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I - INTRODUCTION AND OPERATIONS

Introduction

This report covers the operations and research performed for D.O.E. by the University of Washington Geophysics Program on the seismicity and structure of eastern Washington and north-eastern Oregon for the year, July 1, 1985 to June 30, 1986. This contract helps support parts of the Washington state regional seismograph network. There are presently 111 stations in Washington and north-eastern Oregon whose data are telemetered to the University for recording, analysis and interpretation. The Department of Energy supports the stations on the east flank of the Cascades and throughout eastern Washington and north-eastern Oregon. Other parts of the network are supported by the U.S. Geological Survey. Figure I-1 shows all of the stations of the state-wide network and Table I-1 lists the 44 stations supported by this DOE contract.

Section I of this report covers the operation of the network including station maintenance, data processing and telemetry problems in eastern Washington and the Washington-Oregon border area. A fairly detailed description of the switch to BPA microwave telemetery is included. The seismicity of the past year and a description of the catalog is covered in section II. Section III is a description of our experiments with an earthquake location routine for eastern Washington using a velocity structure including a low-velocity zone. Section IV gives the detailed results of our re-calibration of the U.S.G.S amplitude magnitude scale used between 1969 and 1974 for magnitude determinations in eastern Washington. Section V is an exploration of techniques to improve the location of earthquakes within a swarm or cluster. Several different procedures for improving timing accuracy and relative locations are studied using a well recorded swarm of earthquakes in the Cascades. The appendix includes the catalog of earthquakes located in eastern Washington during the year and a table of station outages.

Network Operations

Technical operations this year have been dominated by the preparation and start of major telemetry route changes. Conversion from primarily telephone telemetry to the B.P.A. micro-wave system was begun. This involved a great deal of effort not only by the technical staff but by the analysis and research staff as well. Two stations were relocated, OMK to FOX and FPW to NEL. Both of these stations had been telephone links and are now VHF radio links. There were a number of periods during the year when several stations were down for extended periods of time. This was usually caused by changes in telemetry routing or the loss of a telephone circuit before a BPA line was ready for connection.

BPA Telemetry

Before any changes in telemetry routing could be made careful design work was done. This involved a number of areas such as: 1. determining radio frequencies which could be used at sites without existing radios, 2. necessary site relocations to radio the signal either directly to a BPA site or to another site to be repeated to BPA, 3. change in VCO center frequencies to prevent interference when stations previously on separate phone lines were now mixed on the same micro-wave channel, 4. minimizing the number of changes to the existing network to maintain a stable network configuration and minimize cost. We have tried to maintain existing major receiving sites. Site changes were determined by scanning topographic maps for existing sites and seeing if there was an accessible hilltop nearby which could radio to another site or direct to BPA. After determining changes from the maps, we had someone visit the proposed sites to be sure the maps were accurate and that the proposed change was really feasible. Radio frequencies were selected by working with Rockwell seismologists and the Hanford radio communications people to be sure that we would not interfere with each other since we use many of the same frequencies. Radio tests were conducted on some of the more questionable frequencies which we thought could have problems. From this information, plans were made for the equipment needed to be purchased or built to accomplish the changes.

In March of 1986, the formal agreement was finalized between the BPA and the USGS for the use of 18 channels on the BPA microwave communications system. At this time we began working with the system engineers at BPA to determine their hardware requirements for the installation of our equipment. Sketches were made of each of the BPA compounds and towers and the proposed location of our equipment within the compound and on the towers. All designs were worked out for the hardware, power requirements and cable runs, and some specially made mounting hardware was designed and constructed.

The effective date of the BPA-USGS agreement is Nov. 5, 1986, however, BPA provided us with six temporary lines for use until the permanent lines are installed. Twelve phone lines were ordered and installed between the BPA's Queen Anne office in Seattle to the seismology lab at the University. After deciding on the priority of six lines either due to cost or persistent phone line problems, we had our first line up on by May 21, 1986. This first line originated from Augspurger and was chosen first, because of the phone problems we had been having and the ease of the conversion. We ran the BPA line simultaneously with the phone line for several weeks to compare quality and then discontinued the phone service. By July 1, 1986 we had three BPA lines in operation. These originated from Augspurger, Wasco (VGB) and Ashe (Gable) with no interruption of data reception.

Our experience with the BPA lines thus far is very good. The signal quality is significantly better than that from the previous telephone lines. We have had very few telemetry interruptions and those were mostly in the first week or so of operation when line testing was still taking place. Access to BPA facilities for our technical staff is available at any time for some sites but others require arrangements to be made ahead to gain access. We hope to improve this arrangement in the future since it is difficult to plan the exact timing of a repair trip to several sites when the extent of necessary repairs can not be determined ahead.

Other Operational Changes

During 1985-86 four more stations were converted to solar power operation. This brought the total to fifteen solar sites in the Hanford Network area. We have seen good service with the solar panels, with only 1 unit having been stolen. The only serious problem we have had has been with the accumulation of bird droppings on several panels, which eventually cut off their charging ability. We have added spiked ridges to the top of the panels to prevent birds from sitting(sic) or resting.

An improved method for calibrating seismometers was developed using a Nicolet Digital Storage Osciloscope. This involves reading stored values from the Nicolet without the use of a strip chart recorder. This method eliminates reading and interpretation errors from strip chart records which have less resolution. We are using this technique to calibrate additional seismometers and to check the calibration on older units and provides faster and more accurate results than our previous technique. Stations currently with good calibration are indicated in Table I-1 with asterisks.

Design of a new telemetry VCO was begun utilizing a CMOS microcontrollerchip to provide frequency stability. This design uses a microprocessor to control a phase lock loop by monitoring the output frequency and compensating a control voltage when temperature or component instability occur. The center frequency is also switch selectable. A prototype was built and is in the process of being field tested. If this unit tests out successfully we will begin using it for new or replacement units. Not only will its frequency stability be much improved over previous units but its cost is far less than units presently commercially available.

We acquired a NOAA data base tape of elevations of the Western USA and wrote a program, *profile* for plotting profile graphs of topography between any two map locations. *Profile* complements another program, *dist* which provides distance and azimuth information between sites. This greatly facilitates the planning of radio paths between two sites and may be useful for plotting topography on various map bases.

Over the past year we have investigated alternative recording systems to the one we use now. Since 1980 we have been using a DEC PDP-11/34 and PDP-11/70 for on-line recording and off-line analysis respectively. These units were originally purchased in 1978 by the US Geological Survey and have been maintained by them since then. Their age and high maintenance costs now make their replacement attractive. We have investigated several alternative systems and have now decided on a system using a Masscomp 5500 computer and software developed by Newt Inc for Los Alamos National Labs. Both on-line event detection and recording as well as off-line processing can be handled by the one system. This system has the capability to integrate both analog and digital telemetry data together as well as sample data at several different rates. Automatic initial post processing is possible as well as interactive processing and database management. We plan to submit a proposal to the USGS within the next few months for funding a new system.

Figure I-1 shows all of the stations in the University of Washington seismograph network as of summer, 1986. The area to the right of the heavy vertical line contains the stations primarily supported by DOE. Table I-1 lists the 44 DOE related stations. Sites with an asterisk are calibrated stations. Calibration data for other station have been taken but not yet reduced to the necessary calibration information.

