FINAL TECHNICAL REPORT: 1984

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Summary

This is the final technical report for USGS contracts 14-08-0001-21861 "Regional Seismic Monitoring in Western Washington" and 14-08-0001-21862 "Earthquake Hazard Investigations in the Pacific Northwest". Network operation, routine data processing, preparation of bulletins, and related functions are covered under "Regional Seismic Monitoring in Western Washington". When current installations are completed, 28 key stations covering much of western Washington will be supported under this contract. Stations on the Olympic peninsula, in the Mt. St. Helens region, in eastern Washington, and in northern Oregon are funded under other contracts. "Earthquake Hazard Investigations in the Pacific Northwest" funds several research tasks on earthquake hazard evaluation and related subjects using seismic network data from Washington, northern Oregon, and adjacent areas. Among the tasks which we are undertaking (either completed or continuing) are the following: a) extensive reevaluation and assembly of our regional earthquake data base (this work underlies much of the rest of our research efforts), b) recalibration of magnitude scaling using machine determined signal durations, c) relocation of all local and regional earthquakes using new velocity models and all available observations (e.g., data from Canadian network), d) preparing our completed Pn study for publication, e) preparing completed automatic phase picking analysis for publication, f) collecting data, verifying, and constructing focal mechanisms for deep and shallow earthquakes west of the Cascades (assembling a focal mechanism data base), g) incorporating automated processing into regular data analysis procedures, h) inversion of Puget Sound regional earthquake and explosion data for crust and upper mantle structure.

Publications supported under these contracts are listed in this report. We have completed the 1979 compilation of earthquake hypocenters in western Washington (Noson, Ludwin, and Crosson, 1985) which has just been published. Subse-

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quent bulletins, 1980 - 1984, were delayed due to changes in network operation and increased seismicity at Mt. St. Helens and in the Mt. St. Helens seismic zone. Upcoming bulletins for these years will include data from all of Washington and the northern part of Oregon. These bulletins will be completed before the end of 1985. In addition, we are revising the format of our quarterly catalogs of earthquake hypocenters, establishing quality control criteria, and including additional information regarding data quality, station histories, and prior seismicity in currently active areas.

A project completed under NSF support has provided an improved crustal model of the Mt. St. Helens area, using an inversion technique and arrival times from earthquakes and explosions. Laboratory velocity measurements made under this project have provided a significant constraint on the composition of the crust in the vicinity of Mt. St. Helens. Final results are being prepared for publication.

Under a contract supported by the Washington Public Power Supply System (WPPSS), we are proceeding with a broadband experimental study, using teleseismic sources of crustal and upper mantle structure on the coastal margin.

Summary of network operation, 4th qtr. 1983 through 4th qtr. 1984

A map view showing locations of University of Washington telemetered seismograph stations is shown in Fig. 1. Appendix 1 lists geographical coordinates of stations used for earthquake location. This contract supports 28 stations west of longitude 121W. A tabular representation of major outages and changes of western Washington stations is presented in Table 1. Brief outages are not included.

Locational capability remained poor in the Skagit Valley area, as it has been since the loss of stations RPW and LYW in 1982 due to termination of a phone line. Replacement stations are planned, pending completion of a new communications link. Coverage of the Puget Sound basin will be enhanced by the installation of two

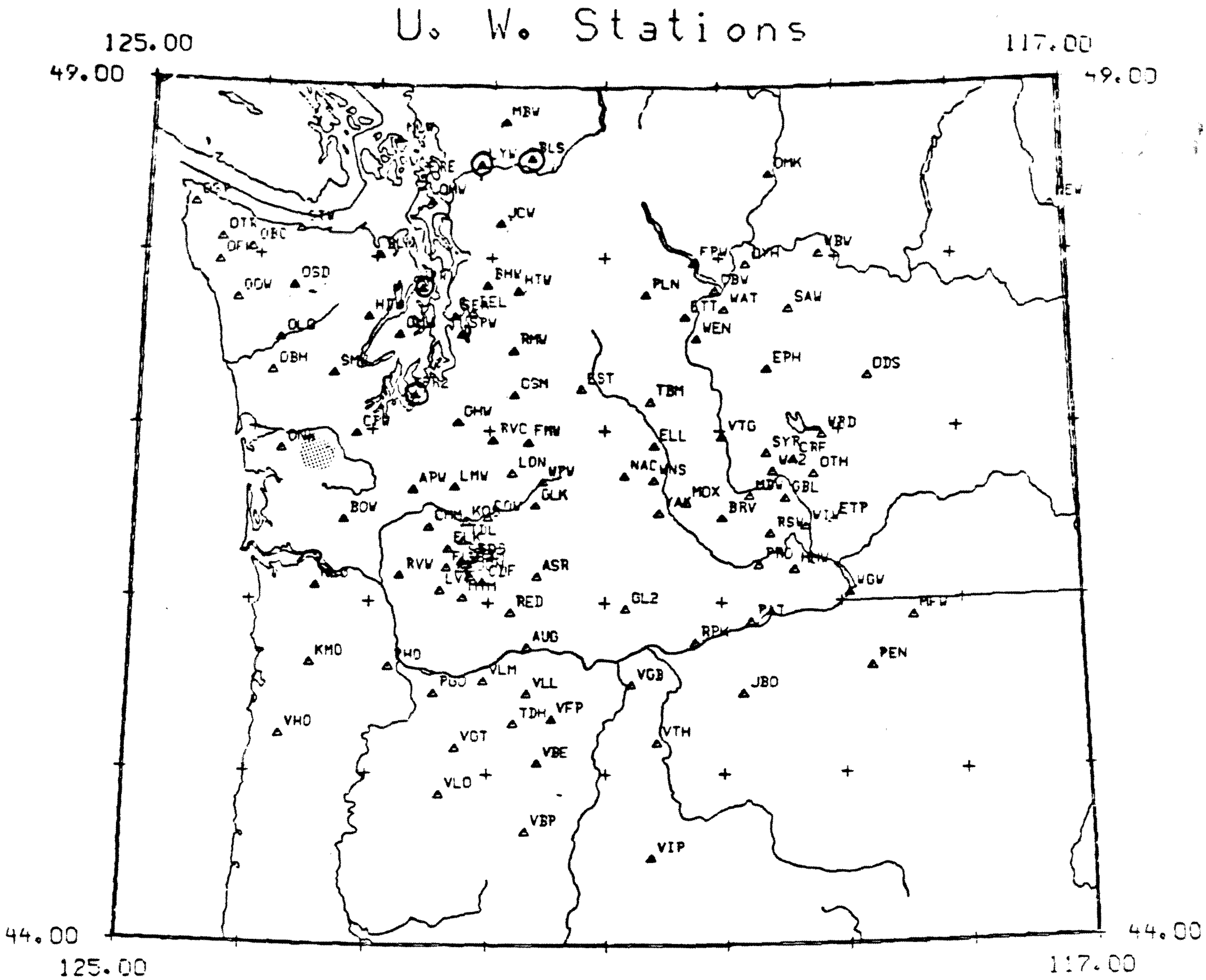


Figure 1. Map of seismographic stations in Washington and northern Oregon. Solid symbols represent stations supported under USGS contract number 14-06-0001-21861. Circled symbols indicate locations of stations currently being installed which will be supported under the same contract. The shaded area near Gray's Harbor is the site of broad-band instruments currently collecting data for use in a structural study funded by W.P.P.S.S..

new stations; on the Kitsap Peninsula near Port Gamble, and on McNeil Island in south Puget Sound. The Olympic Peninsula part of the network was expanded by the addition of station(OSD), which was installed at Snow Dome on Mt. Olympus in September of 1984.

TABLE 1
Western Washington Network
Major station outages and changes, October 1, 1983 - December 30, 1984

Station	Outage Dates	Comments
APW	10/16/83-12/08/83	Vandalized
	11/04/84-12/31/84	Awaits repair
BHW		Replaced MOW on 07/25/84
GSM	11/03/83-07/17/84	struck by lightning
LMW	04/18/84-07/17/84	VCO and transmitter replaced
MCW	12/21/83-03/05/84	pre-amp card and seismometer replaced
MOW	01/18/84 - 07/25/84	Vandalized, replaced by BHW in July, 1984
NLO	04/17/83-09/06/84	longstanding VCO problems resolved
OHW	10/04/83-12/03/83	intermittent
OSD		Installed 09/14/84
RMW	07/24/84-11/07/84	broken cable
RVW	11/16/84-12/31/84	Awaits repair
STW	08/30/84-12/31/84	Destroyed by machinery

The Striped Peak station (STW) was destroyed by state Dept. of Natural Resources road-building equipment in August, 1984. Shortage of parts prevented immediate replacement, and winter weather has prolonged the delay. Station APW on Alpha Peak was damaged by vandalism in October of 1983, but regained function following a site visit in late November, 1983 and some drying-out time. More recently, APW ceased operation in October, 1984 and weather has not permitted a site visit since. The Rose Valley station (RVW) has been inoperative since mid-November, 1984.

NLO (Nicolai Mountain), in a remote area of northwest Oregon, inoperative for some time due to repeated VCO problems, was repaired in September, when a SLU-type VCO was installed. Stations GSM (Grass Mountain), LMW (Ladd Mountain), MCW (Mt. Constitution), OHW (Oak Harbor) , and RMW (Rattlesnake Mountain) also experienced outages, and were repaired.

