnetic tape during the period of December, 1976 to March, 1977. Sixteen earthquakes along with three blasts recorded by eleven well calibrated stations of the array were selected and analyzed in the frequency domain. Source parameters of earthquakes in the seismically active area near Lake Chelan, and the crustal attenuation factors in the surrounding regions have been extracted from the data.

A method of estimating the average crustal Q was developed in this study by measuring ratios of far field seismic spectra which does not require knowing the source spectrum nor the geometrical spreading factor. The average crustal Q thus estimated is 310 ± 100 for direct SV waves. This value is higher than that determined for the region around the San Andreas Fault in central California, but is close to that of the Basin and Range Province. The overall seismic attenuation, where amplitude is proportional to r^{-k}, was also determined with $k = 1.40 \pm .28$ in the frequency range 3-9Hz, and $k = 1.85 \pm .45$ in the range 18-24Hz. Based on the observed data, a local magnitude scale was determined and related to a coda length scale:

$$M_L = -2.15 + 2.50 \log (F - P)$$

For the earthquakes studied, the coda length magnitudes were between 0.86 and 1.80.

Seismic moments were on the order of 10^{18} dynes cm for several events where determined by a spectral level technique, and the corner frequencies then determined do not have any linear relation with the magnitude, but seem to have values around 14Hz. The corresponding source radii calculated by Brune's model are around 100 meters, and the stress drops range between 0.42 and 2.56 bars. An attempt was made to estimate the magnitude of the largest earthquake that would likely occur in this area, the value of which is about 5.8. This is not unreasonable considering that there were local earthquakes with maximum intensity VI reported in Chelan. The determination of the focal plane solutions and the directions of the stress distribution will provide a clearer picture of the tectonic nature of this region.

Regional attenuation from intensity data. A paper has been presented on our work using intensity data to study regional attenuation properties of the state. This paper is included as part of this report and is planned to be submitted to the Bulletin of the Seismological Society of America for publication. It is only in preprint form now and should not be quoted or referenced as belonging to this report in official publication. After publication in BSSA reprints will be forwarded.

III. DETAILED STUDIES

There have been several areas in eastern Washington where we have been doing detailed seismicity studies from time to time because of swarms or unusual seismic activity. Two of these areas are covered in this report: Lake Chelan's continuing seismicity and 1975 Wooded Island swarm.

Lake Chelan Seismicity. The area to the south of Lake Chelan has remained as active as in the past with over 50 events being located there during the past year. With two new stations, ETT and PLN being added last summer in this area our location threshold has lowered to about $M_L = 0.5$. The distribution of well located hypocenters is shown in Figure III-1. The fairly sharp cutoff of activity south of latitude 47.6N and the scattering of events considerably to the north indicates there is some sort of boundary running east-west at this latitude. The apparent grouping of activity into several more concentrated areas is only in space, for the events are scattered fairly uniformly in time. This is, of course, in marked contrast to the seismicity of the central basin where most earthquakes occur as part of distinct swarms.

With the increase in our station coverage in this area and the use of readings from temporary stations operated by Woodward and Clyde Associates several earthquakes have enough first motion observations to allow for tentative focal mechanism solutions. Such an event occurred on August 29, 1977 at 1240Z with a magnitude of $M_L = 2.8$ and a depth of 8.2 ± 0.8 km. First motion data are available for 22 stations for this event. Using a linear velocity gradient with a relationship:

$$V(z) = 5.1 + 0.05z$$

a focal mechanism plot (Figure III-2) is fairly well determined. It shows a thrust solution striking NE-SW with the two planes dipping roughly 45 degrees NW and SE. Four other earthquakes occurring in the same area can be composited with the August 29 one, to further tighten the constraints on the mechanism (Figure III-3). The depths of the events used are plotted against the perpendicular to the strike of the N 66 E plane in the bottom of Figure III-3. This illustrates the possibility that these events lie on the same plane which would be the preferred fault plane. There are, however, many events which do not fit this focal mechanism. For example, Figure III-4 shows a first motion composite plot of five earthquakes whose poorly controlled solution is rotated about 90 degrees from the one mentioned above. Both of these solutions show primarily thrust type of motion with roughly horizontal maximum compression axies and vertical minimum compression axies. The orientation of the maximum compression axis is NW in one case and NE in the other.

The same data as shown in figure V-1 is plotted in cross sections in Figure III-5. The cross section looking from the NE (Figure III-5d) shows what appears to be possible conjugate planes one of which includes the August 29 event (shaded symbol). Because of the 2:1 vertical exaggeration these planes are dipping only 20 to 25 degrees from the horizontal which does not agree well with the focal mechanism. The agreement is close, however, and we feel justified in concluding that these lineups of hypocenters represent possible fault surfaces.

The earthquakes in this area appear to be occurring on at least two and probably several fault planes oriented in different directions. The stress field may also be quite complicated though the above focal mechanisms do not rule out a horizontal roughly north-south compression stress being the dominant one. There are no major topographic or geologic structures which are obvious candidates for association with these earthquakes. While we have gained further insight into the nature of the earthquakes there are still questions to be answered.

Wooded Island Swarm. In the summer of 1975 an earthquake swarm occurred near Wooded Island. We monitored this swarm and have been analyzing the data since then. Mr. George Rothe has used these data as the basis for his Ph. D. dissertation which he has just finished. This dissertation is summarized here and the complete text is included as an addendum to this report.

The basic conclusions of this study are the details of the seismicity in the Wooded Island area, the anisotropy of the Columbia River Basalts, and a hypothesis for the cause of the microearthquake swarms in eastern Washington. Most of the seismicity of eastern Washington is in the form of swarms characterized by a gradual increase and subsequent decrease in the level of activity with no event outstandingly large enough to be considered the main shock. The Wooded Island area on the eastern border of the Hanford Reservation has been recognized as a swarm area since the installation of the regional Hanford Network in 1969. A local array of up to six stations was used to study the details of a microearthquake swarm there in the summer of 1975. The results of this study are applied to the seismicity of eastern Washington in general.

Inconsistent focal mechanisms and a range of V_p/V_s values from standard Wadati plots led to the examination of the stack of basalt flows and interflow zones as giving rise to seismic anisotropy. The upper crust was modeled as a transversely isotropic halfspace, and a method developed for locating earthquakes in this type of medium. Hypocenter locations based on the transversely isotropic model were used to show that the earthquakes at Wooded Island are for the most part occurring on an east-west oriented planar shear zones which dip at about 80 degrees to the north with poorly controlled focal mechanisms consistent with reverse motion along this zone.

Other details of the seismicity, along with geologic evidence, suggest that the seismic energy recorded as microearthquakes is generated by slip along preexisting columnar joints in the competent portions of the basalt flows. A break in the recurrence relation for the Wooded Island swarm suggest that there is a characteristic "size" corresponding to a physical dimension. All the first motion data do not fit the same focal mechanism but rather fit several classes of mechanisms. In addition, not all first motion data sets for individual events could be fitted with the standard two intersecting planes indicative of the double couple mechanism. These events may represent slip along the long dimension of columnar joints at the vertex of the columns, involving two adjacent faces of a particular column. The vertical migration of several groups of events also suggests the migration of the stress discontinuity responsible for the observed seismicity.

Geological evidence for slip along columnar joints is basically slickensides on columnar joints preferentially oriented in the long direction of the columns. Observation of slickensides on these joint surfaces is confined to reions of the Columbia Plateau which show evidence of deformation of the basalt flows, notably the anticlinal ridges. Regional strain data is consistent with a model confining deformation in the form of micro-earthquakes to the regions of maximum deformation of the anticlinal folds.