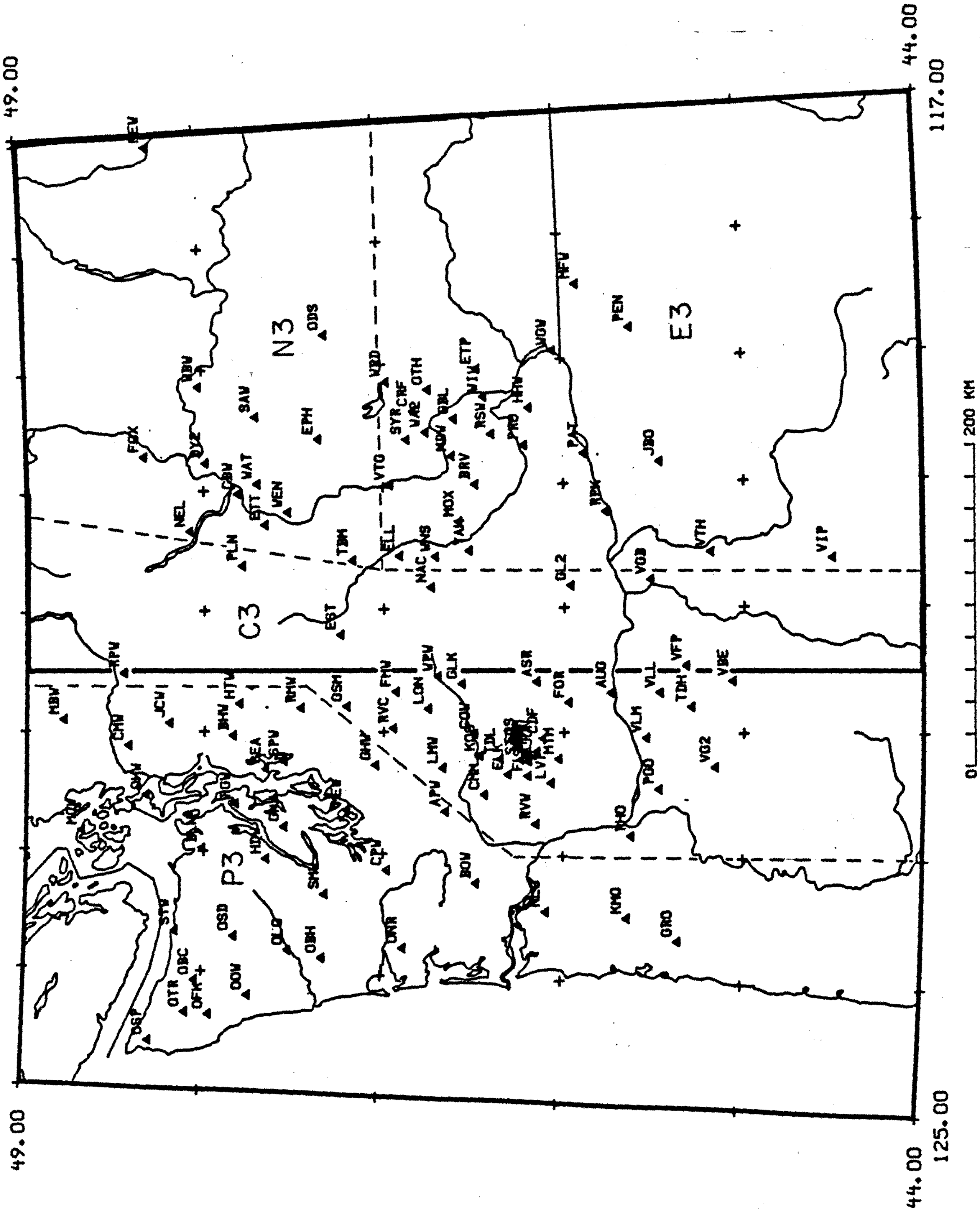


Figure I-1. Seismograph stations as of the summer of 1986 for the state-wide network. Stations east of the heavy vertical line are part of the DOE sponsored eastern Washington network. Areas covered by the various velocity models are indicated by the dashed lines.

Table I-1 DOE Supported or Related Stations

Station designator	Latitude(N) (dg mn sec)	Longitude(W) (dg mn sec)	Elevation (km)	Station name
BRV	46 29 07.2	119 59 29.4	0.925	Black Rock Valley
CBW	47 48 25.5	120 01 57.6	1.160	Chelan Butte
CRF	46 49 30.6	119 23 18.0	0.260	Corfu
DY2	47 59 06.9	119 46 13.0	0.884	Dyer Hill #2
ELL	46 54 35.0	120 34 06.0	0.805	Ellensburg
EPH	47 21 12.8	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
FOX	48 19 50.0	119 42 29.0	0.896	Fox Mountain
GBL*	46 35 51.6	119 27 35.4	0.330	Gable Mountain
GL2*	45 57 35.0	120 49 22.5	1.000	New Goldendale
HHW	46 10 59.0	119 22 59.0	0.415	Horse Heaven Hills
JBO	45 27 41.7	119 50 13.7	0.645	Jordan Butte, Oregon
MDW*	46 36 48.0	119 45 39.0	0.330	Midway
MFW	45 54 10.8	118 24 21.0	0.395	Milton-Freewater, Oregon
MOX	46 34 38.0	120 17 35.0	0.540	Moxie City
NAC	46 44 03.8	120 49 33.2	0.738	Naches
NEL	48 04 41.8	120 20 17.7	1.490	Nelson Butte
NEW	48 15 50.0	117 07 13.0	1.000	Newport Observatory (USGS)
ODS	47 18 24.0	118 44 42.0	0.523	Odessa
OTH	46 44 20.4	119 12 59.4	0.260	Othello
PAT	45 52 50.1	119 45 40.1	0.300	Paterson
PEN	45 36 43.2	118 45 46.5	0.430	Pendleton, Oregon
PLN	47 47 04.8	120 37 58.8	0.700	Plains
PRO	46 12 45.6	119 41 09.0	0.552	Prosser
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 Mt. (East)
SAW	47 42 06.0	119 24 03.6	0.690	St. Andrews
SYR	46 51 46.8	119 37 04.2	0.267	Smyrna
TBM	47 10 10.0	120 35 58.0	1.064	Table Mt.
VGB	45 30 56.4	120 46 39.0	0.729	Gordon Butte, Oregon
VIP	44 30 29.4	120 37 07.8	1.731	Ingram Pt., Oregon
VTG	46 57 28.8	119 59 14.4	0.208	Vantage
VTH	45 10 52.2	120 33 40.8	0.773	The Trough, Oregon
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	0.825	Wilson Butte
WEN	47 31 46.2	120 11 39.0	1.061	Wenatchee
WGW	46 02 40.8	118 55 57.6	0.158	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
WRD	46 58 11.4	119 08 36.0	0.378	Warden
YAK	46 31 15.8	120 31 45.2	0.619	Yakima

II - SEISMICITY JULY 1, 1985 - JUNE 30, 1986

Introduction

From July 1, 1985 to June 30, 1986 we processed 2261 seismic events recorded by the state-wide network. Of the 336 events which we located in eastern Washington and north-eastern Oregon (44-49°N, 117-121.5°W - see Figure I-1) during this time 252 were classified as earthquakes and 114 as confirmed or probable blasts (Figures II-1 and II-2). All earthquakes and blasts are listed in a catalog as Appendix I of this report. Blasts are identified by their characteristic source locations and recorded waveforms.

The largest earthquake in the state was a magnitude M_c =3.9 event on February 10, 1986 located north of Darington, WA in the north Cascades. Of the 18 earthquakes reported felt in the state over the past year, 10 of them were in the Darington area. Most eastern Washington earthquakes were relatively small; the largest was a magnitude M_c = 3.3 event on April 8, 1986 located in the Entiat area south of Lake Chelan. This was the only event in eastern Washington for which we received felt reports.

Seismicity

In general, the seismicity for the period was similar to the seismicity for the previous year. In both years swarms of earthquakes occurred southwest of Grand Coulee dam. In the very active Entiat region south of Lake Chelan, 65 earthquakes occurred (68 in the previous year) with remarkable regularity in time. The largest, in this area (April 8, 1986) occurred at a depth of 18 kilometers, was reported felt but was not well recorded by local stations because of a telemetry outage at the time. Our computed location for this event may be up to several km in error.

The Yakima area and the northwest trending mountain ridges to the north were very active during the year. 66 earthquakes occurred there with magnitudes between 0.9 and 3.0 in six identifiable swarm areas as well as a few isolated locations. Table II-1 lists important characteristics of these six areas.

TABLE II-1 Swarms in Yakima area

Dates	Location (°N °S)	# of Events	Depth (km)	Maximum Magnitude
Aug-Oct, 1985	46.30 120.35	9	1.0+-2.0	2.4
Sep-Oct, 1985	46.80 120.05	10	1.0±1.0	3.0
Oct-Dec, 1985	46.80 120.30	10	3.0±2.0	2.1
Dec 25, 1985	46.10 120.55	5	9.0±2.0	2.4
Jan-Apr, 1986	46.95 120.40	7	3.0±1.0	2.3
Mar, 1986	46.55 120.45	6	7.0±2.0	2.2

Scattered earthquakes occurred north of the Hanford reservation in the Saddle mountains and early in 1986 a small cluster (magnitudes 0.8-2.0) occurred in the southwest corner of the reservation in the Rattlesnake Hills. Three of these events were at depths between 16 and 20 km. There were scattered earthquakes along the Washington-Oregon border.

A total of six earthquakes had well enough recorded first motions at enough stations to determine fault plane solutions. Figure III-3 shows the six individual solutions plotted on a lower hemisphere equal area stereo net. The six events, a-f are indicated on the map of Figure II-1 Note that four of the six solutions have their P axis oriented at a shallow dip to the south-southwest. Event b, located in the Entiat area has a near east-west P axis. This mechanism is not well controlled and has more than a few questionable arrivals. Event f has a P axis oriented horizontal and north-west-southeast. This event is located on the west end of the Ahtanum Ridge, an area where few events have been located previously.