Earthquake Activity in 1984

Major observations of seismicity for western Washington during calendar year 1984 are summarized in his section. Although this does not correspond exactly to the contract period, it is a more useful and standard interval. Events included in this report have preliminary coda-length magnitudes greater than or equal to 1.5 with locations between 45° and 49° north latitude, and 121° and 125° west longitude. Known and probable blasts are excluded. Fig. 2 is an epicenter map, and Appendix 2 is an earthquake catalog. During 1984, 789 earthquakes are tabulated for western Washington and north-western Oregon, of which 8 were felt, and 35 had magnitudes greater than or equal to 2.7. Fig. 3 is an epicenter map showing these larger events.

The largest and most significant earthquake in western Washington during 1984 was a M_C 3.7 earthquake located at a depth of 50 km beneath Longview and widely felt in the Longview-Kelso area on June 4. During 1984 four well located deep events (depth greater than or equal to 35 km) of coda magnitude greater than or equal to 2.0 occurred south of 47° north latitude. An equal number of deep events were located in the same area in the 14 years preceding 1984. Instrumental coverage of the area improved in 1980, and older catalogs are probably not complete at magnitude 2.0. We are initiating further detailed examination of these deep earthquakes in the belief that they are tectonically significant.

Two felt events of magnitudes 2.6 and 3.4 occurred just south of Concrete Washington on March 16. On July 10, a M_C 2.9 event was felt twenty km west of Concrete, near Mt. Vernon. Felt events of magnitudes 3.1 and 3.2 were located just northwest of Concrete on December 2nd and 3rd. Five more events occurred in a tight cluster at the same spot during the remainder of December, including an

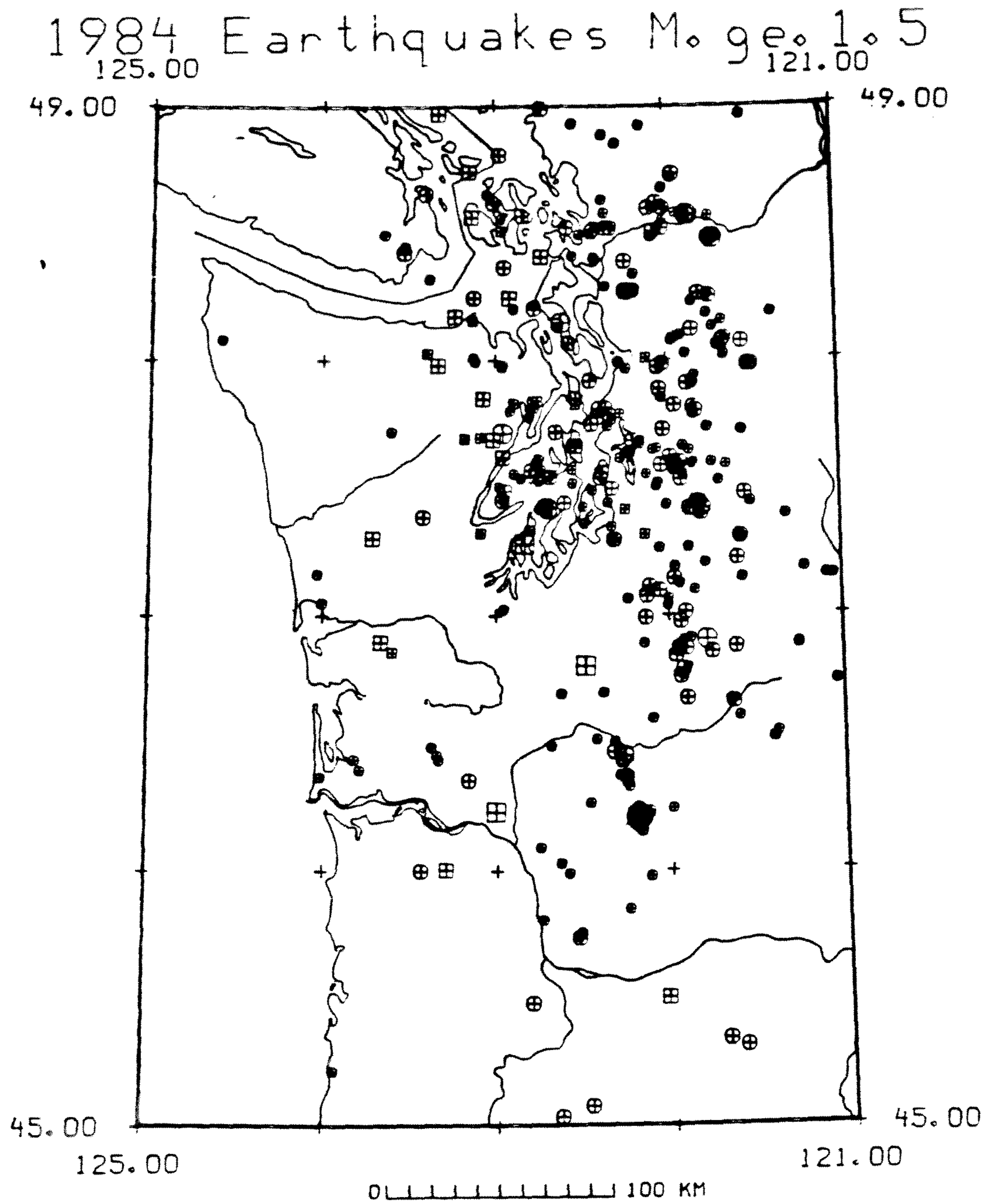


Figure 2. 1984 Earthquake epicenters in western Washington between 121 and 125W longitude; 45 and 49N latitude. Events shown have coda length magnitudes greater than or equal to 1.5. Events shown as octagons are shallower than 35 km, while squares represent events with depths greater than 35 km. Explosions and probable explosions have been excluded.

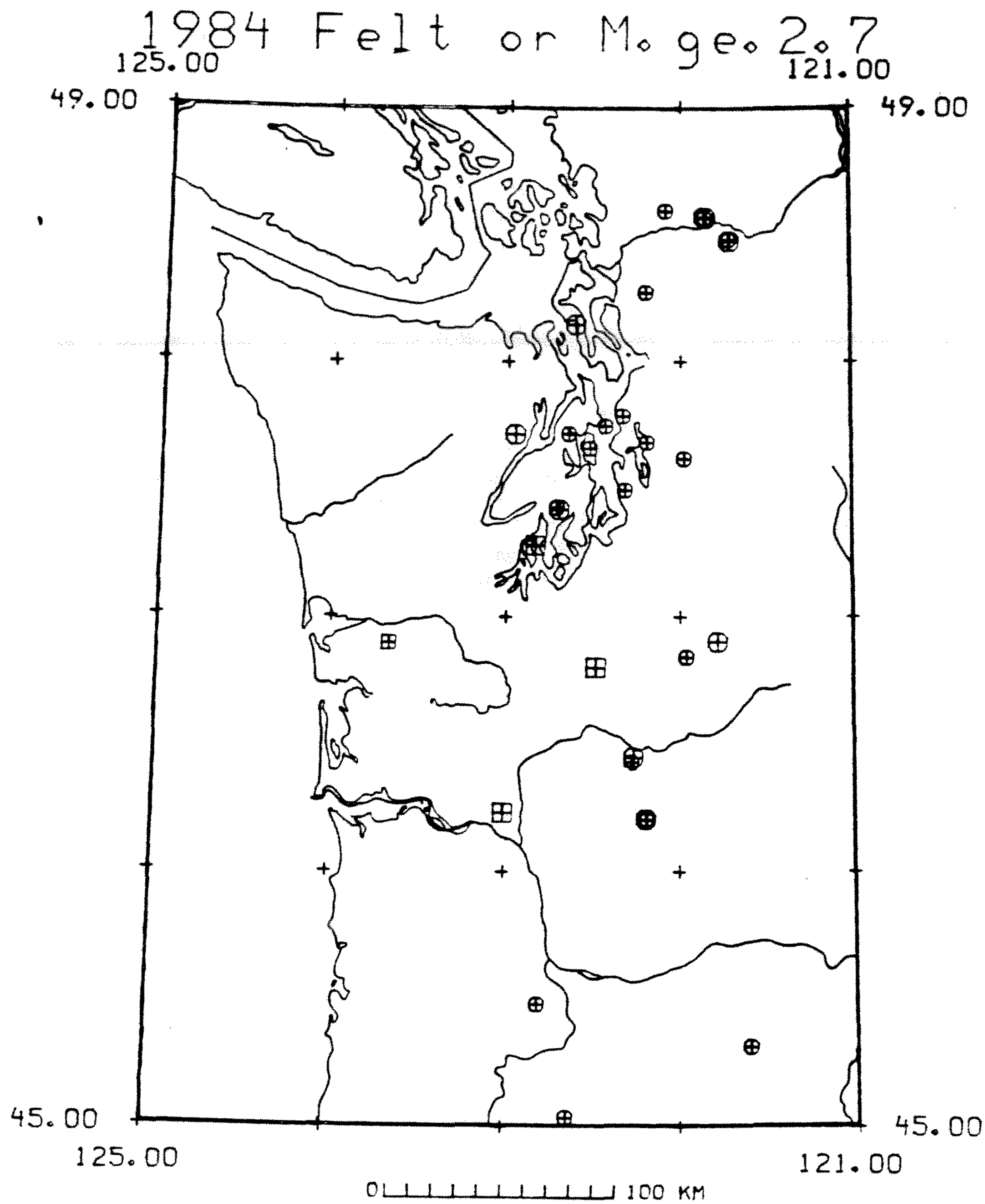


Figure 3. 1984 Earthquake epicenters for events of coda length magnitude greater than or equal to 2.7 between 121 and 125W longitude; 45 and 49N latitude. Events shown as octagons are shallower than 35 km, while squares represent events with depths greater than 35 km. Explosions and probable explosions have been excluded.

unfelt M_C 2.9 on Dec. 23. All events were shallower than 5 km.