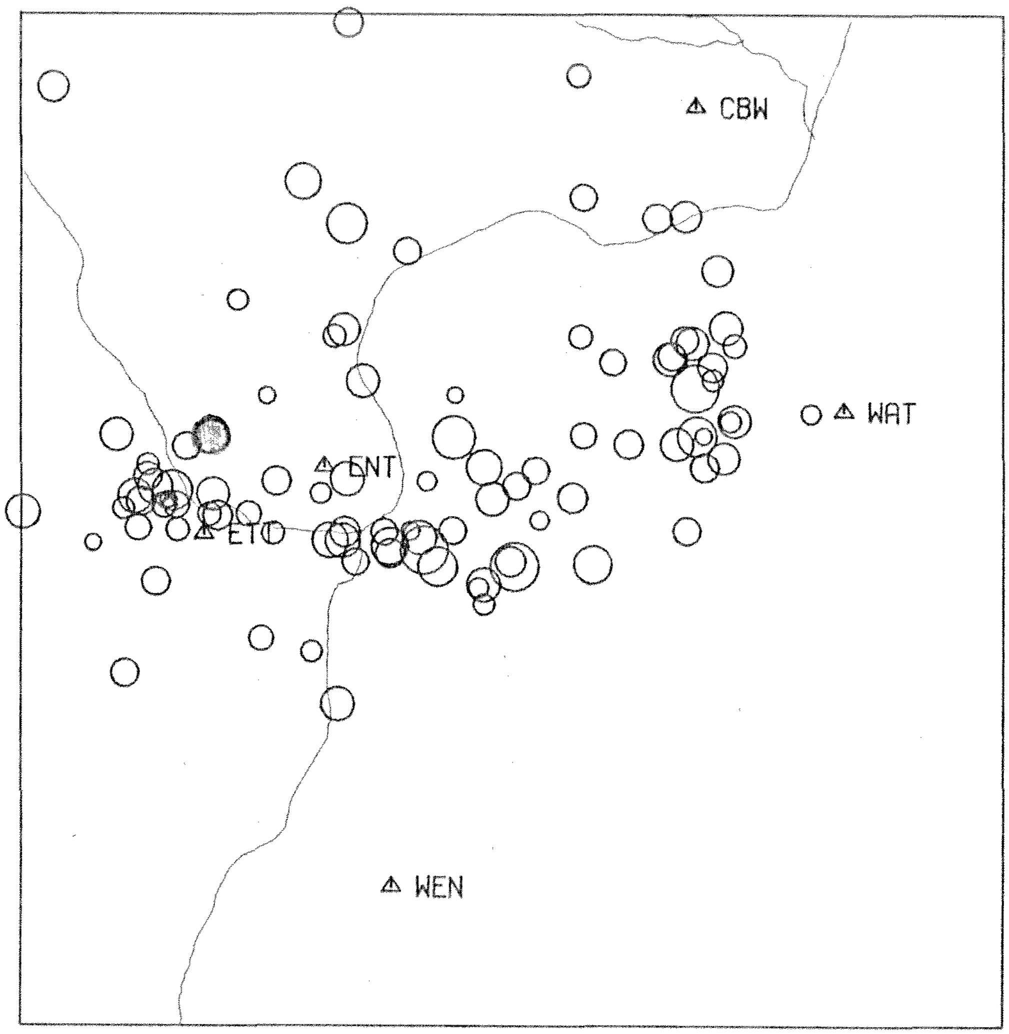

Fig. III-1. LAKE CHELAN EARTHQUAKES 1975-1978 (BEST LOCATIONS)
CENTER OF MAP IS 47.66 N 120.13 W
MAGNITUDE KEY ○ 0.0 ○ 1.3 ○ 2.7 ○ 4.0

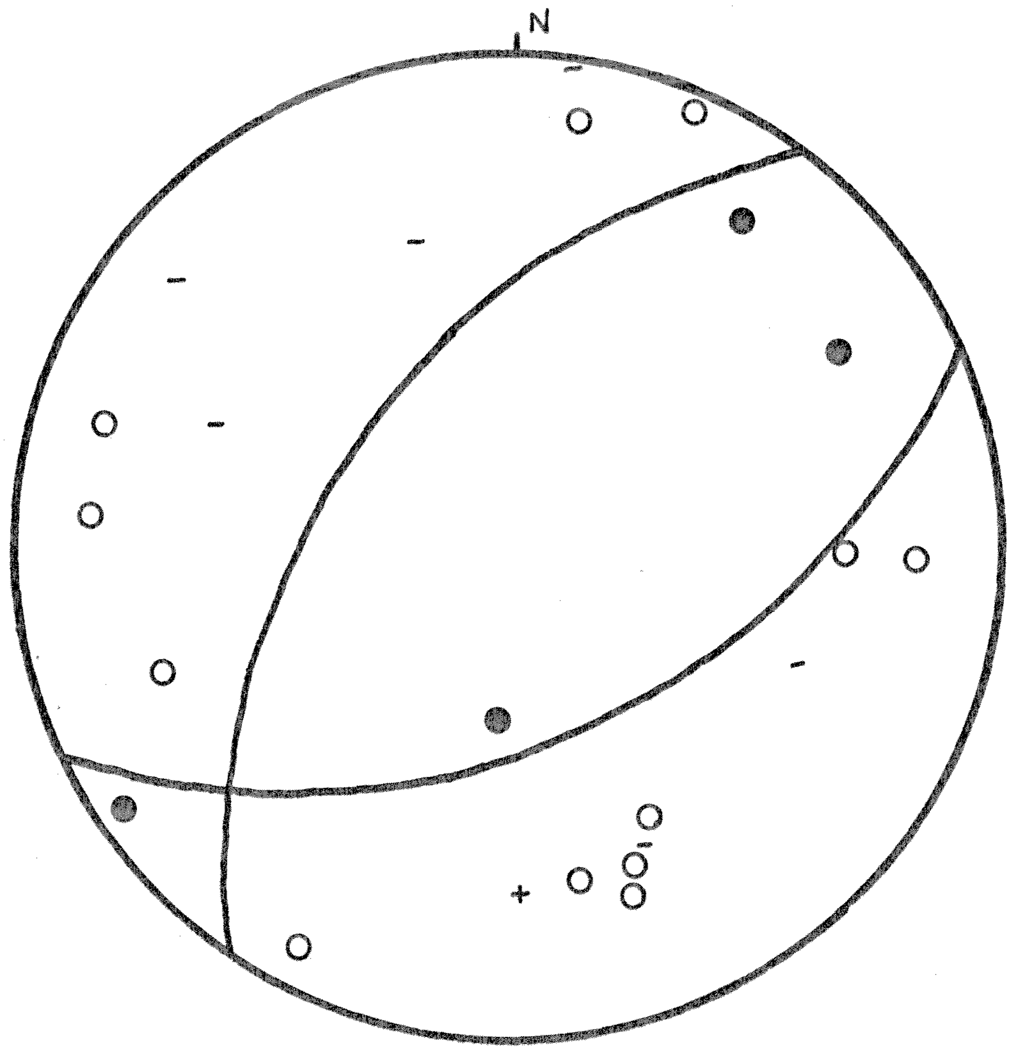

Figure III-2. Focal mechanism plot for the earthquake of Aug. 29,1977; M_L = 2.8; depth = 8.2km. 47°43.1'N 120° 17.1'W

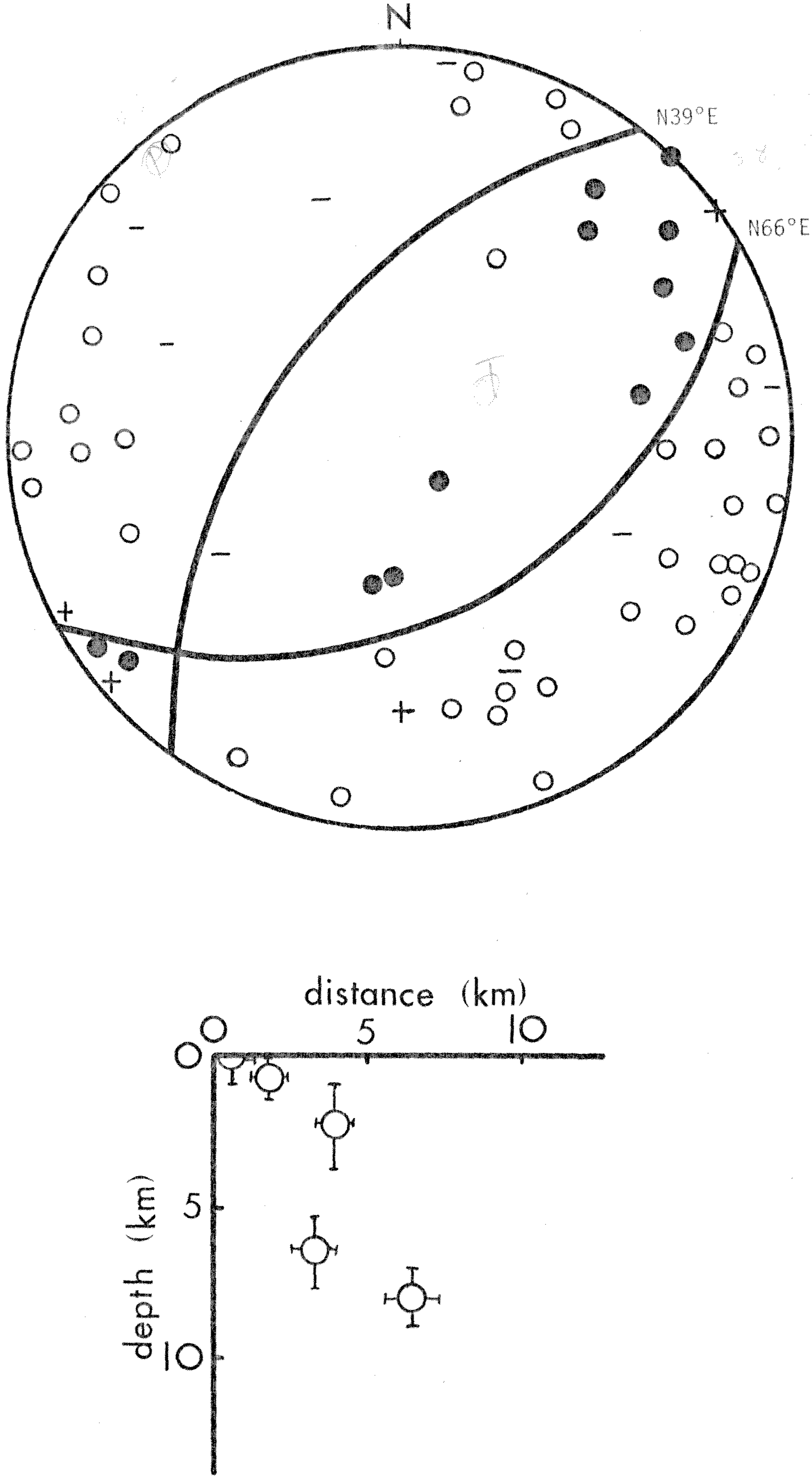

Figure III-3. Composite focal mechanism plot of 5 Lake Chelan earthquakes and plot of their depth verses perpendicular distance from the surface trace of the N 66°E plane.