Catalog

Appendix I is a catalog of located events between July 1, 1985 and June 30, 1986 in eastern Washington and north-eastern Oregon (to the right of the heavy line shown in Figure I-1). Only blasts with magnitude equal to or exceeding 2.5 are listed. The locations reported in the catalog have been determined using a hypocenter computer program *spong*, which is an adaptation of a program originally written by Bob Herrmann at Saint Louis University. There is a special depth adjustment algorithm for events with poorly controlled shallow depths such as those sometimes found in the central Pasco Basin. Different seismic velocity models are used to locate earthquakes in different regions. Table II-2 lists the fundamental parameters used for the new velocity models in each region. Individual minor station corrections were determined for each model but these are not listed in the table. See section III of this report for a discussion of using a low velocity model for earthquakes in the central Plateau. The columns in the catalog are generally self-explanatory except that the following features should be noted:

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

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

c) In most cases the DEPTH, which is given in kilometers, is freely calculated by computer from the arrival-time data. In some instances, the depth must be fixed arbitrarily to obtain a convergent solution. Such depths are noted by an asterisk (*) in the column immediately following the depth. A $ or a # following the depth mean that the maximum number of iterations has been exceeded without meeting convergence tests and the depth has been fixed.

d) MAG is an estimate of local Richter magnitude as calculated using the coda length-magnitude relationship determined for Washington. Where blank, data were insufficient or impossible to obtain for a reliable magnitude determination. Normally, the only earthquakes with undetermined magnitudes are very small ones. Magnitudes are preliminary only and may be revised as we improve our analysis procedure.

e) NS/NP is the number of station observations (NS) and the number of P and S phases (NP) used to calculate the earthquake location. A minimum of three stations and four phases are required. Generally the greater the number of observations used, the better the quality of the solution.

f) The root mean square residual (RMS) is taken about the mean of the station first-arrival residuals. It is only meaningful as a general statistical measure of the goodness of the solution when 5 or more well distributed stations are used in the solution. Good solutions are normally characterized by RMS values less than about 0.3 sec.

g) QUALITY of the hypocenter is a two letter code indicating the general reliability of the solution (**A** is best quality, **D** is worst). Similar quality factors are used by the USGS for events located with the computer program HYPO71. The first letter of the code is a measure of the hypocenter quality based on travel time residuals. For example **A** quality requires an RMS less than 0.15 sec. An RMS of 0.5 sec or more is **D** quality (estimates of the uncertainty in hypocenter depth also affect this quality parameter). The second letter of the quality code depends on the spatial distribution of stations around the epicenter ie number of stations, their azimuthal distribution (GAP), and the minimum distance (DMIN) from the epicenter to a station. Quality **A** requires a solution with 8 or more phases, GAP $\leq 90^\circ$ and DMIN $\leq$ (5 km or depth, whichever is greater). If the number of phases (see paragraph e above) is 5 or less or GAP $> 180^\circ$ or DMIN > 50 km, the solution is assigned quality D. Note: GAP is the largest angular sector in azimuth (measured from the epicenter) containing no stations.

h) MODEL refers to the crustal velocity model used in the location calculations.

P3 is the Puget Sound model
C3 is the Cascade model
S3 is a Mt. St. Helens model including Elk Lake
N3 is the northeastern model
E3 is the southeastern model

i) TYPE of events flagged in the catalog use the following code:

F - earthquakes reported to have been felt
P - probable explosion
L - low frequency earthquakes
H - handpicked from film or paper records

X - known explosion

TABLE II-2 Current Velocity Models

Southeast (E3)		Northeast (N3)	
V (km/sec)	Depth (km)	V (km/sec)	Depth (km)
3.70	0.0	5.1	0.0
5.15	0.4	6.1	0.5
6.10	8.5	6.4	14.0
6.40	13.0	7.1	24.0
7.10	23.0	7.9	38.0
7.90	38.0		

Cascade (C3)	
V (km/sec)	Depth (km)
5.1	0.0
6.0	1.0
6.6	10.0
6.8	18.0
7.1	34.0
7.8	43.0

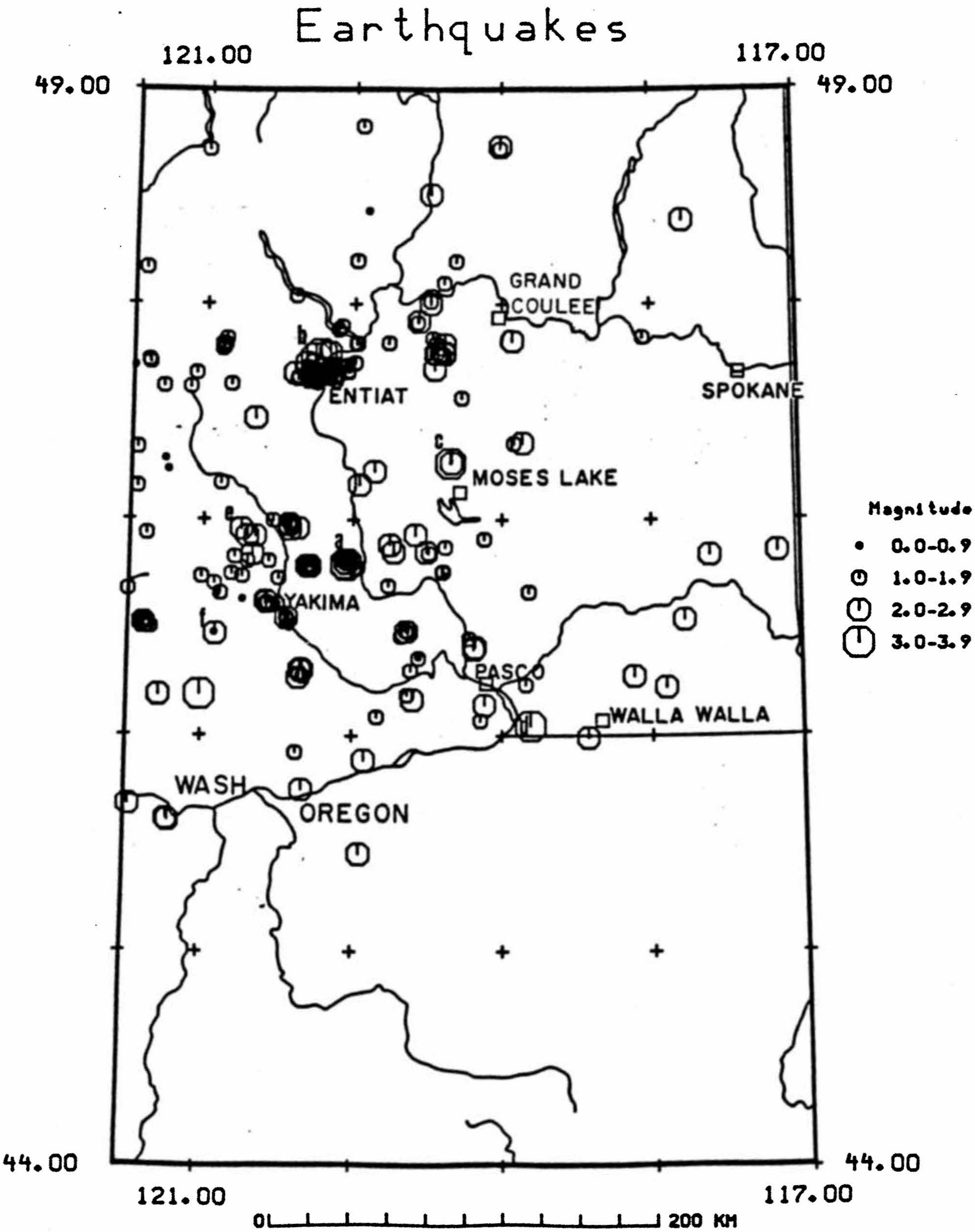


Figure II-1. Earthquakes in eastern Washington July 1, 1985 - June 30, 1986.