On April 27, an earthquake of M_C 2.9, felt at Fall City, was located at a depth of about 8 km. A M_C 2.5 event on December 11 occurred at a depth of about 25 km and was felt in Portland, Oregon. A magnitude 3.6 earthquake located on the southern Kitsap Peninsula on June 2 was not reported felt. Seventeen events of magnitude equal to or greater than 1.0 occurred in the Mt. Rainier vicinity during the fourth quarter of 1984, a slightly elevated rate.

Mt. St. Helens went through four dome-building eruptions in 1984. The first eruption was a continuation of a long-lasting eruption which began early in 1983 and ended in February, 1984. The remaining eruptions, in late March, in June, and in September were brief. The March eruption was preceded and accompanied by a swarm of shallow seismicity which peaked on March 28. The September eruption was accompanied by an intense earthquake swarm with over 500 events large enough to trigger the data acquisition system occurring from September 9 through 12.* The earthquakes were mostly low-frequency type, although medium-high frequency earthquakes also occurred. A large rock and snow avalanche occurred on May 23, and ash plumes on May 14, 26, and 27th. Several mud flows, on May 14, 23, and 26th were accompanied by avalanches.

Uniform Data Base of Pick Files

Considerable progress has been made toward the establishment of a uniform data base of earthquake data. This effort involves "pick files", one for each event, which contain the observations used for location as well as for magnitude and focal mechanism determination. Prior to 1980, eastern and western Washington data were collected on separate networks, with data merged for events recorded on both networks. Arrival times, polarities, and coda lengths for events in western Washington between 1970 and 1980 were picked from film records, recorded in notebooks, and transferred to the U. W. academic computer on punched cards.

* Only selected events from the September eruption were located by network analysts. The catalog of events in Appendix 2 is incomplete in the St. Helens area for events between Sept. 9 and 12, 1984.

Prior to 1975, eastern Washington data was collected by the U. S. Geological Survey, processed similarly to the western Washington data, and stored in Menlo Park, CA. The eastern Washington network covered only the Hanford area until 1975, when it was expanded to about the area of the present network. From 1975 through 1980, eastern Washington data was recorded on film at the U. W. and arrival times were read on a digitizer tablet, automating entry of data into the computer. Various pickfile formats and velocity models were used, in both parts of the network.

In addition to the eastern and western Washington networks, the USGS. collected data in northern Oregon beginning in 1978-9 with the Mt. Hood network, which was replaced by 32 stations spread throughout western Oregon. These data were recorded and archived at the USGS in Menlo Park, CA. In 1983, data from the northern 16 stations was transferred to the University of Washington.

In 1980, an on-line triggered digital system with interactive computer programs was inaugurated, merging the two networks and allowing more efficient processing of data. This move required a new pickfile format. Pre-1980 pickfiles for the eastern and western Washington networks were either stored as cards, or on magnetic tape, and were not available on the computer in the Geophysics Program. In creating a uniform data base, old pickfiles are being retrieved from storage, reformatted, checked against catalogs (to ensure completeness of the data set), and relocated with a current location routine and a single velocity model. Pickfiles since 1980 have also been relocated using the same velocity model and location routine.

Western Washington data from 1970 through 1983 are complete. Eastern Washington data from 1975 through 1979 have been retrieved from cards and reformatted, but not yet checked against catalogs. Data from the Oregon Network and pre-1975 eastern Washington will be obtained from the USGS. Our objective is to integrate all available pick data into a single data base.

Puget Sound Velocity Models

A revised earth crustal model has been computed for the greater Puget Sound region. The new model was derived using a modified version of the method developed by Crosson (1976a). An important modification of the original method is that S wave readings have been incorporated in deriving the new model by using a constant P to S wave velocity ratio determined from observations. Data from 58 events (10 explosions and 48 earthquakes) which occurred from 1980 through 1984 were used. The events were well distributed over the greater western Washington region, and occurred at depths from the surface (including the fixed explosions) to a depth of approximately 53 km. A linear trend in station corrections as a function of distance from the center of the network can bias the model, and was removed from the station corrections at various stages of the inversion processing. All of the arrival time data used to derive this model were obtained by our automated picking algorithm which provides more consistent data quality than hand picking. The final model differs somewhat from the previous model in that (a) the low velocity zone in the depth range from 30 to 40 km is less pronounced (but better constrained), and (b) the shallow surface layer of low velocity rock is much thinner. In addition, a new and more complete set of station corrections was obtained. Event locations in the Puget basin using the new model have generally smaller RMS residuals than locations for the same events using the old model. This indicates that the new Puget Sound model performs as well or better than the previous model (Crosson, 1976b) for routine locations. Table 2 shows the revised crustal velocity structure.

TABLE 2

DEPTH	P VELOCITY	P ERROR	S VELOCITY	S ERROR
0.0	5.40	0.03	3.07	0.06
4.0	6.38	0.01	3.63	0.02
9.0	6.59	0.01	3.75	0.02
16.0	6.73	0.02	3.83	0.04
20.0	6.86	0.01	3.90	0.02
25.0	6.95	0.02	3.95	0.04
32.0	6.90	0.33	3.93	0.60
41.0	7.80	0.02	4.44	0.04

Events in 1979 were located using this "P2" model (Noson, Ludwin, and Crosson, 1985) with station corrections determined for western Washington stations operating in 1979. This model and set of station corrections have also been used to relocate events in our research pickfile database.

An adapted version of the "P2" model will supersede the "P1" model (Crosson, 1976a) now used routinely by the U. W. seismic network. This new version will be named the "P3" model. Because the location routine currently used by the network does not allow low velocity zones, the velocity value of 6.95 will be used between 25 and 41 km depth. Station corrections for all stations in the network are being calculated. The minor adaptations made to the "P2" model to form the "P3" model have no appreciable effect on hypocentral locations.

Regional Seismicity and Tectonics

Figs. 4a and 4b show seismicity above magnitude 2.0 for the period 1974 to 1983. Fig. 4a is for all events shallower than 35 km and Fig. 4b shows all earthquakes deeper than 35 km. The locations of these earthquakes are of high quality based on the new "P2" model for western Washington. They are however preliminary in that we are still integrating and correcting the earthquake data base; in particular, events near the margin of the network may be mislocated in both depth and epicenter. However, the seismicity pattern shown in Fig. 4 is representative, and these results are the best available to date. Comparison of Figs. 4a and 4b show the distinct difference in the distribution of deep and shallow earthquakes.

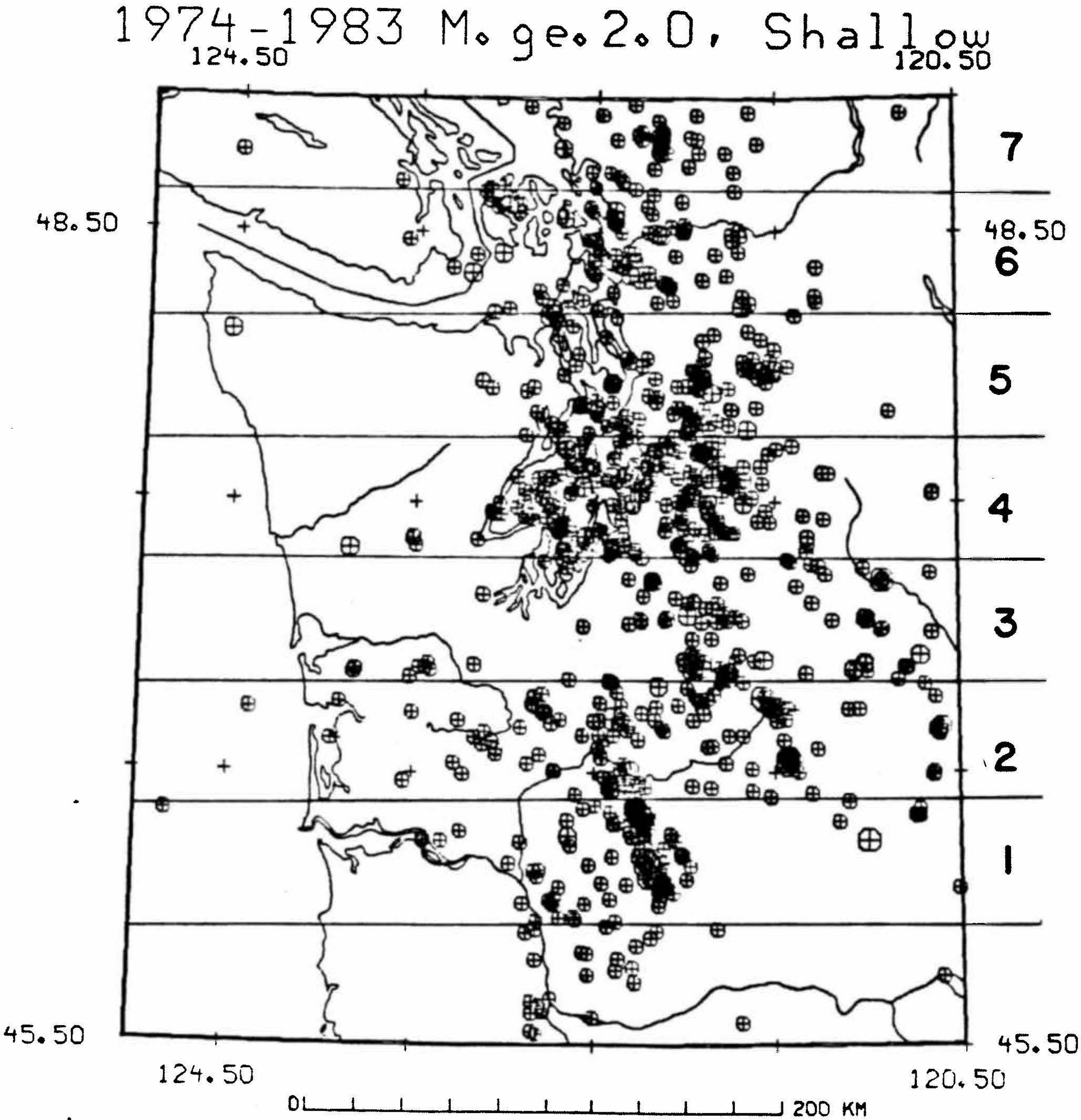


Figure 4a. Map showing epicentral locations of shallow earthquakes for ten year period, 1974 through 1983. Events shown are at depths less than 35 km and magnitudes greater than or equal to 2. The data set was edited to exclude several thousand events in the Mt. St. Helens seismic zone.