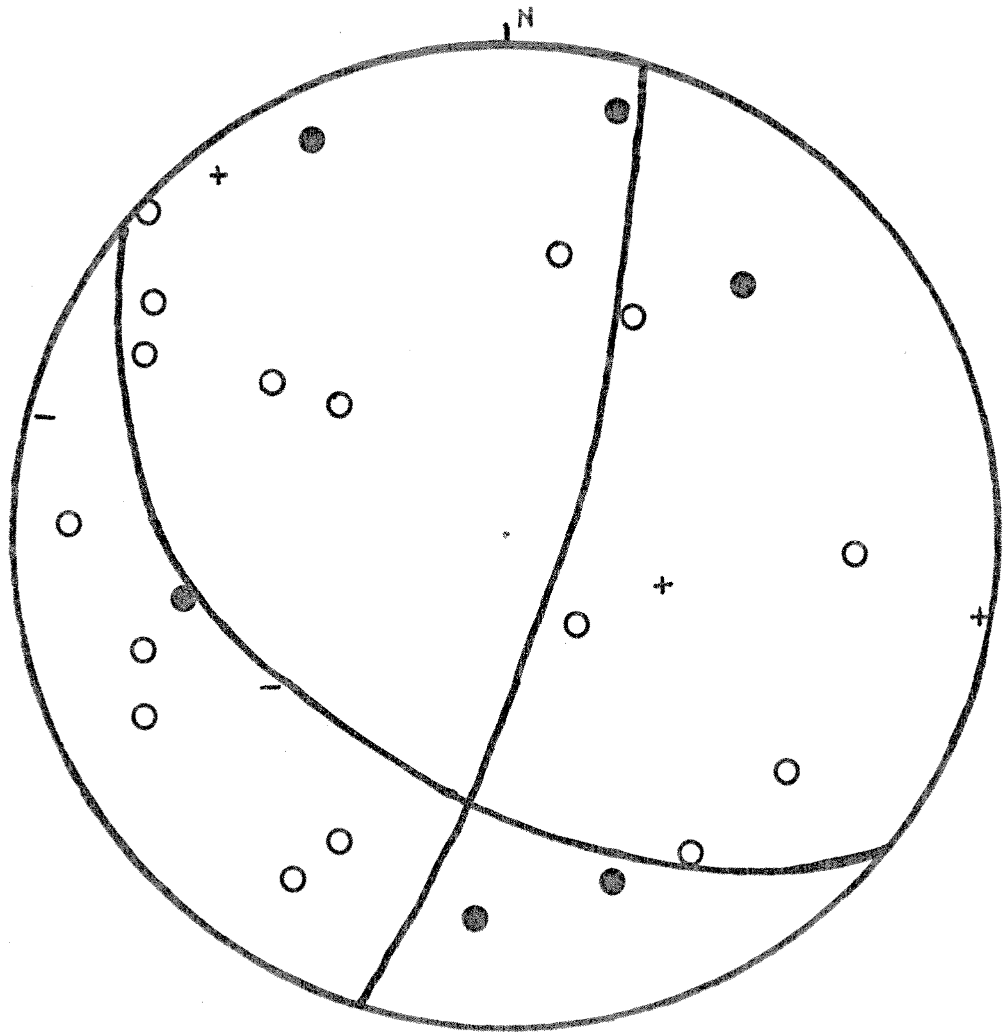

Figure III-4. Composite focal mechanism plot of 5 earthquakes in the Waterville area near Lake Chelan.

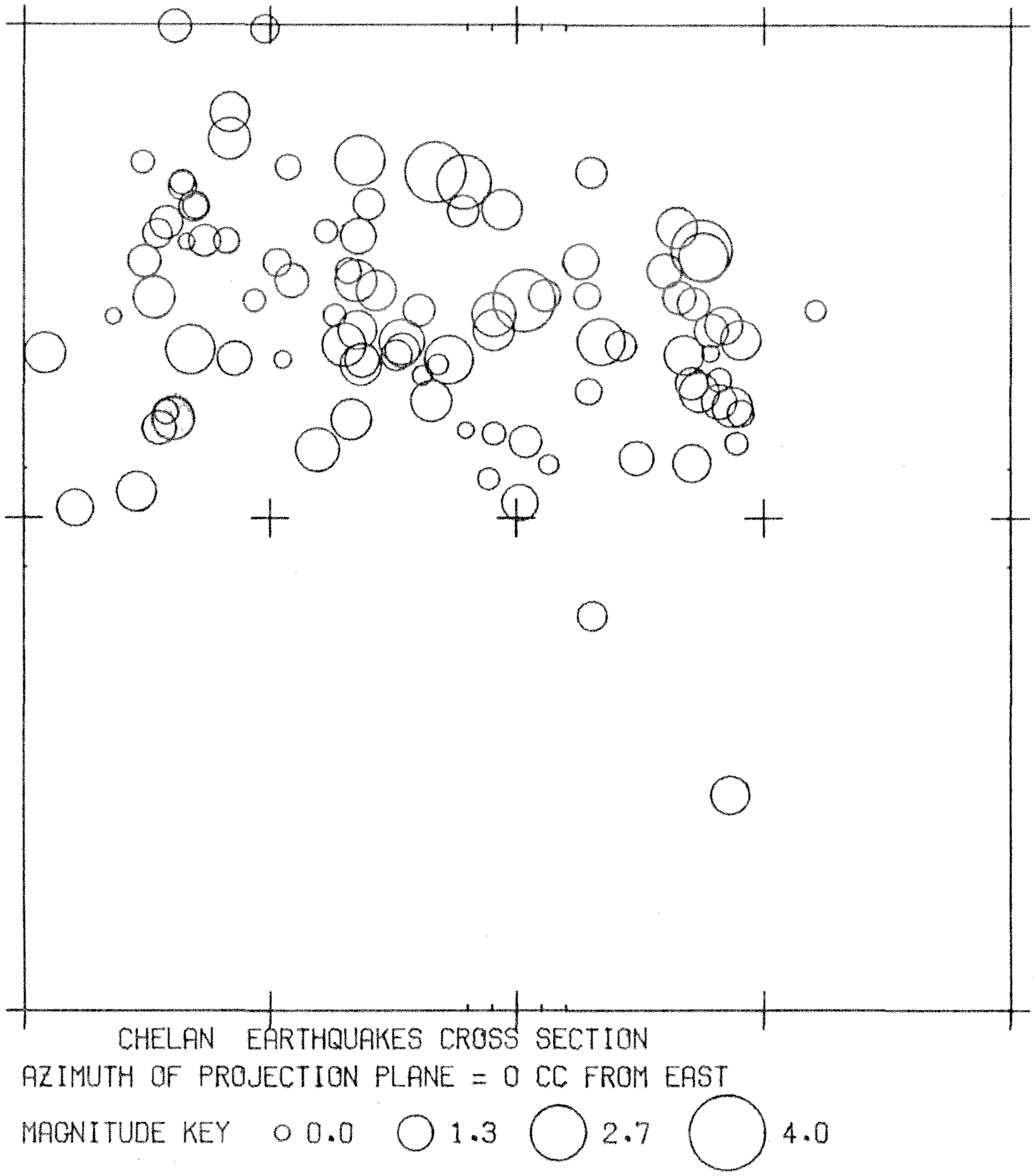

Figure III-5a. Profile looking from south to north. Aug. 29 event is shaded.