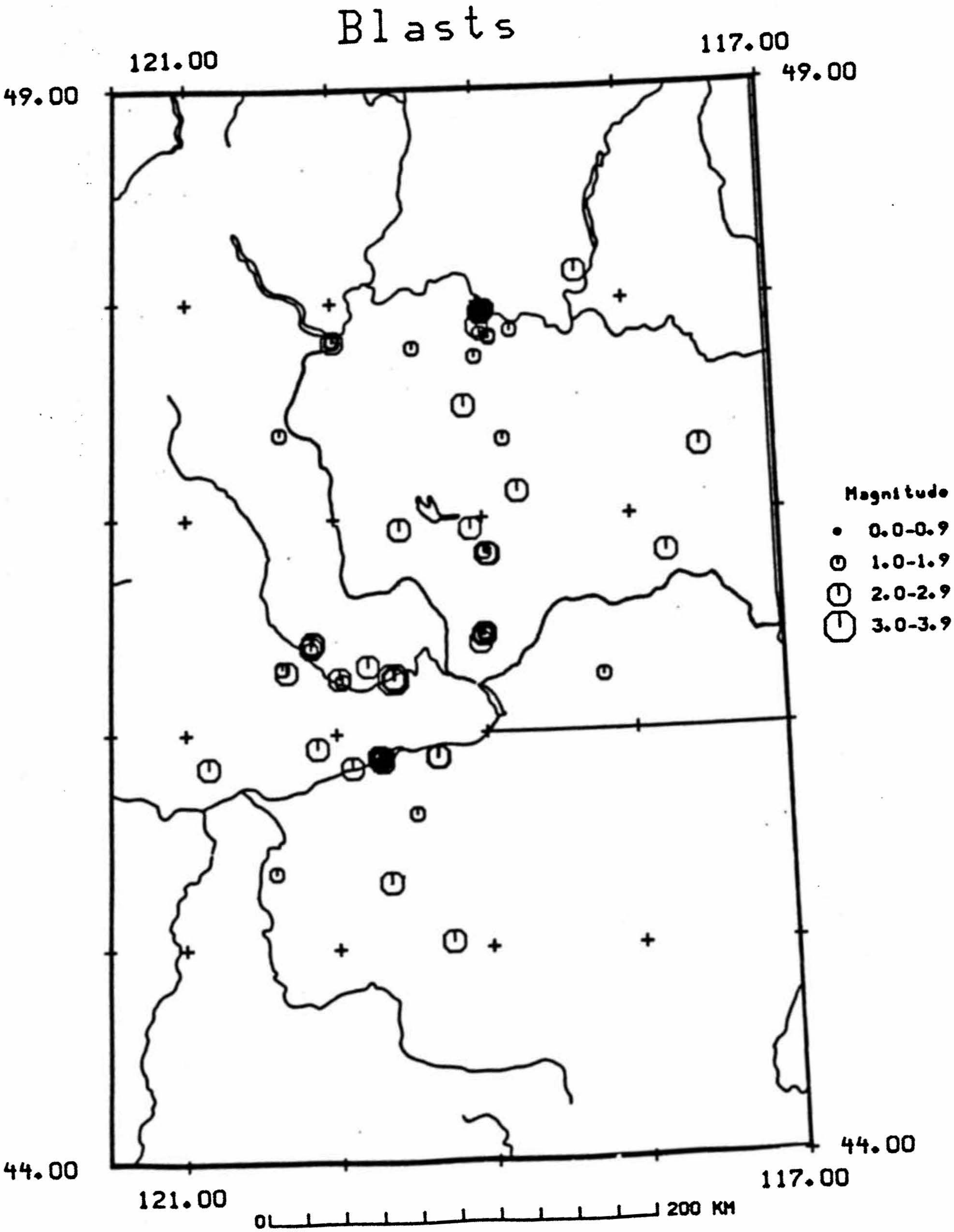


Figure II-2. Known or suspected blasts in eastern Washington for July 1, 1985 - June 30, 1986.

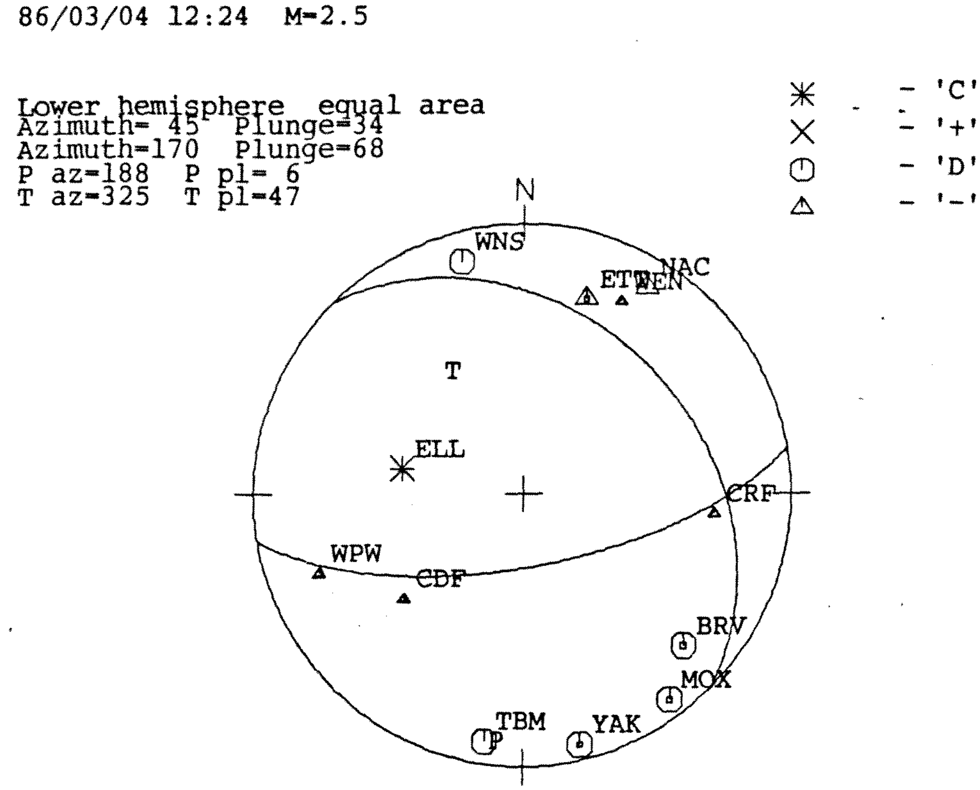


Figure II-3e. Focal mechanism for event on Mar 4, 1986 at 1224 UT, M = 2.5, location: 46° 55'N 120° 40'W.

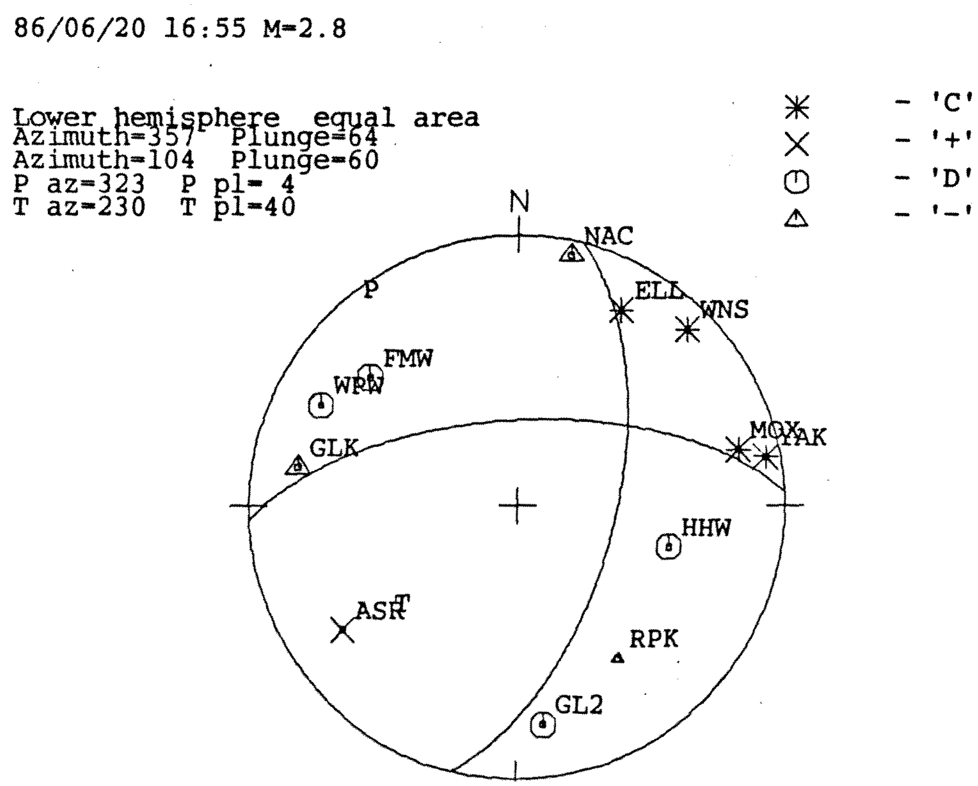


Figure II-3f. Focal mechanism for event on Jun 20, 1986 at 1655 UT, M = 2.8, location: 46° 28'N 120° 55'W.

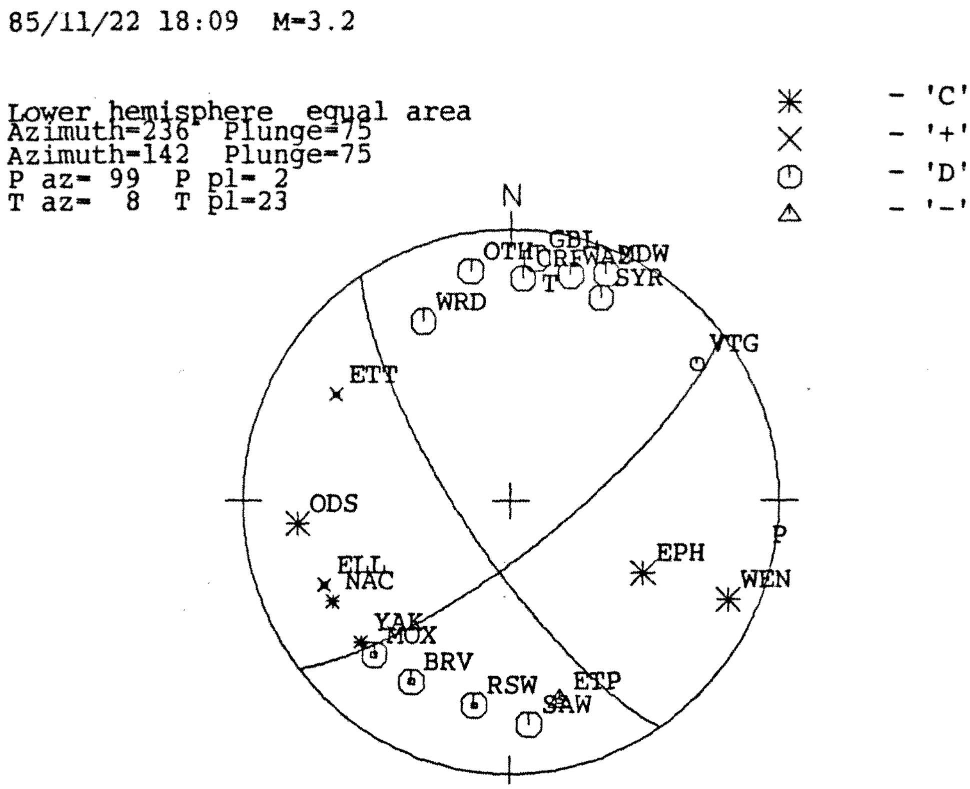


Figure II-3c. Focal mechanism for event on Nov 2, 1985 at 18:09 UT, M = 3.2, location: 47° 16'N 119° 21'W.