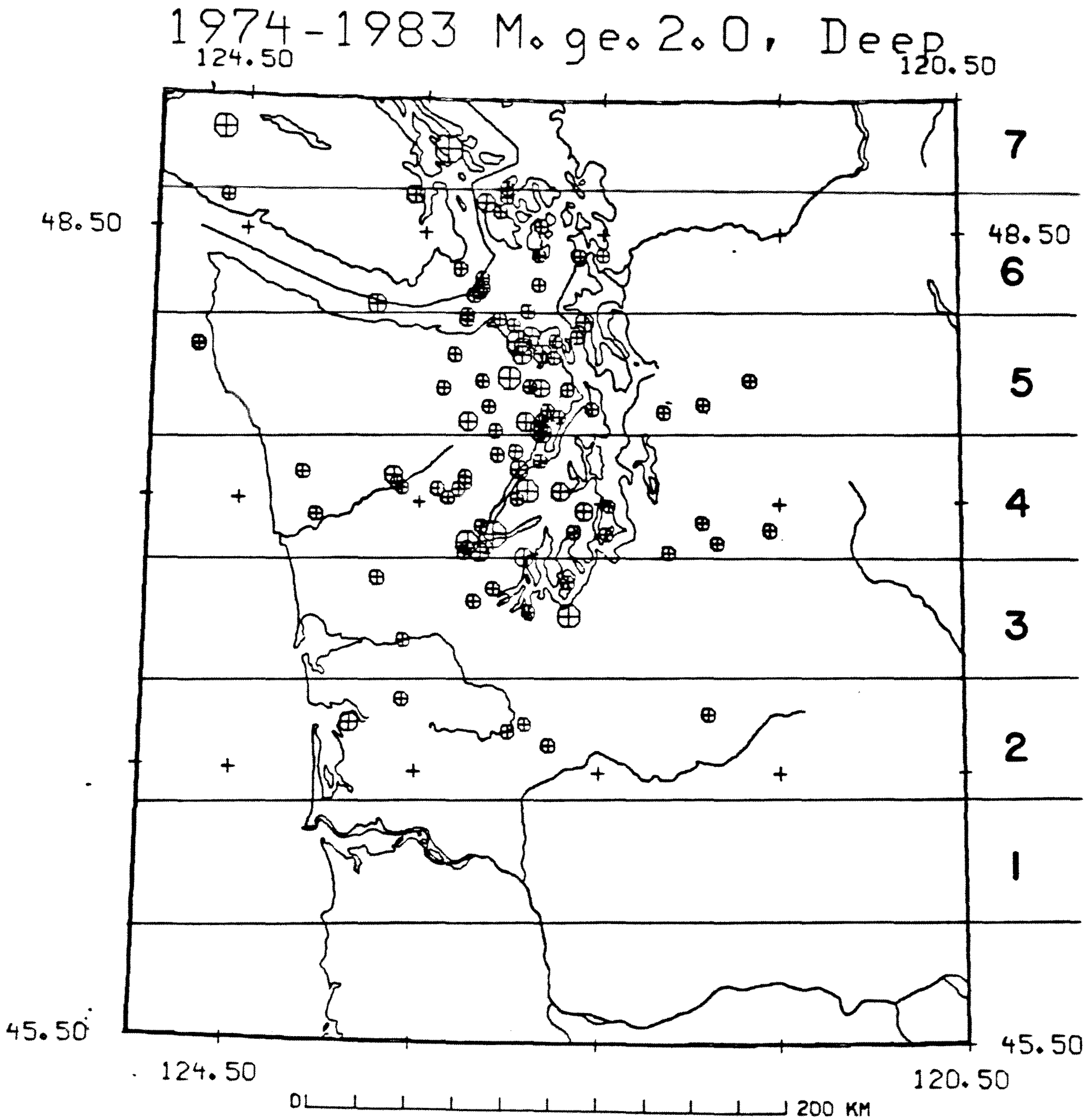


Figure 4b. Map showing epicentral locations of deep earthquakes for ten years, 1974 through 1983. Events shown are at depths greater than or equal to 35 km and magnitudes greater than or equal to 2.

The shallow earthquakes are most numerous, often in tight spatial clusters which may occur as swarms. Some clusters of shallow earthquakes are mainshock/aftershock sequences but many do not have simple time patterns. The St. Helens zone was active before the eruption in 1980, however most seismicity shown is post 1980. Due to the high density of earthquakes at Mt. St. Helens, events in the immediate vicinity are not plotted in Figures 4 and 5.

By contrast with the shallow earthquakes, deep earthquakes occur at a lower rate and more randomly distributed over a sub-planar zone. The large destructive earthquakes in the region such as those in 1946, 1949, and in 1965 have all apparently been in this deep zone. Although most of the deep earthquake activity is concentrated in the Puget Sound region, recently we have detected a few isolated events occurring at depth far south of the Puget Sound region. Although not shown on Fig. 4b, several deep earthquakes south of 47° N latitude occurred in 1984. These isolated detections may be a result of improved station coverage in recent years and constitute perhaps the most direct evidence yet of the presence of a brittle subducting slab beneath the western margin of Oregon.

Fig. 5 shows a successive set of cross sections along the numbered EW corridors shown in Fig. 4. Some interesting details of structure in the deep earthquake suite may be beginning to emerge in these diagrams. In panels 1, 2, and 3, which are south of Puget Sound, there are only scattered deep events and the St. Helens zone shows clearly. By panel 4 the planar nature of the deep earthquakes and the quiet zone separating deep and shallow suites is clear. In this panel, the planar zone is almost flat with an indication of slight shallowing to the west. By panel 5, the deep zone appears to be dipping more steeply to the east and somewhat truncated on the eastern margin. The apparent dip observed in panel 5 may either be due to velocity structure anomalies or to real dip of the hypocenter distribution. By panel 6 the deep suite shows almost no alignment and is disappearing. The

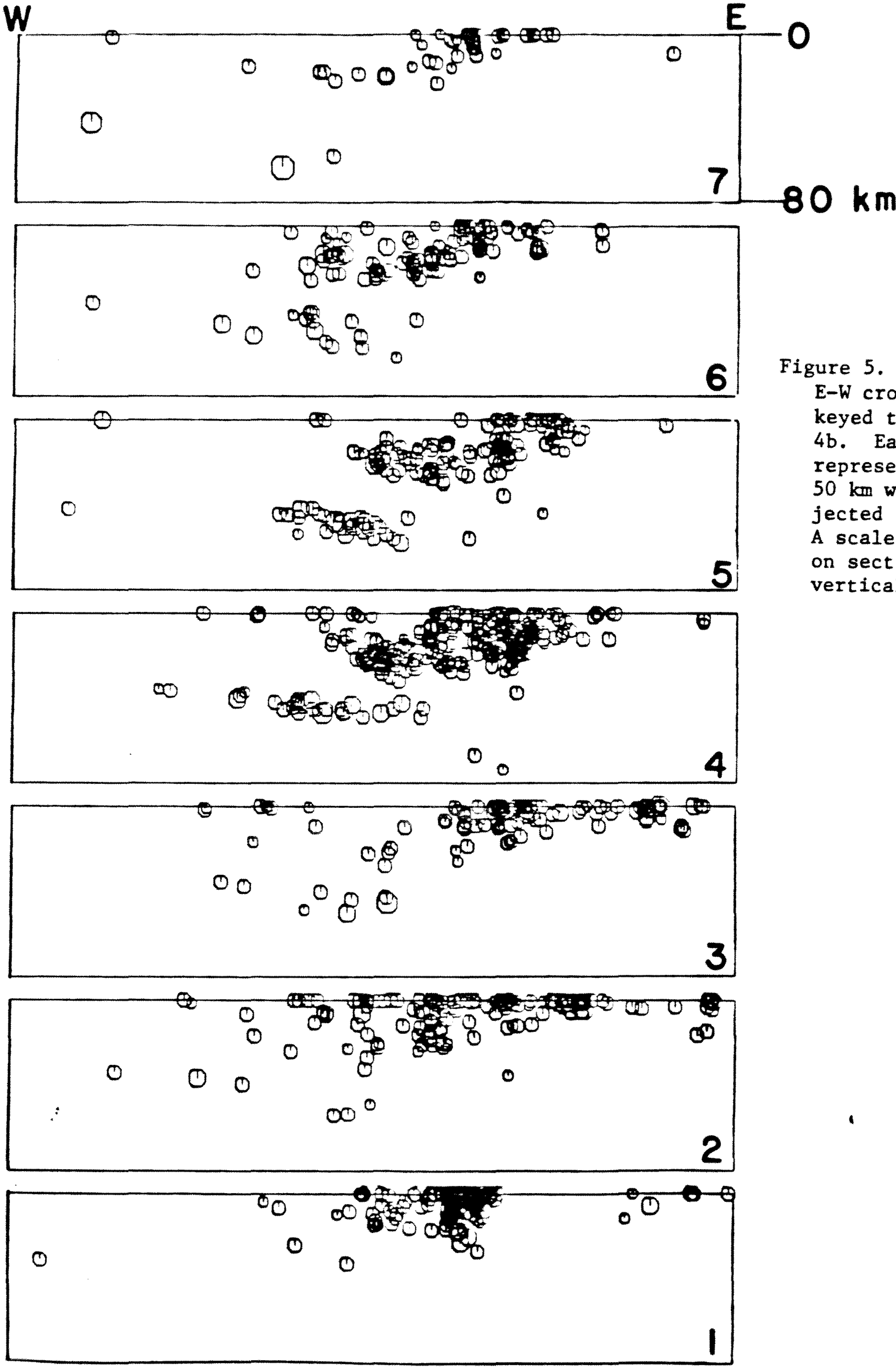


Figure 5.
E-W cross sections keyed to Fig. 4a and 4b. Each cross-section represents events in a 50 km wide zone projected into a plane. A scale is indicated on section 7. No vertical exaggeration.

significance of the deep zone is currently the subject of active research. No single model appears at present to fit all evidence from both structure and seismicity studies.