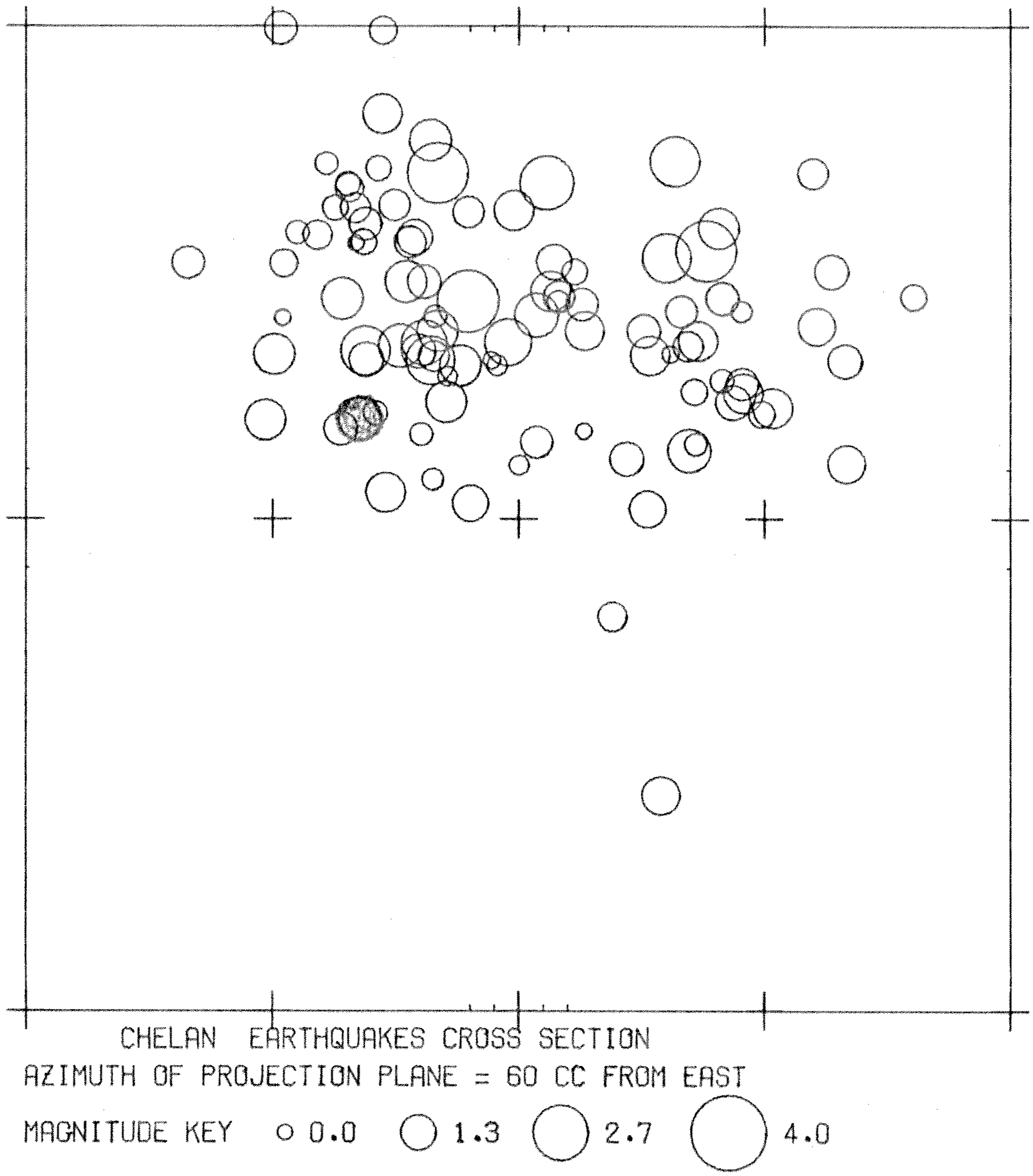

Figure III-5b. Profile looking from south-east to north-west.

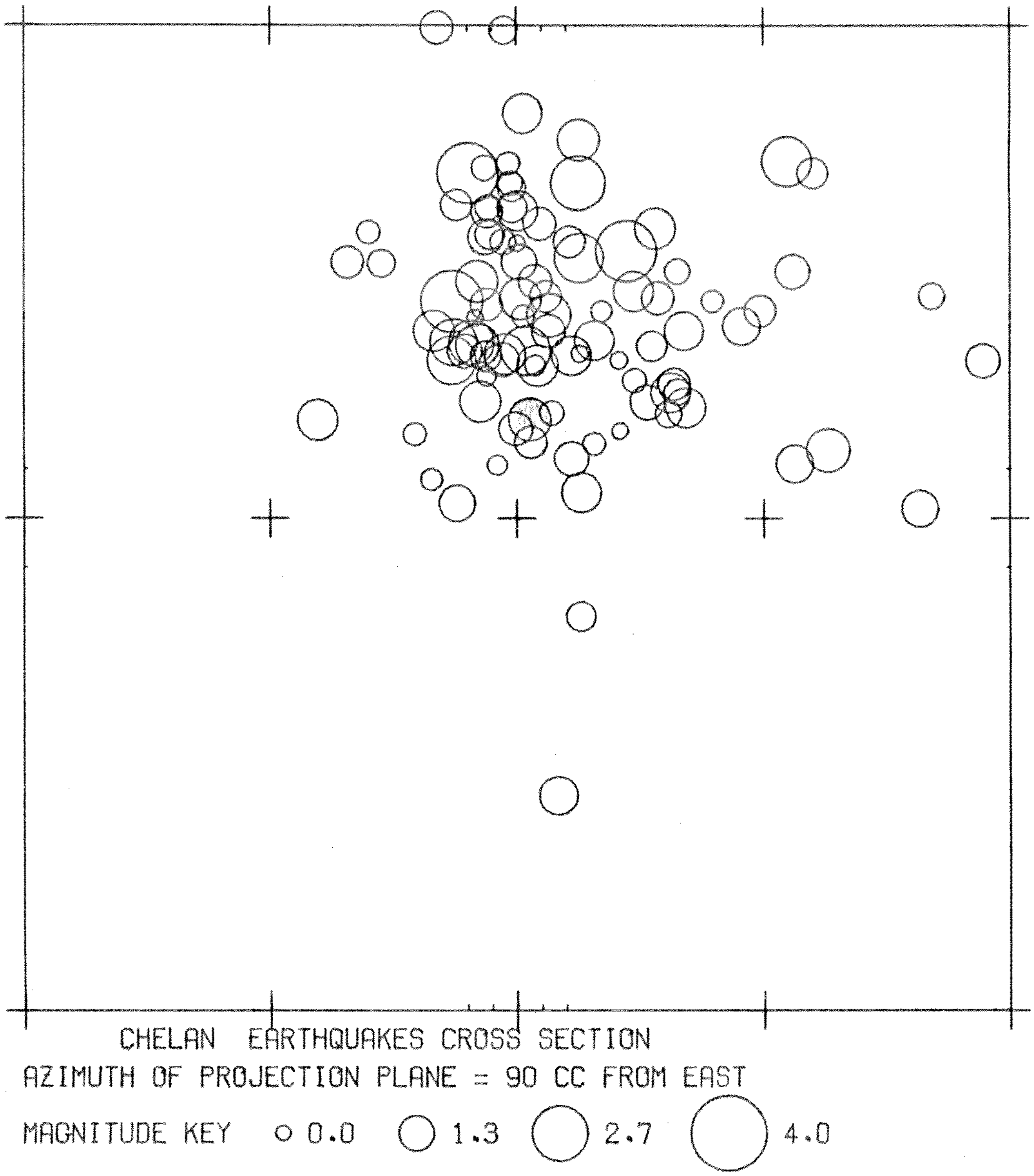

Figure III-5c. Profile looking from east to west.

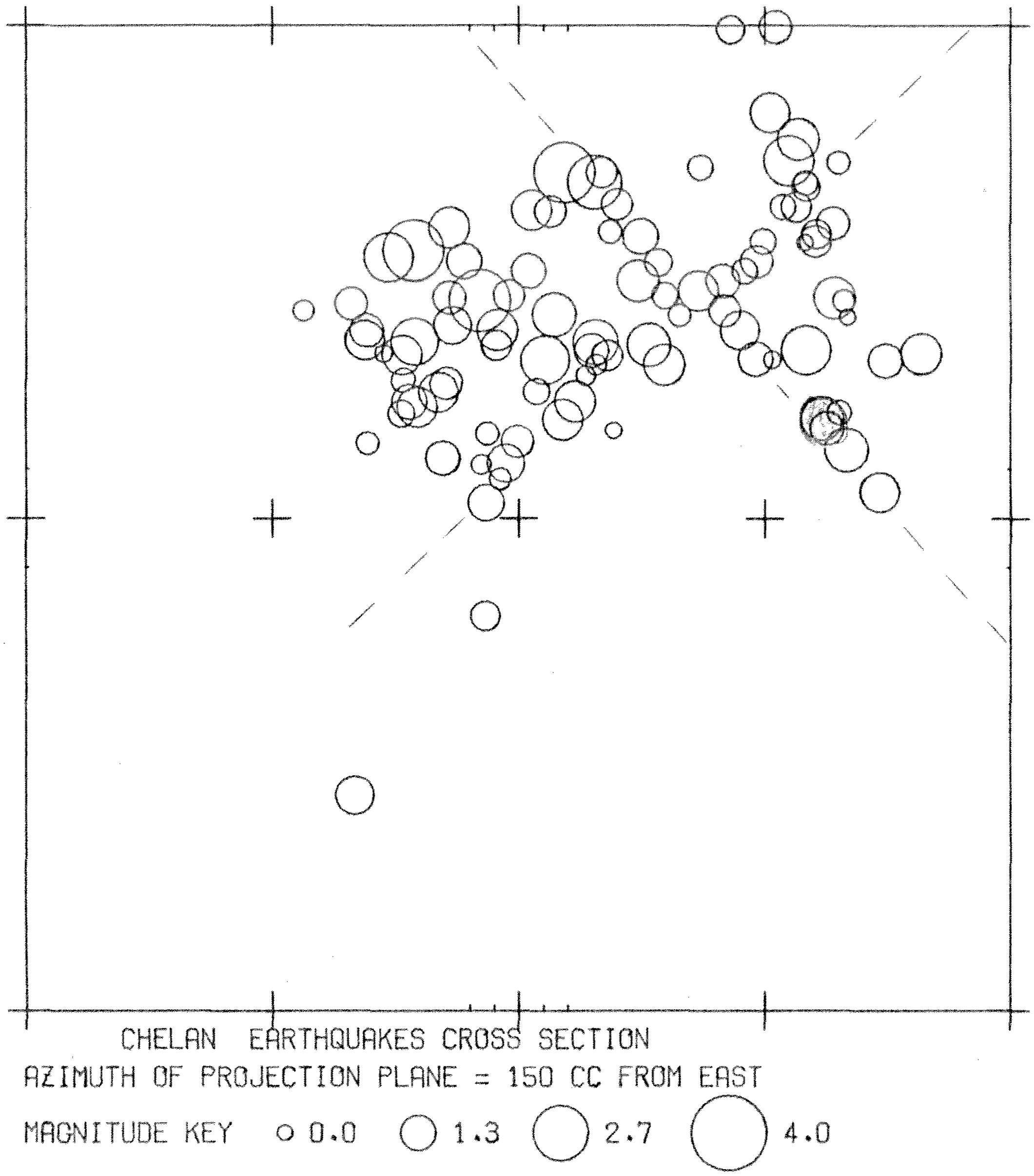

Figure III-5d. Profile looking from north-east to south-west.