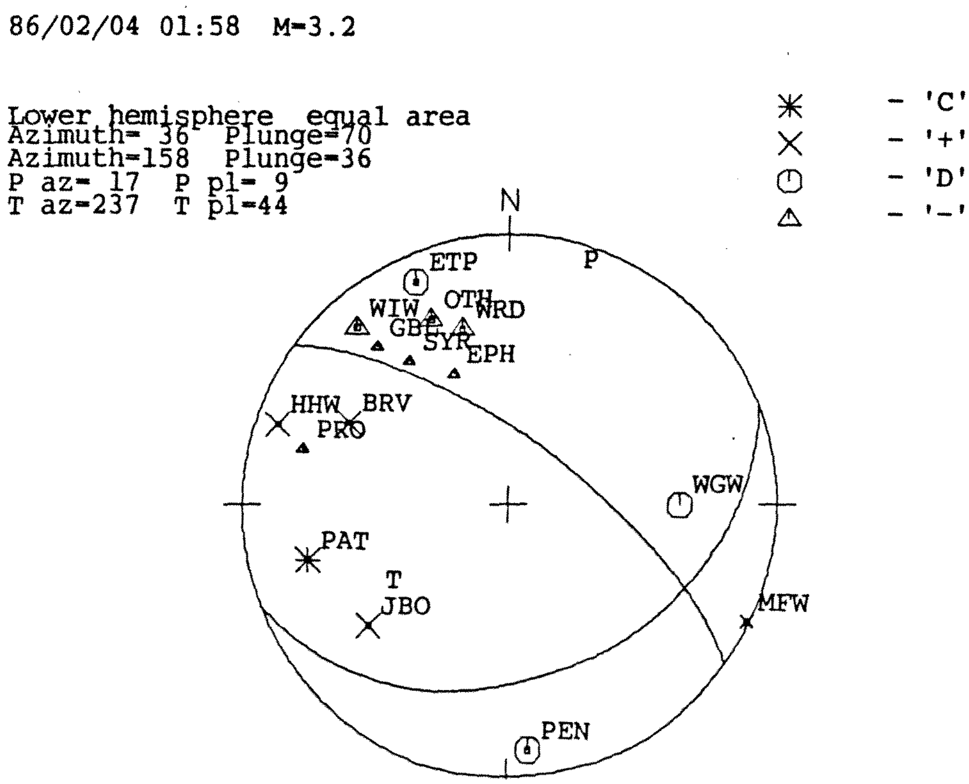


Figure II-3d. Focal mechanism for event on Feb 4, 1986 at 01:58 UT, M = 3.2, location: 46° 3'N 118° 49'W.

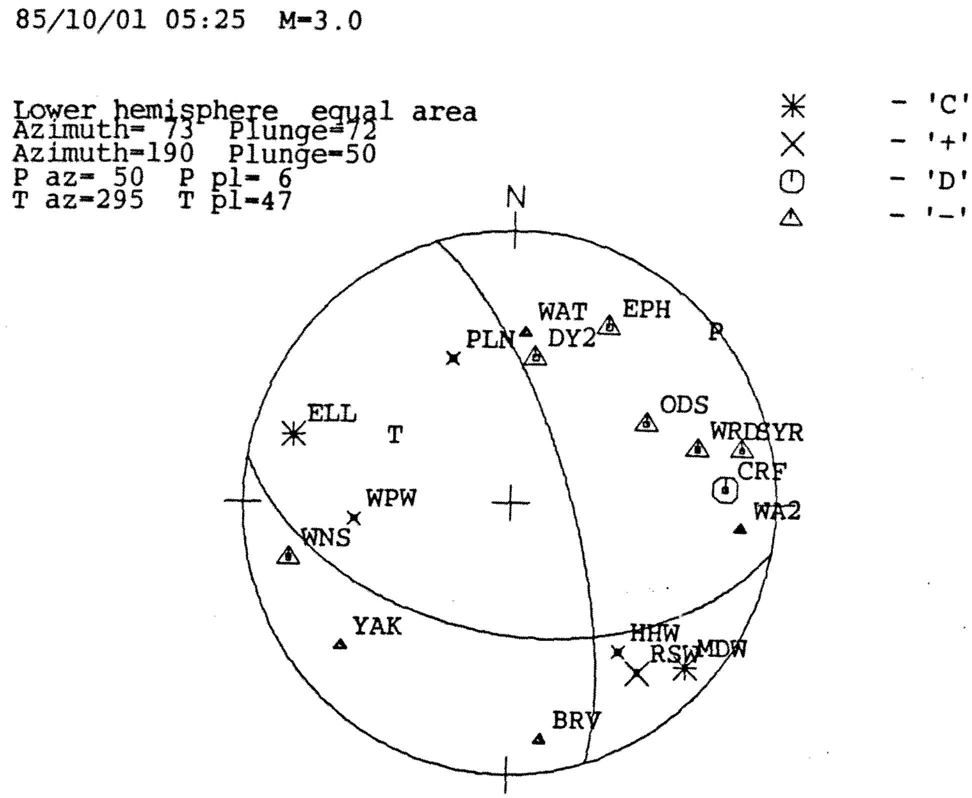


Figure II-3a. Focal mechanism for event on Oct 1, 1985 at 05:25 UT, M = 3.0, location: 46° 47'N 120° 3'W.

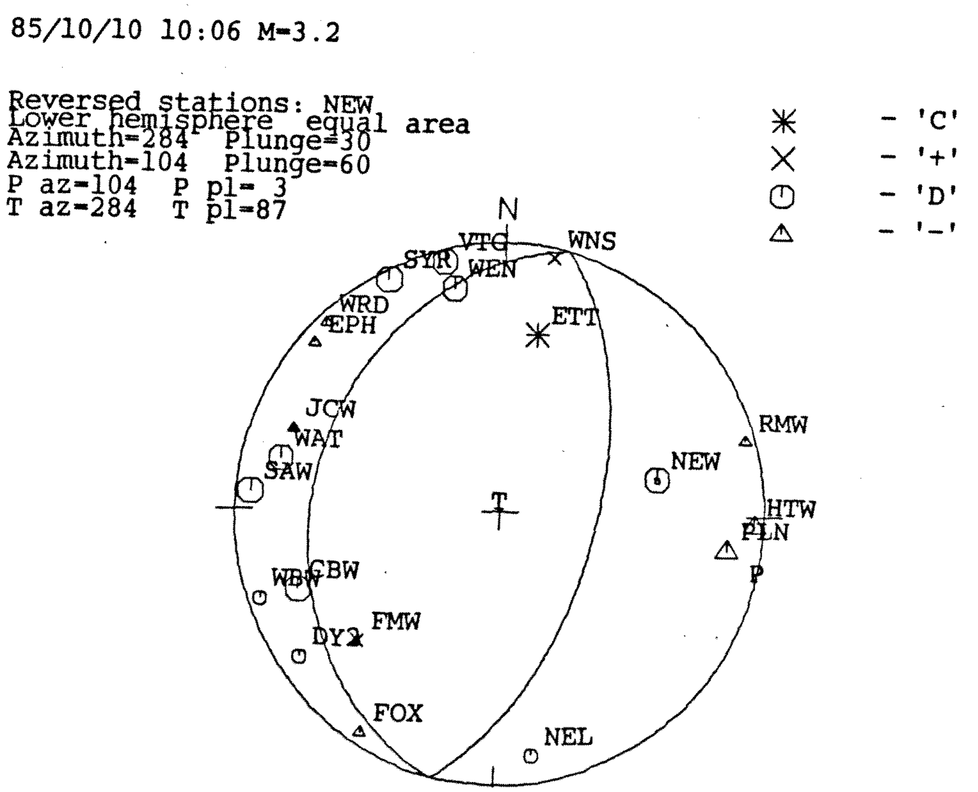


Figure II-3b. Focal mechanism for event on Oct 10, 1985 at 10:06 UT, M = 3.2, location: 47° 45'N 120° 16'W.