The St. Helens seismic zone, shown clearly on Fig. 4a, has been thoroughly discussed by Weaver and Smith (1983). This zone has been a persistent feature of the regional seismicity, even apparent on catalog maps preceding the establishment of the St. Helens high density network (Crosson, 1974; Crosson, 1975; Crosson and Millard, 1975; Crosson and Noson, 1978a; Crosson and Noson, 1978b; Crosson and Noson, 1979; Noson and Crosson, 1980; Noson, Ludwin, and Crosson, 1985). Weaver and Smith (1983) and Grant et al. (1984) have shown that focal mechanisms on the St. Helens zone are consistent with right lateral strike-slip motion along slip surfaces oriented parallel to the trend of the zone. The significance of the zone for earthquake hazards remains somewhat uncertain, however, in view of the absence of surface faulting and the uncertainty of both the length of the zone and the largest magnitude event that may occur there (the Elk Lake earthquake of Feb. 14, 1981 was of magnitude 5.5). In detail, earthquakes on the zone occur in 3 main and quite distinct clusters. The zone may represent a distributed zone of deformation without a single dominant fault. Although Weaver and Smith have argued that the focal mechanism evidence from this zone indicates that the principal P tectonic axis is rotated to a northeasterly direction compared to the northerly direction in Puget Sound, Ludwin and Crosson (1984) have argued that the St. Helens zone mechanisms may indeed be consistent with the same stress distribution as Puget Sound earthquakes, provided preexisting fractures control the faulting. Indeed, we have found central Puget Sound earthquakes with mechanisms virtually identical to those on the St. Helens zone.

On a decade length time scale, the temporal pattern of seismicity in western Washington has remained fairly stable. There have been a number of swarms and sequences of earthquakes that produce complex time variations in detail, particularly in the shallow lithosphere. Weaver (personal communication) has suggested that there may be zones of quiescence on longer time scales developing on the eastern Puget Sound basin. Careful examination of the pre-digital network earthquake data base may shed light on longer term variations. The most striking single time variation in the seismicity pattern is associated with the increase of activity in the St. Helens region.

Automatic Event Processing

Automatic picking of time, polarity and coda-lengths of seismic signals is currently being tested on all incoming data, and will eventually replace some of the analysis currently done by network staff. Automatic picking was particularly useful during the September, 1984 dome-building activity at Mt. St. Helens. Several hundred events were located in the vicinity by the auto-picker. Because of the large volume of data, many of these events were not processed by the network staff. The auto-picked locations were available quickly for use in research. A manuscript on the autopicking algorithm is being prepared for publication.

Magnitude Calibration

The automatic picking program currently in the final stages of testing and evaluation should provide consistent measurement of coda lengths, and therefore improve the consistency of magnitude estimation. To calibrate the coda-length magnitude estimates, events are selected which were recorded on Wood-Anderson instruments, and also recorded digitally by the U. W. Seismic Network online system which began operation in 1980. Each digitally recorded event is run through the autopicking algorithms, which estimate coda length by fitting an exponential curve to the amplitude envelope of the data. Simultaneously, each Wood- Anderson recording is read manually, and a Richter magnitude computed. Some events have to be discarded because of amplitude clipping on the Wood-Anderson records. The mean, median, and standard deviation of the coda lengths determined by the auto-picker are calculated, and plots showing these values versus the Richter magnitudes are made. Hopefully, a simple linear relation between the Richter magnitude and some statistical measure of the coda lengths will become evident. At present, we are still compiling and auto-picking the set of events which have both Wood-Anderson and digital records.

Magnitude Threshold Analysis

The area shown in Fig. 6 was evaluated to determine the magnitude levels at which the catalog is complete. The region was divided into one degree quadrangles as shown, and a magnitude completeness level was determined for each quadrangle where events were located between 1981 and 1983. The number of events per subregion varied from zero (in areas at the edge of the network), to over three thousand, near Mt. St. Helens. Fig. 6 and Table 3 list number of events. Two methods were used to evaluate magnitude completeness, depending on number of located events. In areas where at least 25 events occurred the linear relation;

$$\log N = A - bM$$

where N is the number of earthquakes of magnitude M or greater (A and b are constants) was used. Reduced network sensitivity to events of small magnitude results in a departure from linearity. By plotting log N versus M; the magnitude level of completeness is determined empirically to be the point where the linear relation no longer holds. Where 25 or fewer events occurred the linear relation is difficult to determine, and another method was used.

Using regions where the first method applies, the average difference between the magnitude completeness level and the smallest event located in an area was

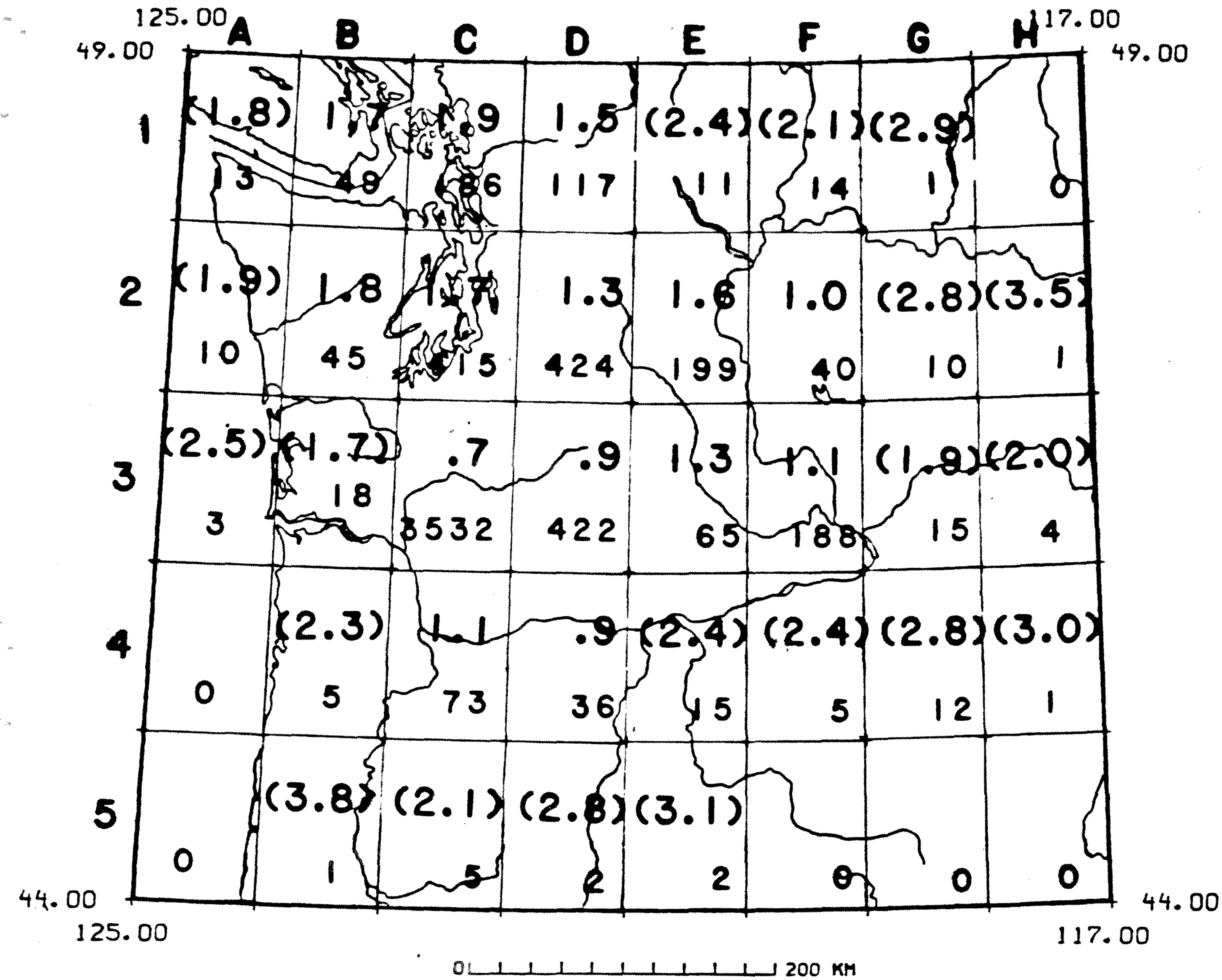


Figure 6 : Estimated magnitude completeness levels (large numbers), and number of located events 1981 through 1983 (small numbers). Magnitude completeness levels were estimated on the basis of log N vs. M plots when 25 or more events were located in an area. Where less than 25 events occurred, 1.3 magnitude units were added to the smallest located event in the area, and the magnitude completeness level is shown in parenthesis. The value of 1.3 magnitude units is an average from the areas with 25 or more events, representing the difference between smallest event located, and completeness magnitude.

determined. The difference between completeness and smallest located event had a mean (and mode) of 1.3 magnitude units. In the second method, this value was added to the magnitude of the smallest located event in sub-regions where 25 or fewer events occurred to give an estimate of completeness.