IV TILTMETER

Two borehole Kinemetrics TM-1B biaxial tiltmeters have been operating side by side for the past year near the Wooded Island seismometer station. To date, the data raises serious questions as to the long term stability of short baseline type tiltmeters.

Installation. Both tiltmeters occupy the same sites used by USGS in a previous tiltmeter experiment. The site has three holes drilled for tiltmeters. We have used two of the holes for the installation of the Kinemetrics tiltmeters. Tiltmeter T1 is installed in a borehole about 3.5 meters to the N.E. of tiltmeter T2. Each tiltmeter installation consists of a 1 meter deep hole secured with a culvert nearly 1-1/2 meters in diameter. The tiltmeter electronics and telemetry packages sit at the bottom of the pit. Another hole, 25 cm. in diameter, has been augered to a depth greater than 1-1/2 meters below the base of the pit. A 25 cm. diameter pipe was installed, then the tiltmeter was placed in the pipe. The pipe was filled with nearly pure quartz sand. The top of each tiltmeter is located about 1/2 meter below the bottom of the culvert hole. This is very similar to the installation used by USGS in their California network of tiltmeters.

Both factory calibrated tiltmeters were originally installed in July, 1977. Upon installation of T2, it was discovered that it was drifting rapidly. We confirmed its drift by testing it on the seismic pier at the U. of W. and sent it back to Kinemetrics for repair. During this period, some design bugs were corrected in the telemetry. In early September, tiltmeter T2 was reinstalled as well as the telemetry. Later, on November 26, styrofoam insulation was placed in the holes. Also, the heavy conduit leading from the tiltmeters to the electronics package was clamped to the top of the 25 cm. diameter pipe. Both instruments ran until the end of March, 1978, when their batteries died.

At the end of May, 1978, both tiltmeters were dug up and reinstalled. It was found that tiltmeter T1 had been installed originally such that it was rotated 90° from T2's axis. This was corrected. Extra care was taken in tamping the sand during reinstallation of both instruments. The conduit clamp was left off since most USGS installations have no conduit clamp (Carl Mortensen, Personal Communication, 1977). Batteries for both tiltmeters were placed in a third culvert hole so that they can be serviced without disturbing the instruments.

In January, 1978, a minor modification was made on the telemetry receiver so that the strip chart recorder became more sensitive to tilts by displaying the seven least significant bits of a twelve bit word. Simple switching allows the operator to read the entire twelve bit word, too.

Data. Fig. IV-1 shows the complete set of long period data for both tiltmeters. The plot has been corrected for the rotation of tiltmeter T1. The first plot consists of data taken before the installation of the insulation and the second plot is the data taken after the first servicing and before the batteries died. The total data set is 202 days long. The two components from each tiltmeter are plotted. Tilting in the positive X and the positive Y directions are measures of the Earth's surface dipping the east and north respectively. Each plotted data point is a single observation of the output of the tiltmeter telemetry. Readings were made once per day whenever possible. Missing readings are either due to the phone line problems or no attempt was made at observation.

Rainfall, which has been identified by others including Wood and King (1977) as a contaminant to tilt data, is plotted along with the tilt data. However, the rainfall data for Richland is complete through February, 1978. In general, there appears to be no obvious visual correlation between the tilt and the rainfall.

Since both tiltmeters are next to each other, it is hoped that there would be tracking between the two X components and the two Y components. If both instruments do track, then tiltmeters would be capable of representing the tilt for the region between the two instruments. For this experiment, the region is a very modest 3-1/2 meters. If the instruments do not track, then the tiltmeters are incapable of measuring tilt. They would prove themselves to be sensitive to very local site conditions.

It is obvious that for both data sets, there was no tracking between similar components. Table 1 summarizes the lack of tracking by computing linear regression coefficients between each of the components of tilt. If two components track with the same magnitude of tilt, then the regression coefficient would be unity. Tracking in opposite directions would yield a regression coefficient of -1.0. High correlation coefficients are indicative that both components track linearily with a ratio of their magnitude of tilts equal to their regression coefficient. The data in Table V confirms that the similar components did not track. During the first period,

TABLE V

Regression analysis of the components of tilt for both data sets

	Data Set I		Data Set II	
Dates	9/12/77 to 11/26/77		11/28/77 to 3/30/78	
Number of Days	79		122	
Number of Points	38		85	
Tilt Components	Regression Coefficient	Correlation Coefficient	Regression Coefficient	Correlation Coefficient
T1X - T1Y	.44	.40	-.50	.29
T1X - T2X	-1.18	.96	.17	.07
T1X - T2Y	- .89	.95	.28	.08
T1Y - T2X	- .68	.61	1.21	.91
T1Y - T2Y	- .54	.63	-1.86	.95
T2X - T2Y	1.27	.97	-1.41	.96

components T1X, T2X, and T2Y nearly tracked in same or opposite directions. In the second period, a different set of components, T1Y, T2X, and T2Y, showed similar trends. In both data sets, three of the four tilt components showed high, nearly linear drift rates, while the other had a low drift rate, over the entire measurement periods.

The linear drift rate for each component was computed using least squares. Again, the correlation coefficient is a measure of the data's closeness to a linear trend. Table VI presents the drift computations.

TABLE VI

Linear drift of each component of tilt

	Data Set I		Data Set II	
	Drift Rate µRAD/YR	Correlation Coefficient	Drift Rate µRAD/YR	Correlation Coefficient
T1X	32.38	.98	- 1.93	.28
T1Y	19.45	.54	- 9.02	.75
T2X	-40.41	.99	-14.49	.91
T2Y	-29.82	.96	19.05	.81

The drift rate during the first period is by a factor of two greater than that of the second period.

Data after reinstallation is incomplete for any long term analysis. So far, its record is similar in character to the data taken before the November servicing.

Short term tilt variations have been observed. Daily temperature and earthtides are the principal natural causes for daily tilt fluctuations. The measured daily tilt fluctuations are on the order of 0.4 μradians.

During the servicing in November, we statically loaded and unloaded the area around each tiltmeter. Each component of tilt responded to the load with tilt of 0.4 μradians. The expected direction of tilt corresponded to the azimuth of the load with the tiltmeter.

It appears that each tiltmeter is indeed coupled to the Earth. However, individual site conditions mask out any long term tilting since the components of the tiltmeters do not track.

Using data from only a single tiltmeter, one may conclude that the drift rate of 10 μradians/year could be reasonable for downhill slumping of the tiltmeter site. However, the data from the second tiltmeter does not support the data of the first. Since both tiltmeters are separated by a distance much smaller than the wavelength of the small topographic features near the Wooded Island site, it appears that each instrument is sensitive to only the very local tilts associated with its site.

Reference:

Wood, M.D. & N.E. King; "Relation between Earthquakes, Weather and Soil Tilt" Science, Vol. 197 #4299, p. 154.