III - STRUCTURAL STUDIES

Introduction

The August 1984 seismic refraction experiment conducted in Eastern Washington by the United States Geological Survey, the Basalt Waste Isolation Project of Rockwell Hanford Operations, and the University of Washington (UW) confirmed the presence of a low velocity sedimentary layer (LVL) beneath the basalts. The standard velocity model used for eastern Washington (E3) was updated to include a low velocity model and then used to study how this affected the locations of earthquakes. The seismic velocity model used by the UW prior to this study (E3) located earthquakes in the low-velocity sedimentary layer. Since sediments typically deform relatively easily, and thus can relieve stress aseismically, it might be expected that this layer could not contain sources of earthquakes.

Data and Analysis

The standard location routine, SPONG, does not allow for a velocity model that includes a low-velocity zone. The subroutine *TRVDRV*, which calculates travel-times and derivatives needed to be modified to work with velocity reversals. Some of the computational optimization had to be eliminated and new tests for successful ray termination were introduced so that it could work with any general one-dimensional velocity model of ten or fewer flat layers (appendix III contains the modified code for *TRVDRV*). This general capability slows down the program by about a factor of two; however there may be additional techniques available to optimize the new version of *TRVDRV*.

Using data from David W. Glover's Master of Science Thesis which covers the structure of the central Columbia River Plateau and includes borehole results, a one-dimensional velocity model was constructed which was approximately valid inside the region bounded by 45.5 and 47°N latitude and 118.5 and 120.5°W longitude (see Figure III-1). A special option of *SPONG* uses the location in the pickfile to compute distances, azimuths, and residuals without iterating for a position. It also allows for taking out the average residual and adjusting the origin time. This option was used on fourteen distinct blasts that were fixed at their respective known locations. First order station corrections were then estimated from average weighted residuals. Using this model with station corrections, twenty-four high quality earthquakes were located (magnitude greater than two, small gap, and both P and S arrivals. Second order station corrections were estimated using average weighted residuals from these locations. This became the working velocity model (EL). sp2

velocity model E3		
velocity of layer	depth to top of layer (km)	thickness of layer (km)
3.70	0.0	0.4
5.15	0.4	8.1
6.10	8.5	4.5
6.40	13.0	10.0
7.10	23.0	15.0
7.90	38.0	

velocity model EL		
velocity of layer	depth to top of layer (km)	thickness of layer (km)
3.70	0.0	0.5
5.18	0.5	3.5
4.70	4.0	4.0
6.20	8.0	12.0
7.20	20.0	18.0
7.90	38.0	

In the hopes of obtaining an unbiased data set, all of the earthquakes that occurred from 1 January 1981 through 3 July 1986 in the region where the velocity model was expected to be valid were selected (see Figure III-1). These 379 earthquakes were located using both the E3 and the EL velocity models and the solutions compared to one another. The two models appear to locate events in the area equally well: statistics on the quality of locations are similar although the epicenter distribution does change slightly. The average RMS residual for these events was 0.21 $\pm$0.14 when located with the E3 model, and 0.22 $\pm$0.13 when located with the EL model. The location of an event does not seem to be highly dependent on velocity model. Eighty percent of the epicenters move less than 1.5 kilometers and ninety-one percent move less than 2.5 kilometers). The events whose locations are strongly dependent on the velocity model are events with poor data coverage, *i.e.* large gap and no direct arrivals, or events with only P waves and a poor distance distribution.

Results

As the histograms shown in Figure III-2 illustrate, there is a systematic change in distribution of earthquakes with respect to depth. In particular, the number of earthquakes located in the region corresponding to the sedimentary layer in the velocity model EL increases when the EL model is used to locate events and fewer earthquakes are located close to the surface. (Using the E3 model, 70 events are located in the depth interval 4-8 kilometers, versus 106 in the same region using the EL model) On the average, the EL model located earthquakes 0.19 kilometers (variance of 2.6 kilometers) deeper than the E3 model.

Since the sediments and basalt flows do not consist of flat parallel layers everywhere, it may not be reasonable to expect that the sediments would necessarily show up as a void in a plot of distribution of earthquakes versus depth. There is a lens of sediments centered around 46.45N latitude and 120.40W longitude (see David W. Glover's Master of Science Thesis). One of the most interesting plots of earthquakes in the region is Figure III-3. This consists of all of the earthquakes of magnitude two or greater whose epicenters fall inside the box on Figure III-1 projected along the cross section A-B. (Note: epicenters inside the small box but outside the large box are not shown on figure.) This cross section is approximately normal to the steepest gradients of the sediments. It should be noted that there is a fair amount of uncertainty in the depth of some of the locations. The station distribution is unfortunately not sufficiently dense for all events to record even one direct arrival, especially with the EL model.

Earthquakes still seem to be originating in the sedimentary layer; this does not appear to be simply an artifact of an incorrect velocity model. There does however appear to be a gap in hypocenter distribution for earthquakes larger than magnitude 2 where the sediments are thickest. Larger earthquakes are, however, located in the region where sediments thin most quickly. The data are not extensive enough to say if this observation is just a coincidence or if there may be a causal relationship. It is possible that the steeper interface between sedimentary layer and overlying basalt causes a stress concentration resulting in increased seismic activity.

In this part of Eastern Washington, the nonuniform basalt flows and sedimentary layers make it difficult for a one-dimensional velocity model to be valid for a large area. Indeed, the approximations to flat lying layers is poor. Our tests comparing new and the old velocity models yield essentially the same results. We conclude it is neither necessary nor is it efficient to use a velocity model that includes a low-velocity zone when locating events in Eastern Washington with the U of W regional network. It is possible that when using a more dense array over a limited area the use of a low-velocity layer for hypocenter determination may yield better resolution than without it. Until it is practical (or necessary) to use a three-dimensional velocity model, it seems that the E3 velocity model is sufficient.

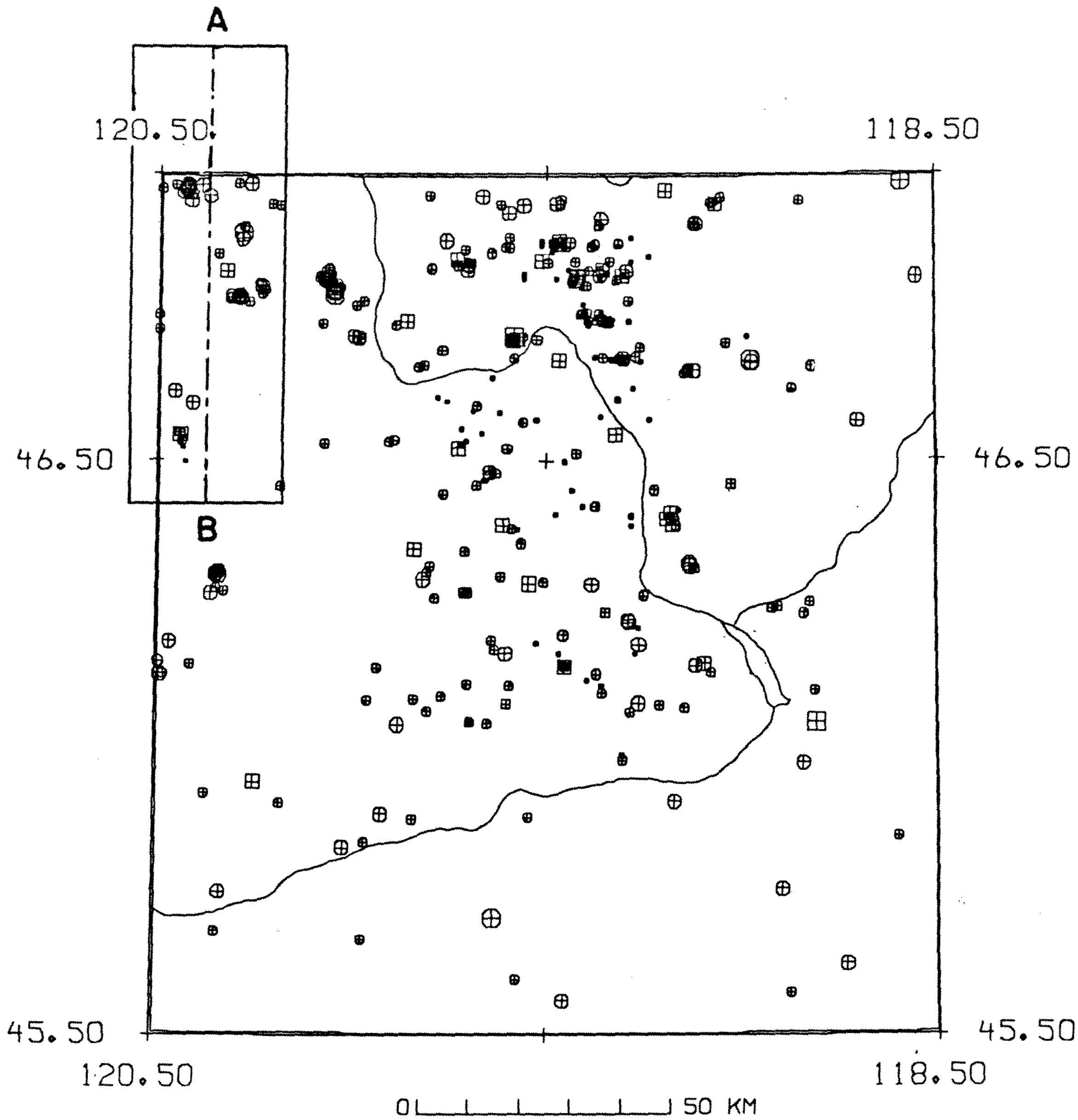


Figure III-1. Region where UW velocity model E4 is expected to be valid. The epicenters of the fourteen blasts and twenty-four high quality earthquakes are indicated by squares. The epicenters of the large (unbiased) sample of 379 earthquakes are indicated by circles. All locations are from the E3 model except for blasts which are fixed at their known locations. Symbols representing epicenters are sized proportional to magnitude.