Results are shown in Fig. 6 and Table 3. Where 25 or fewer events were located, the magnitude completeness is in parenthesis, and was determined by the second method. No magnitude completeness level is given for areas where no earthquakes were located (1981-1983). Where only one event was recorded (e.g. quadrangles B5, G1, H2, and H4) the method used may not be a reliable indicator of completeness. Table 3 and Fig. 6 are revised versions, and replace all previously published similar figures.

TABLE 3

DATA USED IN FIGURE 6

AREA	# OF EVENTS	COMPLETE AT	AREA	# OF EVENTS	COMPLETE AT
A1	13	(1.6)	E1	11	(2.4)
A2	10	(1.9)	E2	199	1.6
A3	3	(2.5)	E3	65	1.3
A4	0	-	E4	15	(2.4)
A5	0	-	E5	2	(3.1)
B1	49	1.7	F1	14	(2.1)
B2	45	1.6	F2	40	1.0
B3	18	(1.7)	F3	166	1.1
B4	5	(2.3)	F4	5	(2.4)
B5	1	(3.6)	F5	0	-
C1	186	1.9	G1	1	(2.9)
C2	415	1.7	G2	10	(2.5)
C3	3532	.7	G3	15	(1.9)
C4	73	1.1	G4	12	(2.6)
C5	2	(2.6)	G5	0	-
D1	117	1.5	H1	0	-
D2	424	1.3	H2	1	(3.5)
D3	422	.9	H3	4	(2.0)
D4	36	(.9)	H4	1	(3.0)
D5	2	(2.1)	H4	0	-

Calibrated Telemetry Stations

Since early 1982, some stations in the statewide telemetered network have been calibrated so that recovery of absolute ground motion is possible. Fig. 7 shows those sites at which calibrated equipment has operated or is to be installed in the immediate future. Our objective is to provide at least skeletal network-wide coverage with calibrated stations, concentrating on areas of significant seismicity. Additional calibrated equipment will gradually be installed at selected stations as part of our program to upgrade data quality and increase operational reliability.

Equipment at each calibrated station consists of a Geotech S-13 seismometer and a Morrissey-Interface Technology amplifier/VCO package. All stations operating as of March 1985 have a seismometer free period of 1.00 second. Future installations may utilize a seismometer free period of 1.25 second to take advantage of the slightly more broad-band characteristic of the lengthened period. Although standard damping is 0.70 critical for best flat velocity response, several early installations were damped about 0.60 through error. Most calibrated stations use a Morrissey-Interface Technology discriminator, but some use Emtel discriminators which have similar response characteristics. The complete systems should all have similarly-shaped response curves differing only in absolute gain level. Fig. 8 shows an approximate response curve for the whole system (with a 1-second seismometer free period) as recorded on the digital system at the University of Washington.

Calibration is performed at the U. W. using sine-wave and transfer function techniques. The noise level in Seattle is fairly high and restricts useful sine-wave calibration frequencies to the range between 0.1 and 8 Hz. The noise level also prohibits definitive determination of calibration coil motor constants, although verification of the Geotech determinations within a few percent is possible. Verification of response after installation is possible because the Morrissey-Interface Technology amplifier/VCO has a calibrator which generates a DC pulse

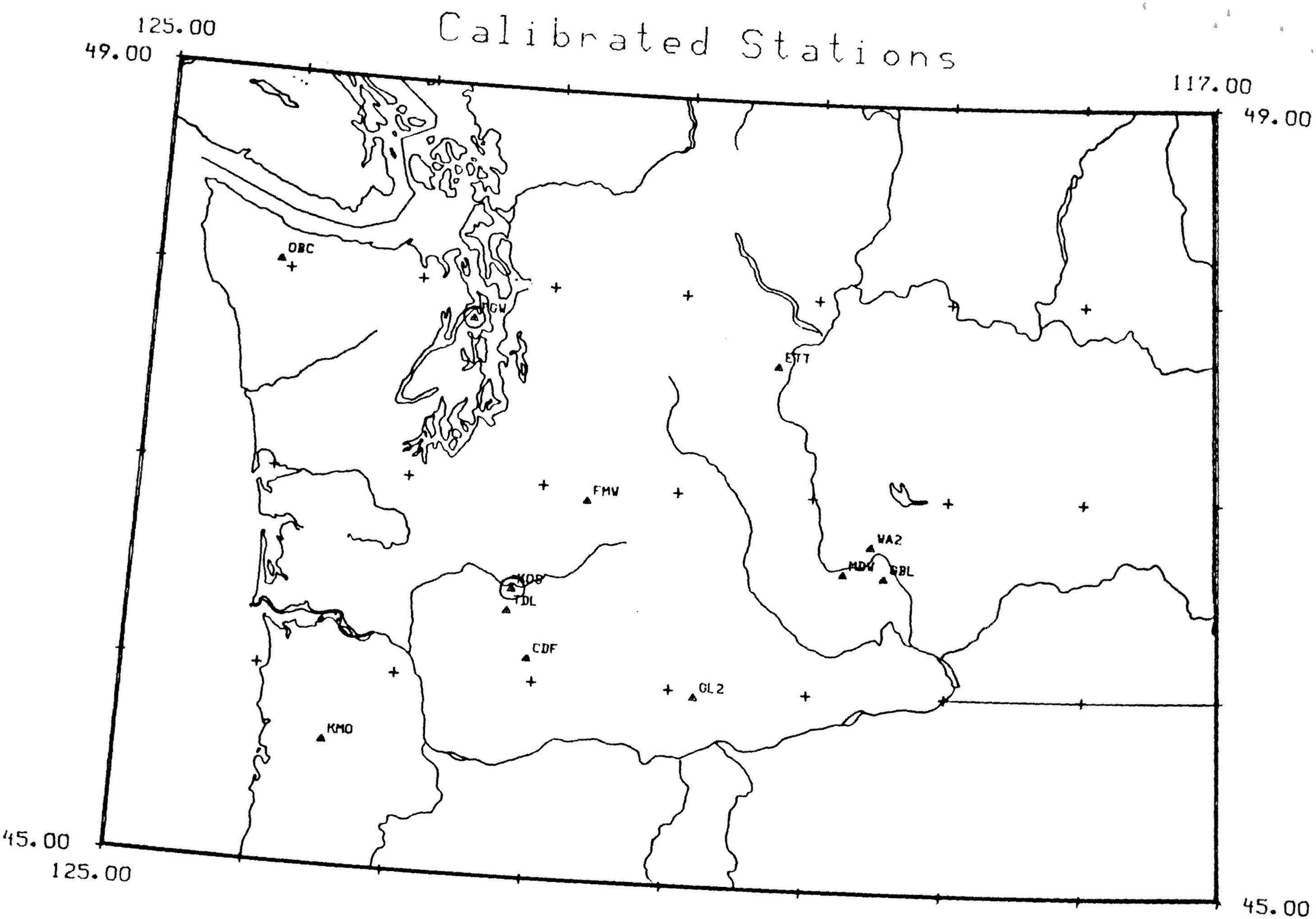
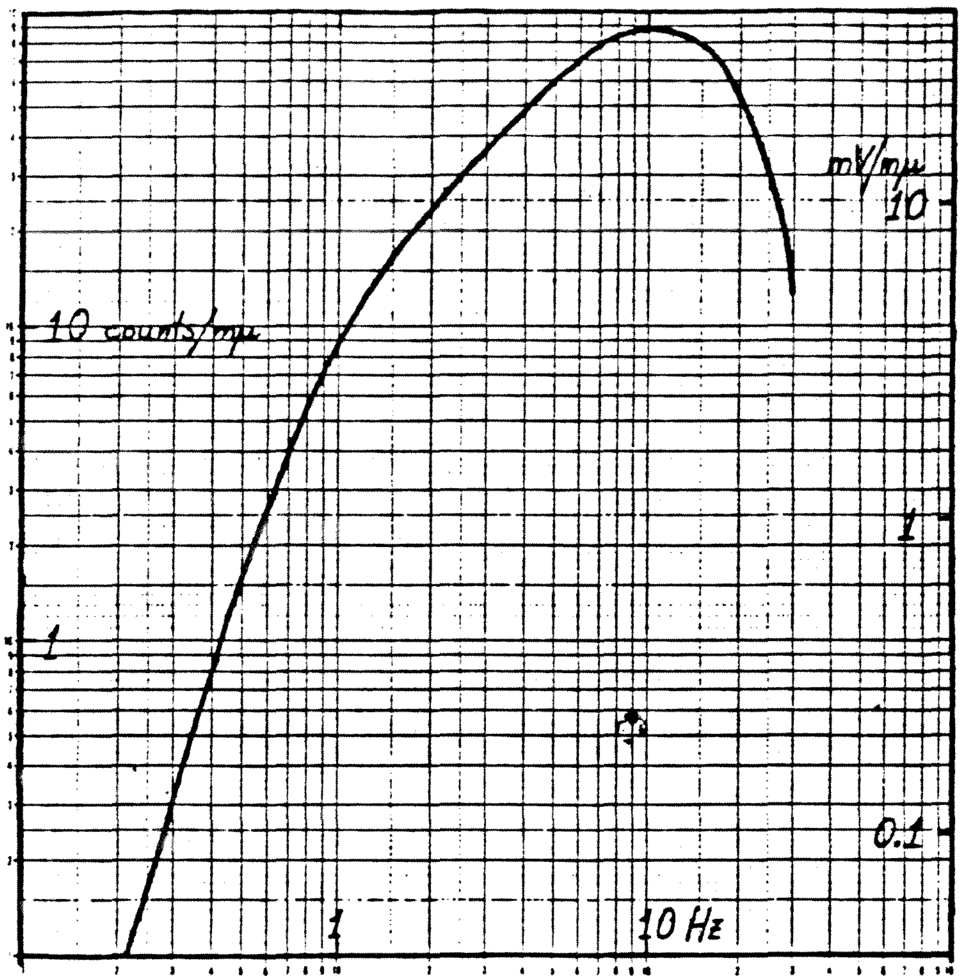


Figure 7. Map of calibrated stations in U.W. seismic network Circled symbols indicate locations of new calibrated stations currently being installed.