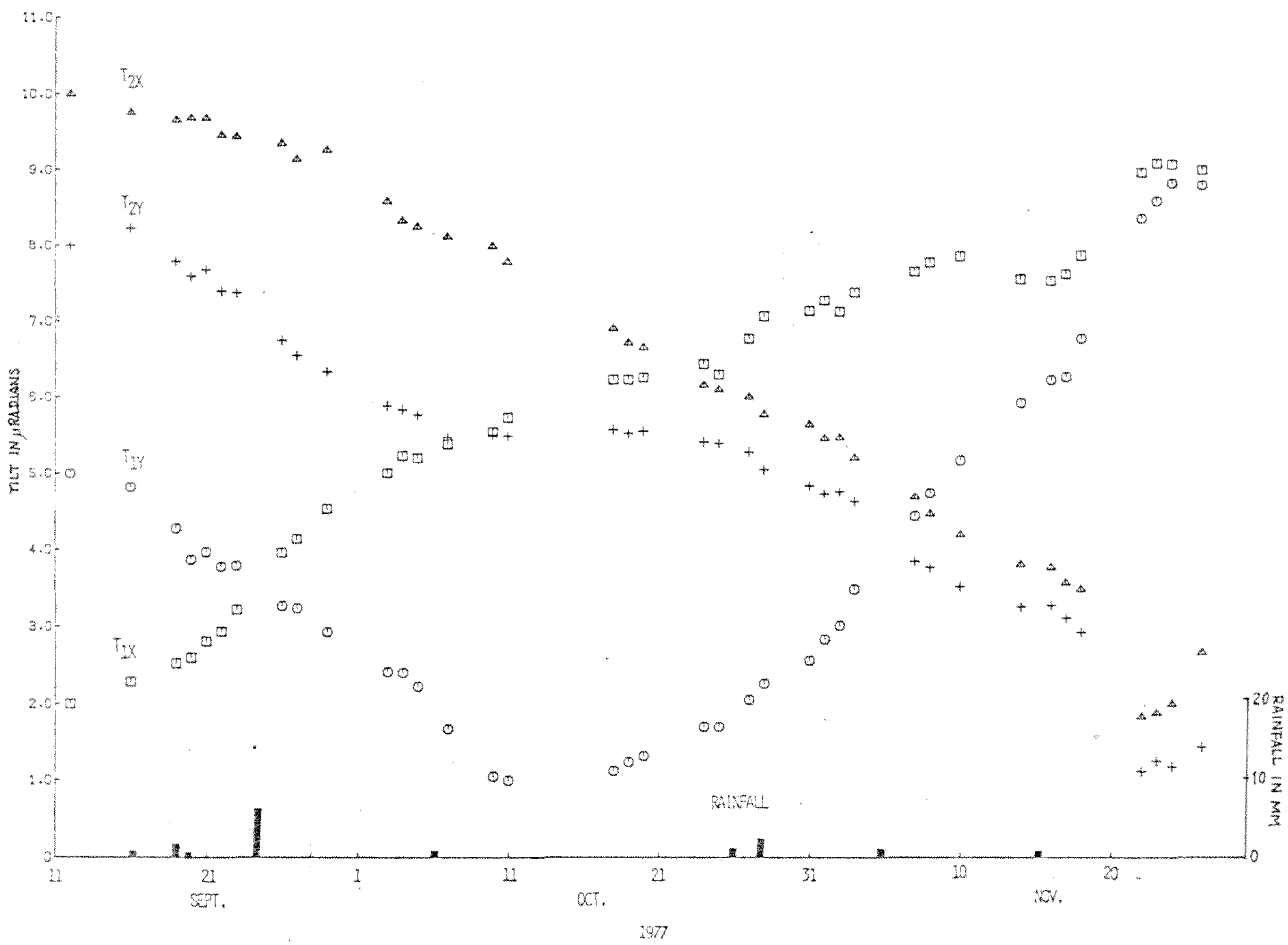

Figure IV-1 Wooded Island tilt data and local rainfall, 1977

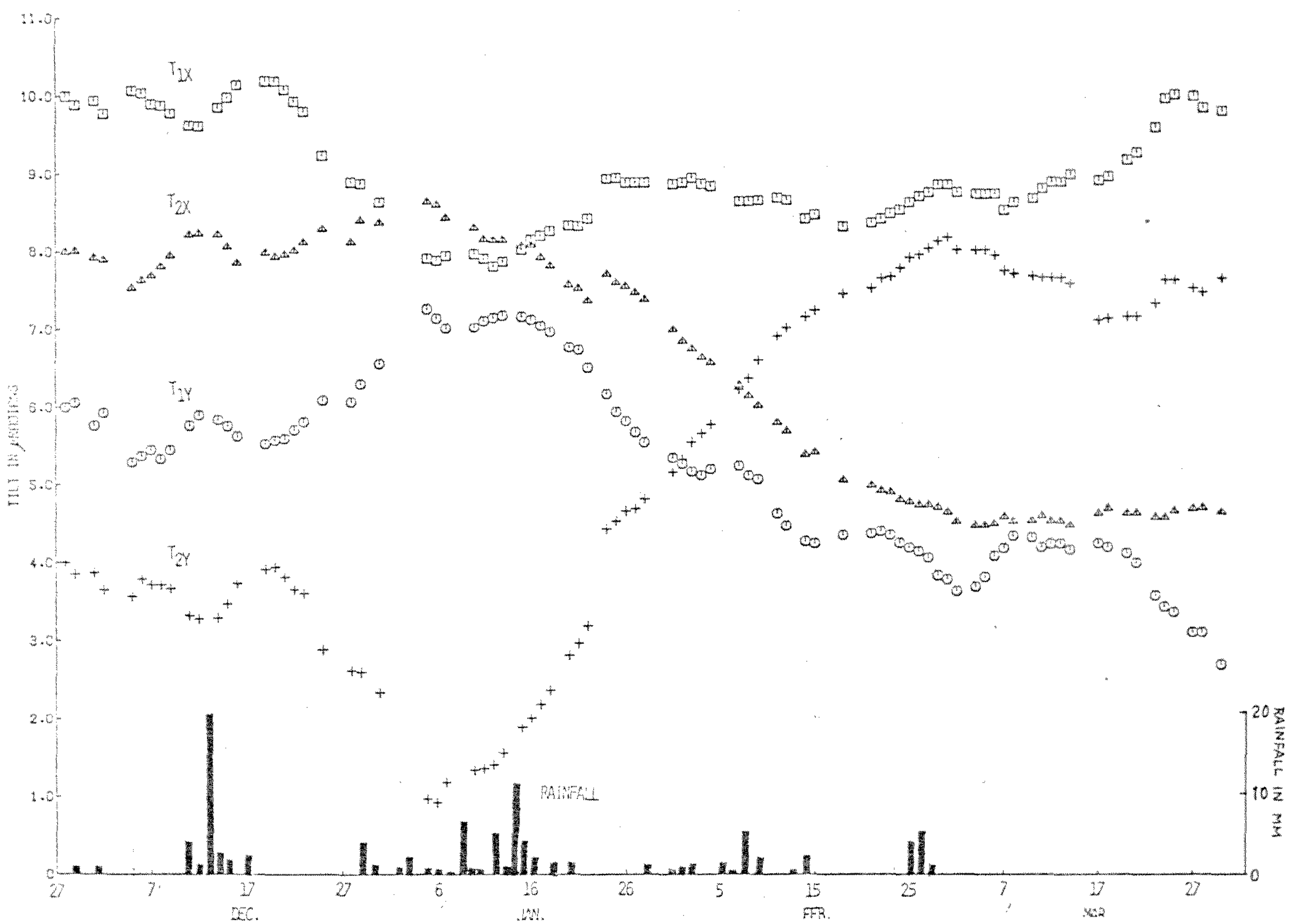

Figure IV-1 cont. Wooded Island tilt data and rainfall, 1977-1978

V. DIGITAL DATA COLLECTION

During the past year we have started preliminary using digital seismograph systems for recording earthquakes with the range and resolution to improve our interpretation of the seismicity. Our early efforts have been toward the use of digital event recorders which were funded by WPPSS. These instruments are quite complicated, being essentially state of the art, and have produced numerous problems in operation. We have been trying to use them in the Cascades for monitoring purposes, along with several regular telemetry stations and one locally recorded station (GLD). The amount of down time for the event recorders has been unreasonably large, though we have recorded several earthquakes in the Cascades.

In this report we describe one such earthquake, a magnitude 3.7 event which occurred south of Cle Elum, Washington on June 26. A preliminary study of this event illustrates the value of having good digital data. We also used several of the recorders to study a swarm on the north side of the Saddle Mountains. We illustrate the usefulness of digital data for studying very small local earthquakes in this case.

June 26 Earthquake. On the evening of June 26, 1978 at 1919PDT, a magnitude 3.7 earthquake occurred approximately 35km south of Cle Elum, Washington where two digital event recorders were operating. This area is only sparsely populated but the earthquake was lightly felt in the town of Naches (Fig V-1). Routine location of this event was attempted using readings from permanent stations in Washington. The depth was poorly controlled since no permanent stations are nearer than 55 km. The addition of the data from the two temporary digital stations allowed the depth to be calculated. This event was so large that no S waves could be seen on the develocorders, but good S wave arrivals were obtained on the event recorders (see Fig V-2). One possible foreshock occurred on June 10th (mag. 3.0) but no aftershocks were observed. This earthquake is particularly interesting as it illustrates the problem of earthquake locations in the Cascades from stations in the different physiographic provinces of Puget Sound and the Columbia Plateau. It is known that there are distinct differences in the crustal structure of these provinces (Fig. V-3, Table IV). There is probably a difference in structure between the North and South Cascades also. No single model composed of flat layers can be expected to predict the arrival times for this earthquake. The best location in terms of smallest error was 46° 52' N, 121° 00' W, depth 16 km., using a model developed for the North Cascades (Fig. V-3), and limiting the stations used to those within 110 km. of the epicenter. It was hoped that this limitation would reduce the effect of the different structural provinces of the stations. This allowed only 13 readings to be used for the location. In addition, the earthquake was located very near one of the layer boundaries of the model, which may be an artifact of the model. This boundary was smoothed by using a velocity gradient of 0.06 km/sec/km approximated by 5km thick layers, and the program was run with many combinations of weighting functions, especially including arrival times out to 150km distance (25 readings). This did not change the epicenter by more than 1 km (approximately the calculated error of the epicenter). The depths now varied from 11 to 17 km with the average about 14 km, again consistent with the calculated error for depth.