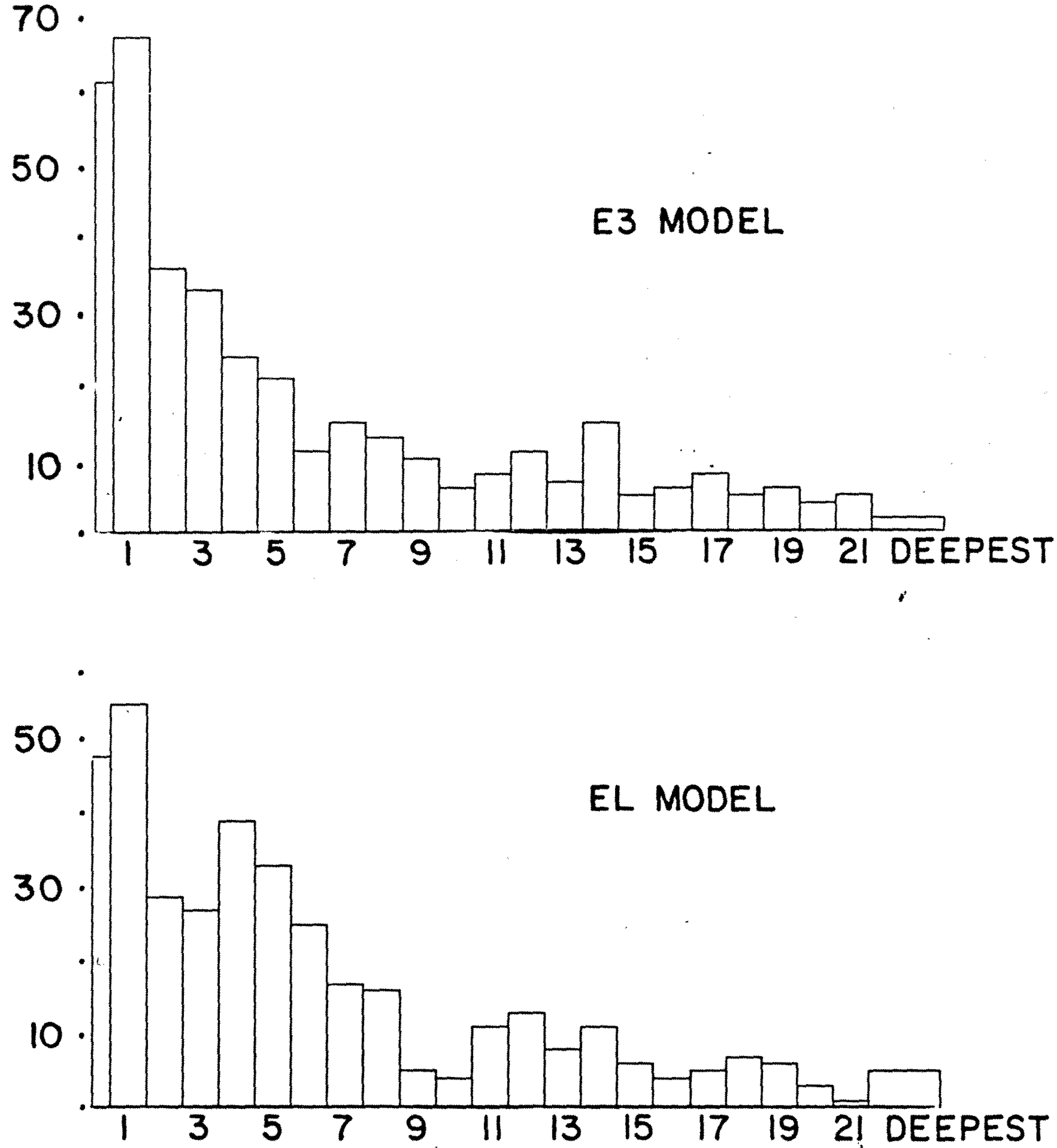


Figure III-2 Histograms of number of earthquakes versus depth. All bins are 1 kilometer in depth wide except for the first bin which is 0.5 kilometer wide and the last bin which includes all the earthquakes 21.5 kilometers or deeper. Note that these two bins are drawn respectively narrower and wider than the bins of uniform width. Scale on the depth axis corresponds to the depth of the center of the bin.

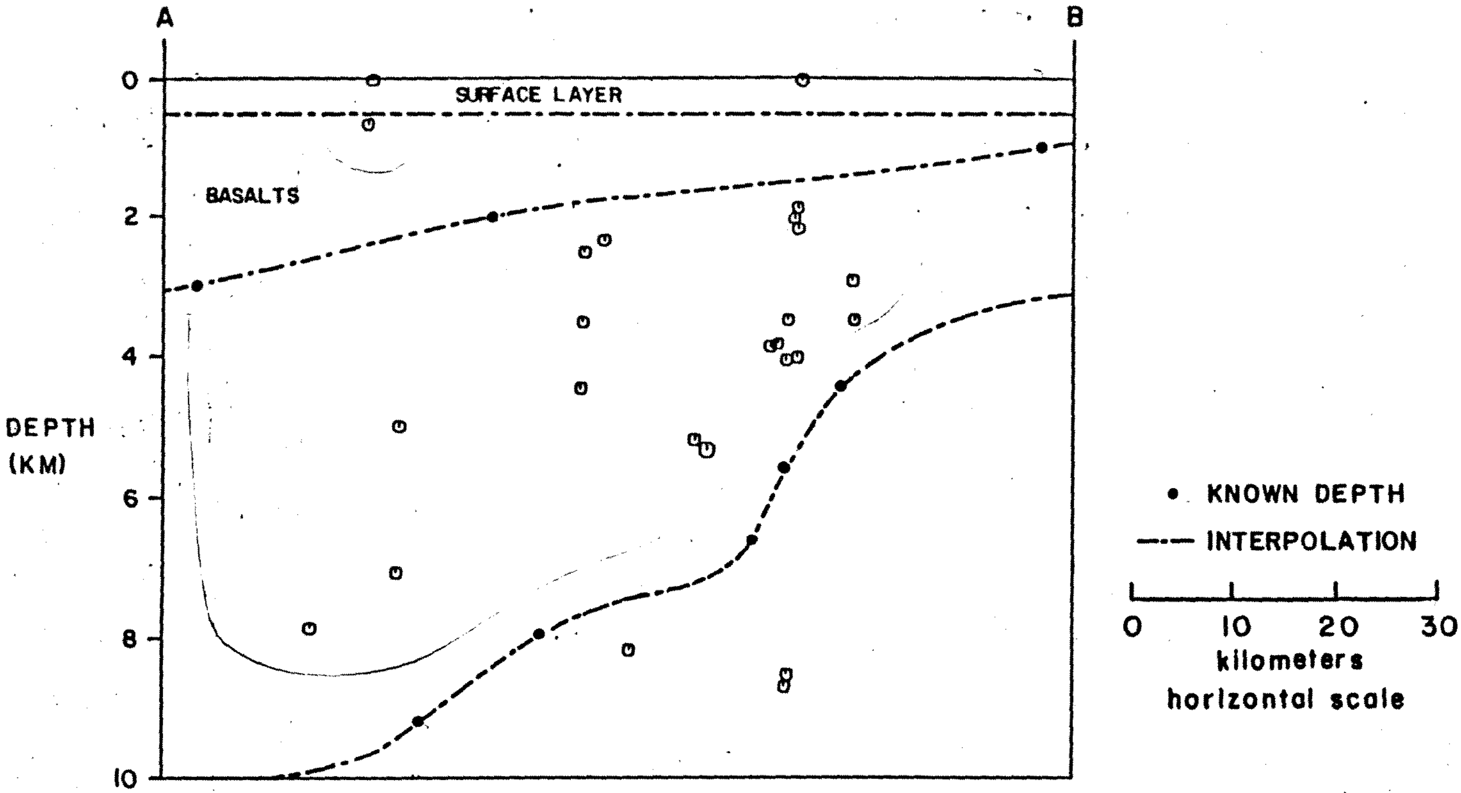


Figure III-3 Plot of all earthquakes of magnitude two or greater whose epicenters fall inside the small box on figure KW-1 projected onto cross section AB. Layer boundaries indicated correspond to cross section AB which was chosen to optimize the two-dimensionality of the structure especially in the region where the sediments thin most quickly. Points indicated as known depth are taken from David W. Glover's MS thesis; the dashed lines are interpolation. Vertical exaggeration is approximately 6.9.