RESPONSE OF COMPLETE ENTIAT TELEMETRY SYSTEM AS RECEIVED AND RECORDED AT THE UNIVERSITY

Figure 8. Relative magnification curve for complete calibrated short-period system into online computer.

and sine waves at two frequencies (3 and 10 Hz). Daily calibration times are set using inexpensive crystal-oscillator wristwatchs. Unfortunately, we are not able to utilize these calibration signals fully with the present digital data acquisition system.

Structure of continental margin using broad-band teleseismic data

Under other contract support, we are proceeding with a broadband experimental study on the coastal margin. We mention this study because of its relevance to the structure, tectonics, and earthquake hazard of western Washington. The purpose of the broadband study is to obtain a vertical structure model in a critically important margin region where the plate depth and dip may be determined with certainty. In this project, we are operating a network of 4 broadband digital stations in the area indicated in Fig. 1, and developing data analysis techniques for receiver function modeling along lines first suggested by Langston (1979). In the broadband analysis, we are collaborating with Dr. Tom Owens at University of Missouri, Columbia who recently completed the receiver function analysis for several RSTN stations (Owens, 1984; Owens et al, 1984). Dr. Owens will spend time at the University of Washington in the summer of 1985 to work on this project.

Stress determination from focal mechanisms of shallow events

Over the years, various studies of focal mechanisms have been undertaken, but no system has been established to comprehensively compile and classify all available mechanisms. Therefore, we are creating a data base of events for which focal mechanisms have been determined and trace data checked. A search is also being made to identify other events for which focal mechanisms can be determined so that a complete data base of focal mechanisms will be available. To date, evidence from focal mechanisms is difficult to reconcile with regional stress; focal mechanism data seem to favor NS compression rather than the N70E direction predicted by Savage et al. (1981) on the basis of geodetic strain measurements, or the N50E direction of plate convergence determined from ocean-floor magnetic anomalies (Riddihough, 1984). Furthermore, some focal mechanisms (e.g., Taber, 1983) have been observed that reflect stress orientations which contradict the expectation from locked subduction. Although Weaver and Smith have argued that the focal mechanism evidence from the St. Helens seismic zone indicates that the principal P tectonic axis is rotated to a northeasterly direction compared to the northerly direction in Puget Sound, Ludwin and Crosson (1984) argue that the St. Helens zone mechanisms may be consistent with the same stress distribution as Puget Sound earthquakes, provided preexisting fractures control the faulting. Indeed, we have found central Puget Sound earthquakes with mechanisms virtually identical to those on the St. Helens zone.

If earthquakes occur on preexisting fractures which are planes of weakness, then the apparent stress direction from focal mechanisms does not necessarily define the true stress direction (McKenzie, 1969). McKenzie made the single assumption that the slip vector is always parallel to the direction of resolved shearing stress in the fault plane. Using this assumption, for a particular ratio of principal stresses and a particular fault surface, all possible orientations of true principal stress can be defined. The actual axis of greatest principal stress may be as much as 90 degrees away from the apparent axis determined by the P axis of a focal mechanism.

Recently, Gephart and Forsyth (1984) have devised a method of determining tectonic stress orientation, which also gives information about the ratio of principal stresses. This method depends on a statistical distribution of focal mechanisms and uses physical principles stated by McKenzie (1969) in addition to a "minimum rotation" criteria. This method, or a modification of it, promises to provide a powerful tool for extracting stress information from focal mechanism data; and may help resolve the question of tectonic stress in the Pacific Northwest margin area. We will address the question of whether single uniform tectonic stress fields are responsible for the deep or shallow earthquake suites or whether complex fields are called for.

Pn analysis

A study of critically refracted compressional (Pn) waves in Washington by Chris Zervas has been completed as a M.S. thesis. An article on the same topic by Zervas and Crosson is being prepared for publication. Appendix 3 is a preprint of the article. Preliminary results were discussed in the 1983 Final Technical Report for USGS contract number 14-08-21192.

Publications supported under this contract

Articles:

Noson, Linda Lawrance, Ruth S. Ludwin, Robert S. Crosson, 1985, Compilation of Earthquake Hypocenters in Western Washington - 1979, State of Washington Department of Natural Resources Information Circular 79.

Ludwin, R. S., S.D. Malone, R.S. Crosson, 1985 (in press), Washington Earthquakes 1983, National Earthquake Information Service.

Zervas, C.E., and R.S. Crosson, 1985 (in preparation), Pn Observations and Interpretations in Washington.

Crosson, R.S., 1985 (in preparation), Comment on 'Geodetic Strain Measurements in Washington' by J.C. Savage, M. Lisowski, and W.H. Prescott, to be submitted to JGR.

Crosson, R.S., 1985 (in preparation), A New Algorithm for Automated Determination of Phase Arrival Times and its Application to Regional Network Data, to be submitted to B.S.S.A..

Abstracts:

Zervas, C., and R.S. Crosson, Pn velocities and station delays in Washington, EOS, 65, no. 17, p. 330, 1984.

Ludwin, R. S. and R.S. Crosson, The Azimuth of Regional Tectonic Compression in the Pacific Northwest from Shallow Thrust Earthquakes, EOS, 65, no. 45, p. 986, 1984.

Theses:

Zervas, Chris Eugene, 1984, A time term analysis of Pn Velocities in Washington, M. S. Thesis, University of Washington Geophysics Program

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Bibliography

Crosson, R.S., *Compilation of earthquake hypocenters in western Washington, July 1970 to December 1972*, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1974.

Crosson, R.S., *Compilation of earthquake hypocenters in western Washington, 1973*, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1975.

Crosson, R.S. and R.C. Millard, *Compilation of earthquake hypocenters in western Washington, 1974*, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1975.

Crosson, R.S. and L.L. Noson, *Compilation of earthquake hypocenters in western Washington, 1976*, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1978.

Crosson, R.S. and L.L. Noson, *Compilation of earthquake hypocenters in western Washington, 1975*, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1978.

Crosson, R.S. and L.L. Noson, *Compilation of earthquake hypocenters in western Washington, 1977*, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1979.

Gephart, J.W. and D.W. Forsyth, An improved method for determining the regional stress tensor using earthquake focal mechanism data: Application to the San Fernando earthquake sequence, *J. Geophys. Res.*, **89**, 9305-9320, 1984.

Grant, W.C., C.S. Weaver, and J.E. Zollweg, The 14 February 1981 Elk Lake, Washington earthquake sequence, *Bull. Seis. Soc. Am.*, **74**, 1289-1309, 1984.

Langston, C.A., Structure under Mt. Rainier, Washington, inferred from teleseismic body waves, *J. Geophys. Res.*, **84**(B9), 4749-4762, 1979.

Ludwin, R. S. and R. S. Crosson, The Azimuth of Regional Tectonic Compression in the Pacific Northwest from Shallow Thrust Earthquakes, *EOS*, **65**(45), 1015, 1984.

McKenzie, D.P., The relation between fault plane solutions for earthquakes and the directions of the principle stresses, *Bull. Seis. Soc. Am.*, **59**(2), 591-601, 1969.

Noson, L.L. and R.S. Crosson, *Compilation of earthquake hypocenters in western Washington, 1978*, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1980.

Noson, L.L., R. S. Ludwin, and R. S. Crosson, *Compilation of earthquake hypocenters in Western Washington, 1979*, State of Washington Department of Natural Resources , 1985.

Owens, T.J., G. Zandt, and S.R. Taylor, Seismic evidence for an ancient rift beneath the Cumberland Plateau, TN: A detailed analysis of broadband teleseismic P-waveforms, *J. Geophys. Res.*, **89**, 7783-7795, 1984.

Owens, T.J., *Determination of crustal and upper mantle structure from analysis of broadband teleseismic P-waveforms*, Univ. of Utah, Dept. of Geology and Geophysics, 1984. Ph.D. Thesis

Riddihough, R., Recent movements of the Juan de Fuca plate system, *J. Geophys. Res.*, **89**(B8), 6980-6994, 1984.

Savage, J. C., M. Lisowski, and W. H. Prescott, Geodetic strain measurements in Washington, *J. Geophys. Res.*, **86**(B6), 4929-4940, 1981.

Taber, J.J., *Crustal structure and seismicity of the Washington continental margin*, University of Washington Geophysics Program, 1983. Ph.D. Thesis

Weaver, C. S. and S. W. Smith, Regional tectonic and earthquake hazard implications of a crustal fault zone in southwestern Washington, *J. Geophys. Res.*, **88** (B12), 10,371-10,383, 1983.

APPENDIX 1.