One way of correcting arrival times from one structure to another is to use station delays which are appropriate for certain azimuths and distances. One such set of correction terms has been calculated using blast sources in NE Washington recorded on the Columbia Plateau. The geology and shallow velocity structure of NE Washington are similar to the North Cascades, but the mantle velocity is higher and the Moho is much shallower. Delays vary from 0 to 0.5 due to the thickness of the overlying basalts. This model gives very shallow locations, and also larger errors for the June 26 event. The epicenter was moved 4 km south of the previous location. It is apparent that there is a tradeoff in time residual between the depth of the earthquake and depth of the Moho. By forcing a shallow depth, the location must move to the south to fit the observed S wave travel times.

A focal mechanism for this earthquake is shown in Figure V-4a,plotted on the lower hemisphere. Takeoff angles were computed using the North Cascades model with the linear velocity gradient. One of the possible fault planes has equal components of right lateral and thrust (the northern block moves up) motion on a fault plane striking N85°W and dipping 80° North. The second possibility is for nearly horizontal left lateral slip on a fault plane striking N15°E and dipping 46°E. The movement on either of these planes would be caused by compression in the direction N26°W, inclined 23°, and tension in the direction S43°W, inclined 52°.

The focal mechanism for the eastern Washington model is shown in Figure V-4b. This focal mechanism is approximately the same as the first, except that the two event recorders are shown to be receiving an initially downgoing (refracted) ray. This puts the compressional arrivals clearly in the dilitational wave field for this earthquake. Thus the deeper location is more consistent with the polarity of the arrivals. Additional evidence of a deep source is the lack of any visible second arrival from the upper crustal layers. The P wave train looks significantly like a direct (upgoing) wave.

The two horizontal seismometers at each event recorder clearly show an improved recording of the shear wave phases as compared to the vertical seismometer. This earthquake occurred almost due south of the event recorders, and the ratio of the NS and Vertical motion implies an angle of incidence of 35°. The computed angle of incidence is 41°for the North Cascades model and 57° for the eastern Washington model. Again it seems that the deeper location is preferred when interpreting the waveform recorded at Cle Elum. One can also see that the first arrival of S has a first motion vector with components to the west and south directions. The first motion polarity should be perpendicular to the fault planes. For either direct or refracted raypaths, the polarity should be to the east and south. This clear mismatch does not bear on whether the earthquake was deep or shallow, however.

<u>Saddle Mountain Swarms</u>. In late May of this year when we had located some of the swarm events in the Saddle Mountains area we decided to test our new event recorders there. We set up three units about one kilometer apart directly over one of the swarms. During the next three weeks we obtained over 60 recordings from local earthquakes. These data have only had very preliminary analysis. Because of continuing problems with the recorders many events were recorded on only one or two units, but there were several events which recorded on all three units. Because during the three weeks of recording there were several swarms active at the same time we have recordings of similar sized earthquakes at a range of epicentral distances from 1 km to 10 km.

These data will be very useful in studying the attenuation characteristics of shallow earthquake generated waves in the basalt. Figure V-5 shows three seismograms and their spectra for events at different distances. These are three different events recorded on the same instrument. While for attenuation studies it is best to record the same event on three instruments it is observable in the spectra shown here that attenuation plays an important role in their shape. Note that there is much more high frequency energy in the event at 1.6 km than the other two. As the events get farther away there is a rounding to the spectra which decreases the high frequency component. However, even for the event at 8.6 km a sudden breakover at about 30 Hz is observable which may be the source corner frequency. Because we have not analyzed these data extensively we don't know the cause of many of the observable features such as the single low frequency pulse late in the S phase of the event at 4.5 km. Some of the data do show dramatic evidence of S-wave splitting as described in the previous section on the Wooded Island swarm. Note the multiple S arrivals marked on the seismogram in Figure V-6. Again we have not had the time to go into this observation in any detail but it does seem to confirm the model proposed by George Rothe on the transversely isotropic nature of the Basalts.

We have learned a great deal about the use of digital event recorders in this and the Cle Elum study. The superiority of the data from these instruments is obvious. There are many special studies that will be possible with these instruments though there are certain limitations. Even when all the technical problems with these instruments are solved there will be certain types of studies where they are not the best instrument to use. Using the existing trigger we feel that a routine monitoring use is ill advised. If the purpose is simply to see if there are microearthquakes or not then much less expensive, more reliable systems exist. Since one is counting on automatic event detection with these instruments there is always the chance that earthquakes, particularly small ones, will be missed by the detection logic when a skilled record analyst would easily spot the event. Also since the amount of recording time is limited (15 minutes of tape) there often is the case where it is used up due to many earthquakes or earthquake-like noises occurring. Even when our equipment was working well there were times when the tape had run out and events were missed since it is very difficult to know how often to service the units. We feel that the superior quality of the data far outweighs these disadvantages if they are recognized. It simply means that the event recorders should not replace all other types of seismograph stations but should be used with them for special purposes. This feeling may change with improved triggering logic and more experience in operating this equipment.

Hydrophone testing. We obtained a very small diameter high sensitivity hydrophone last year to be used in a deep well in the central basin. There were several technical problems with the instrument during bench tests which required factory modification. This summer we ran tests both on the bench and in the field to gain experience using it. The frequency response of the hydrophone-preamp system has been shaped to look very much like one of our standard seismic systems (flat to velocity between 2 and 30 Hz). This unit was connected to a cable and tested in a 350 meter deep hole in a glacier in Alaska. Natural earthquakes and "glacier-quakes" were recorded using both the hydrophone and a nearby seismometer. Figure V-7 shows the seismogram of an ice-quake recorded on the hydrophone and two surface seismometers. The size and frequency content of these types of events is similar to small local earthquakes in the basalts. We feel we have now solved the technical problems of frequency response and gain and with the help of personnel at Rockwell Hanford Operations we hope to place this unit in a deep well in the central basin some time this fall.

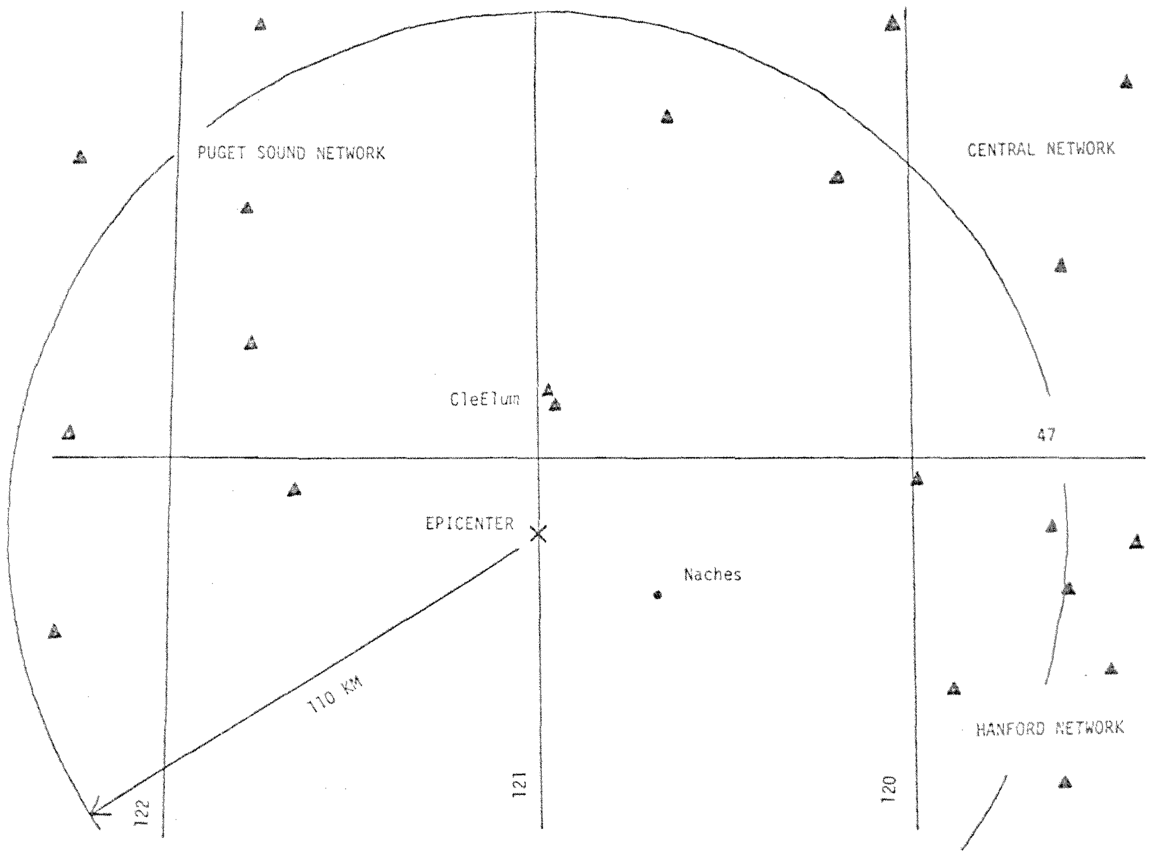

Figure V-1 Epicenter of Naches earthquake of June 26, 1978 and nearby seismic stations.

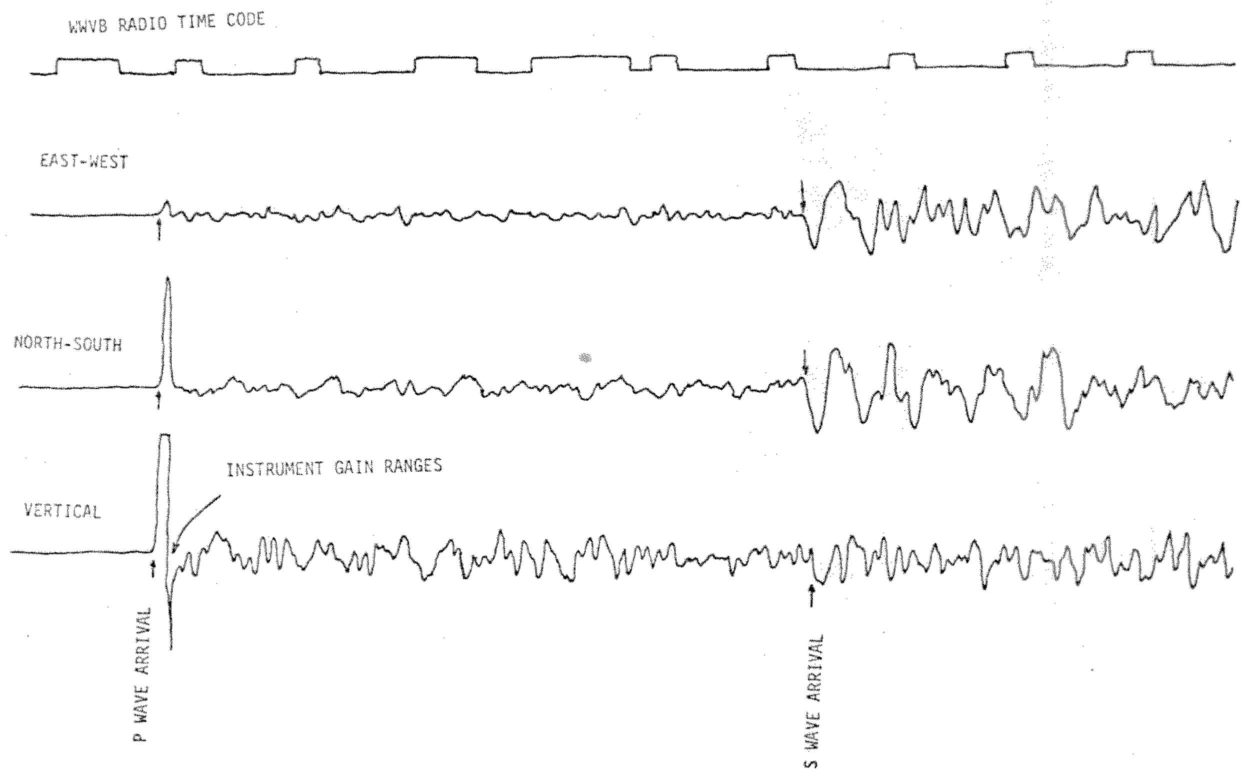

Figure V-2 Seismograms from digital event recorder near Cle Elum (CE1) for Naches earthquake.

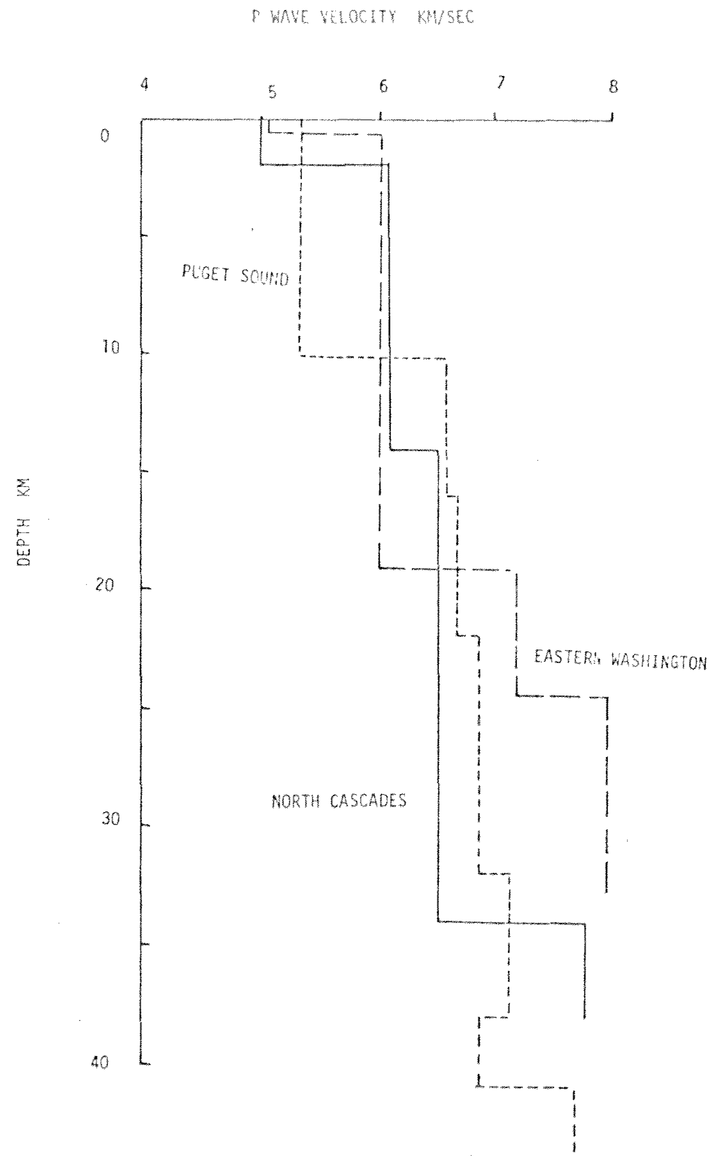

Figure V-3. Comparison of seismic velocity models used to locate earthquakes in Washington State.

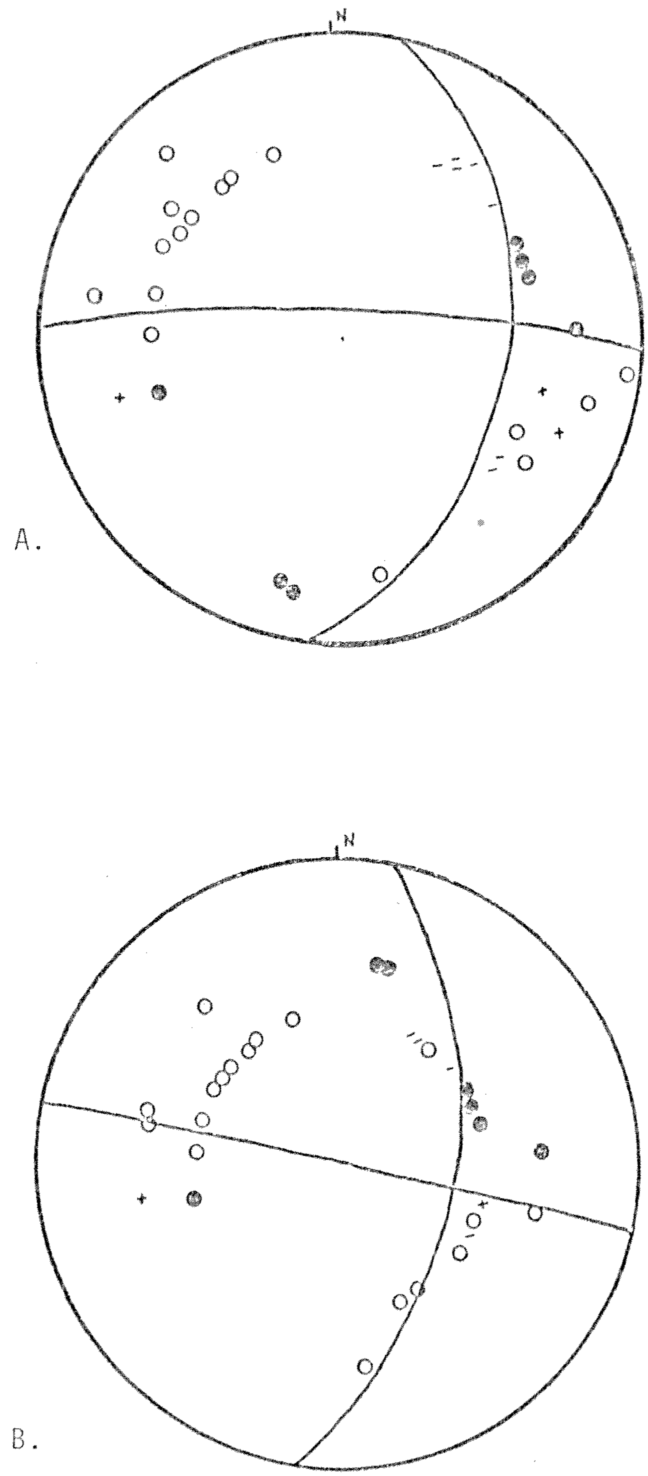

Figure V-4. Focal mechanism plots of Naches earthquake assuming a focal depth of 14 km. (A) and of 3 km. (B)