STATIONS USED FOR LOCATION OF WESTERN WASHINGTON EVENTS

STATIONS USED FOR LOCATION OF WESTERN WASHINGTON EVENTS

The listing of stations used in locating seismic events in western Washington consists of stations located in western Washington and north-west Oregon which were supported under USGS contract 14-08-0001-21861, and stations located in eastern Washington and north-east Oregon supported under other contracts. The first column gives the 3-letter station designator. Station north latitude and west longitude are given in the second and third columns in degrees, minutes and seconds. The fourth column gives station elevation in km, and the fifth indicates landmarks for which stations were named.

TABLE 3

Stations used to locate events

STATIONS SUPPORTED UNDER USGS CONTRACT NUMBER 14-08-0001-21861

	LAT	LONG	EL	NAME
APW	46 39 06.0	122 38 51.0	0.457	Alpha Peak
BHW	47 50 12.6	122 01 55.8	0.198	Bald Hill
BLN	48 00 26.5	122 58 18.6	0.585	Blyn Mountain
BOW	46 28 30.0	123 13 41.0	0.870	Boistfort Mountain
CPW	46 58 25.8	123 08 10.8	0.792	Capitol Peak
FMW	46 55 54.0	121 40 19.2	1.890	Mt. Fremont
GHW	47 02 30.0	122 16 21.0	0.268	Garrison Hill
GMW	47 32 52.5	122 47 10.8	0.506	Gold Mountain
GSM	47 12 11.4	121 47 40.2	1.305	Grass Mountain
HDW	47 38 54.6	123 03 15.2	1.006	Hoodsport
HTW	47 48 12.5	121 46 08.6	0.829	Haystack Lookout
JCW	48 11 36.6	121 55 46.2	0.616	Jim Creek
LMW	46 40 04.8	122 17 28.8	1.195	Ladd Mountain
MBW	48 47 02.4	121 53 58.8	1.676	Mt. Baker
MCW	48 40 46.8	122 49 56.4	0.693	Mt. Constitution
NLO	46 05 18.0	123 27 00.0	0.900	Nicolai Mountain
OSD	47 49 15.0	123 42 06.0	2.010	Snow Dome
OHW	48 19 24.0	122 31 54.6	0.054	Oak Harbor
RMW	47 27 35.0	121 48 19.2	1.024	Rattlesnake Mountain
RVW	46 08 58.2	122 44 37.2	0.460	Rose Valley
SHW	46 11 33.0	122 14 12.0	1.423	Mt. St. Helens
SMW	47 19 10.2	123 20 30.0	0.840	South Mountain
SPW	47 33 13.3	122 14 45.1	0.008	Seward Park
STW	48 09 00.8	123 40 12.0	0.308	Striped Peak

STATIONS SUPPORTED UNDER OTHER CONTRACTS

	LAT	LONG	EL	NAME
ASR	46 09 02.4	121 35 33.6	-	Mt. Adams - Stagman Ridge
AUG	45 44 10.0	121 40 50.0	0.865	Augspurger Mountain
BRV	46 29 07.2	119 59 29.4	0.200	Black Rock Valley
CBW	47 48 25.5	120 01 57.6	1.160	Chelan Butte
CDF	46 06 58.2	122 02 51.0	0.780	Cedar Flat
CMM	46 26 07.0	122 30 21.0	0.620	Crazy Man Mountain
COW	46 29 27.6	122 00 43.6	0.305	Cowlitz River
CRF	46 49 30.6	119 23 18.0	0.260	Corfu
DYH	47 57 37.8	119 46 09.6	-	Dyer Hill
EDM	46 11 50.4	122 09 00.0	1.609	East Dome, Mt. St. Helens
ELK	46 18 20.0	122 20 27.0	1.270	Elk Rock
ELL	46 54 35.0	120 34 06.0	0.805	Ellensburg
EPH	47 21 07.8	119 35 46.2	0.628	Ephrata
EST	47 14 16.8	121 12 21.8	0.756	Easton
ETP	46 27 53.4	119 03 32.4	0.250	Eltopia
ETT	47 39 18.0	120 17 36.0	0.439	Entiat
FL2	46 11 47.0	122 21 01.0	1.378	Flat Top 2
FPW	47 58 09.0	120 12 46.5	0.352	Fields Point
GBL	46 35 51.6	119 27 35.4	0.330	Gable Mountain
GLK	46 33 50.2	121 36 30.7	1.320	Glacier Lake
GL2	45 57 50.0	120 49 15.0	1.000	New Goldendale
HHW	46 10 59.0	119 22 59.0	0.415	Horse Heaven Hills
KMO	45 38 07.8	123 29 22.2	-	Kings Mountain
KOS	46 27 40.8	122 11 25.8	0.828	Kosmos
JBO	45 27 41.7	119 50 13.3	-	Jordan Butte
JUN	46 08 48.0	122 09 10.8	1.049	June Lake
LON	46 45 00.0	121 48 36.0	0.853	Longmire(WWSSS and DWWSS)
LVP	46 04 06.0	122 24 30.0	1.170	Lake View Peak
MDW	46 36 48.0	119 45 39.0	0.330	Midway
MFW	45 54 10.8	118 24 21.0	-	Milton-Freewater
MOX	46 34 38.0	120 17 35.0	0.540	Moxie City
MTM	46 01 31.8	122 12 42.0	1.121	Mt. Mitchell
NAC	46 44 03.8	120 49 33.2	0.738	Naches
NEW	48 15 50.0	117 07 13.0	1.000	Newport Observatory (USGS)
OBC	48 02 07.1	124 04 39.0	0.938	Olympics - Bonidu Creek
OBH	47 19 34.5	123 51 57.0	0.383	Olympics - Burnt Hill
ODS	47 18 24.0	118 44 42.0	-	Odessa
OFK	47 57 00.0	124 21 28.1	0.134	Olympics - Forks
OLQ	47 30 58.1	123 48 31.5	0.121	Olympics - Lake Quinalt
OMK	48 28 49.2	119 33 39.0	0.421	Omak
ONR	46 52 37.5	123 46 16.5	0.257	Olympics - North River
OOW	47 44 12.0	124 11 22.0	0.743	Octopus West
OSP	48 17 05.5	124 35 23.3	-	Olympics - Sooes Peak
OTH	46 44 20.4	119 12 59.4	0.260	Othello
OTR	48 05 08	124 20 39	0.712	Tyee Ridge
PAT	45 52 50.1	119 45 40.1	0.300	Paterson
PEN	45 36 43.2	118 45 46.5	-	Pendleton
PGO	45 28 00.0	122 27 10.0	0.237	Portland - Gresham
PHO	45 37 07.8	122 49 50.2	0.299	Portland - Portland Hills
PLN	47 47 04.8	120 37 58.8	2.000	Plains
PRO	46 12 45.6	119 41 09.0	0.552	Prosser

continued

	LAT	LONG	EL	NAME
RED	45 56 13.2	121 49 10.8	1.510	Red Mountain
RPK	45 45 42.0	120 13 50.0	0.330	Roosevelt Peak
RSW	46 23 28.2	119 35 19.2	1.037	Rattlesnake Mountain
RVC	46 56 34.5	121 58 17.3	1.000	Mt. Rainier - Voight Creek
SAW	47 42 06.0	119 24 03.6	-	St. Andrews
SEA	47 39 18.0	122 18 30.0	0.030	Seattle
SOS	46 14 38.5	122 08 12.0	1.270	Source of Smith Creek
STD	46 14 16.0	122 13 21.9	1.268	Studebaker Ridge
SUG	46 12 52.2	122 10 29.4	1.859	Sugar Bowl - Mt. St. Helens
SYR	46 51 46.8	119 37 04.2	-	Smyrna
TBM	47 10 10.0	120 35 58.0	-	Table Mountain
TDH	45 17 23.4	121 47 25.2	-	Tom, Dick, and Harry
TDL	46 21 03.0	122 12 57.0	1.400	Tradedollar Lake
VBE	45 03 37.2	121 35 12.6	1.544	Oregon Volcano Net - Beaver Butte
VBP	44 39 37.8	121 41 20.4	1.876	Oregon Volcano Net - Bald Peter
VFP	45 19 05.0	121 27 54.3	1.716	Mt. Hood - Flag Point
VGB	45 30 56.4	120 46 39.0	0.729	Oregon Volcano Net - Gordon Butte
VGT	45 08 59.4	122 15 55.2	0.993	Oregon Volcano Net - Goat Mtn.
VHO	45 13 09.0	123 43 31.2	0.951	Oregon Volcano Net - Mt. Hebo
VIP	44 30 29.4	120 37 07.8	1.731	Oregon Volcano Net - Ingram Point
VLL	45 27 48.0	121 40 45.0	1.195	Mt. Hood - Laurance Lake
VLM	45 32 18.6	122 02 21.0	1.150	Oregon Volc. Net-Little Larch Mtn.
VTG	46 57 28.8	119 59 14.4	0.208	Vantage
VTH	45 10 52.2	120 33 40.8	0.773	Oregon Volcano Net - The Trough
WA2	46 45 24.2	119 33 45.5	0.230	Wahluke Slope
WAT	47 41 55.0	119 57 15.0	0.900	Waterville
WBW	48 01 04.2	119 08 13.8	-	Wilson Butte
WEN	47 31 46.2	120 11 39.0	1.061	Wenatchee
WGW	46 02 40.8	118 55 57.6	-	Wallula Gap
WIW	46 25 48.8	119 17 13.4	0.130	Wooded Island
WNS	46 42 37.0	120 34 30.0	1.000	Wenas
WPW	46 41 53.4	121 32 48.0	1.250	White Pass
WRD	46 58 11.4	119 08 36.0	-	Warden
YAK	46 31 15.8	120 31 45.2	0.619	Yakima
YEL	46 12 35.6	122 11 16.5	1.750	Yellow Rock - Mt. St. Helens Crater