IV - MAGNITUDE CALIBRATION 1969-1974

Introduction

In recent years the uniformity of seismic activity in Eastern Washington has become a topic of great interest. Even though there is now good data for over fifteen years, it has been difficult to precisely characterize the temporal changes in this seismicity because of changes in the way earthquake magnitudes have been calculated over the years. What has been needed is a way to determine earthquake magnitudes in the a uniform manner for the entire period from 1969 to the present.

From 1969-1974 the eastern Washington network was operated by the US Geological Survey under the direction of Mitch Pitt in Menlo Park, California. In the early part of this period, earthquake magnitudes (denoted M_{amp} here) were computed from the maximum recorded peak-to-peak wave amplitudes measured off film records (See USGS Open-File Report 75-311). Later, magnitudes were calculated by averaging estimates based on amplitudes with estimates based on the duration of the seismic signals. After 1975 magnitudes have been computed from the duration of seismic signals only ("coda length"). Since 1975 we have used the relation

$$M_c = -2.46 + 2.82 \log(T_c). \qquad (1)$$

M_c is the coda magnitude and T_c is the duration of the seismic signal in seconds from P onset until the coda has decayed back to twice background noise level. This magnitude scale (1) was calibrated by plotting the Richter local-magnitude versus the log of the duration of the seismic signal. Equation (1) is the best fit line through the data. (See Annual Technical Report, 1977).

Results

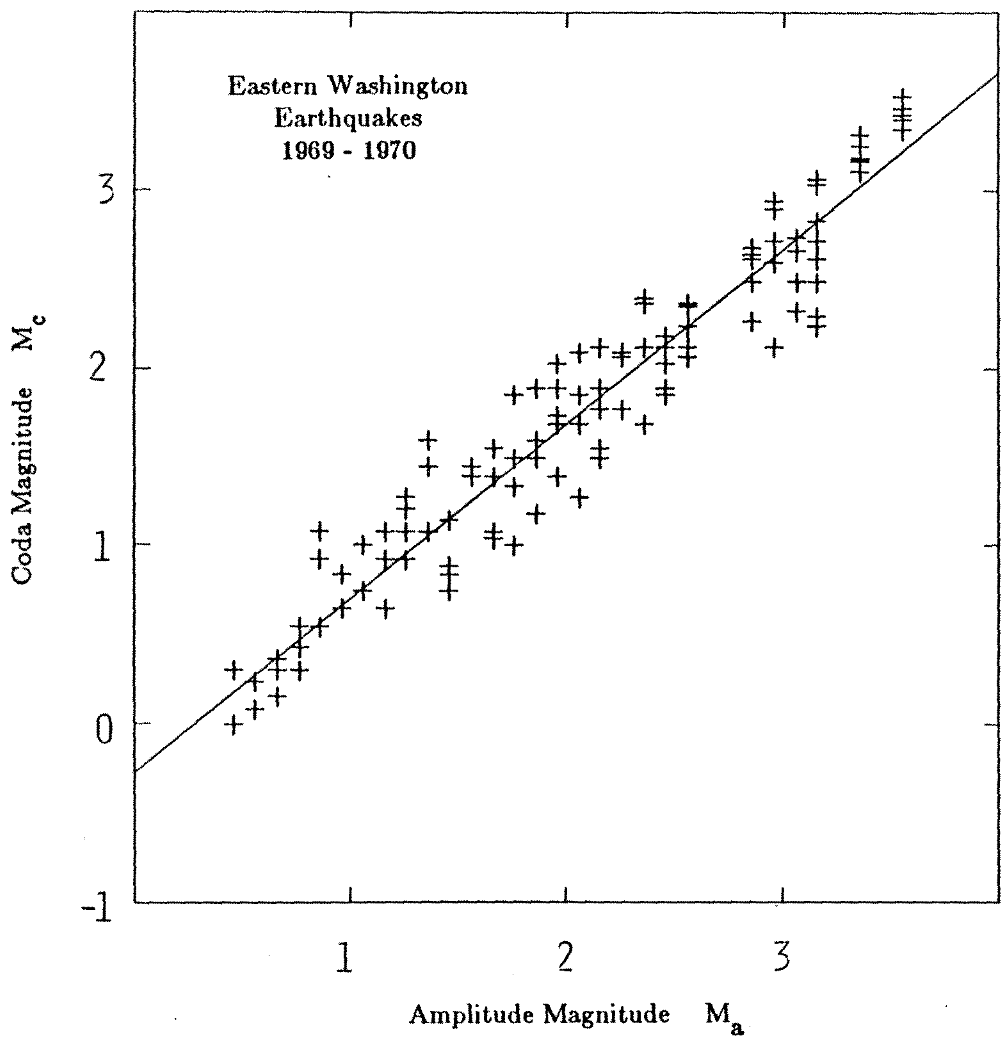
In an attempt to obtain a way to recover the coda magnitudes for the period 1969 to 1974, we examined the relationship between the amplitude magnitude M_{amp} and the coda magnitude M_c used today. Coda-lengths were measured for earthquakes within the Eastern Washington network by viewing develocorder film records in Menlo Park. The convention used to measure coda-length is the same used by UW since 1975: coda-length equals the duration of the seismic signal from the the first arrival until the amplitude has decayed to twice the background noise level. Using a number of stations in eastern Washington and 31 earthquakes in 1969 and 1970 resulted in:

$$M_c = -0.278 + 0.984 \ M_{amp}. \qquad (2)$$

Figure IV-1 shows the fit of this equation to the data used in the study. Note that the slope of this line is nearly 1.0, and that the $M_{amp} = 0$ intercept is about -0.3. Therefore, M_c is expected to differ from M_{amp} by no more than 0.3, for magnitudes between 0 and 3. Furthermore, note that M_c is slightly lower than M_{amp} in this same magnitude range.

Using (2) we can convert the M_{amp} values to coda magnitude. During the period when the USGS was averaging M_{amp} and M_c a direct conversion using (2) is not possible. However, we can calculate M_{amp} directly by using peak-to-peak amplitude data and then use (2) to convert it to M_c.

Results of this work indicate that the magnitude estimates currently in the catalogs need little adjustment to be considered uniform. Until the catalogs are updated correcting magnitudes for the 1969-1984 period there will be little error in using the listed magnitudes. We are currently working to complete a data base for Eastern Washington which contains a continuous and consistent record of earthquake coda-magnitudes from 1969 to the present.



Coda Magnitude M_c versus the early USGS amplitude Magnitude, M_{amp}, for 31 earthquakes in Eastern Washington which occurred in 1969 and 1970. Also shown is the linear relation $M_c = -0.278 + 0.984{*}M_{amp}$ which best fits the data.

V - SWARM RELOCATION TECHNIQUE

Introduction

Standard locations of earthquakes recorded on a regional network such as that of the University of Washington are not accurate nor precise enough to interpret small geological structures. Epicentral and depth errors for eastern Washington locations are commonly 1.5 and 3 km respectively, and can be greater, depending on station density. Although some of the error is due to lack of close-in stations and an inappropriate velocity model or set of station corrections, part of the error is merely due to mispicked first arrivals because of poor signal to noise ratio. More distant stations often are timed late, especially for smaller earthquakes where the first arrival may be lost in noise. This forces the hypocenter to be falsely located, often much too shallow. Errors such as this are too large to be able to draw any conclusions about the spatial distribution of earthquakes that are clustered in small volumes, say 1 or 2 km on a side. With this in mind, further processing of routine earthquake hypocentral data is necessary before detailed analysis of small geological structures can begin. Since many of the earthquakes in eastern Washington, especially those in the greater Pasco Basin, occur in spacial cluster or swarms precise relative locations may be useful in studying the causitive geologic structures. We have previously developed a very high precision relative location procedure which has a precicion on the order of a few meters. Unfortunately this technique only works on earthquakes within multiplet in which the seismogram for each event is a near duplicate of another. Most events, even those in swarms, are not part of a multiplet.

We are presently working on a technique that can be used to improve the timing of first arrivals for earthquakes that are not part of a multiplet, and thus improve the precision of earthquake locations within swarms or clusters. We have applied this technique to a swarm of earthquakes and compare these relocations with both the standard locations and the relocations obtained by the master event technique.

Data and Analysis

The data used are seismograms from an earthquake swarm that occurred in March, 1986 near Darrington, Washington, 80 km northeast of Seattle (Figure V-1). The swarm consisted of 25 earthquakes with M >= 1.0. The largest was M=3.6. This swarm provided a rare opportunity to study a group of tightly clustered events and to compare the results of various hypocenter location techniques. Because of the proximity of the swarm to Seattle, we were able to set up portable stations in the epicentral area quickly and service them daily.

The method that we used to improve the precision of hypocentral locations is appropriate for application to clustered events, as it is based on the ability of cross-correlation of waveforms to improve the timing accuracy of first arrivals. This cross-correlation method of retiming and relocating earthquakes is a simple technique, however details and complexities in the automatic application of the process to any earthquake sequence have thus far hindered its development into a routine procedure.

Cross-correlation is a way to measure the degree of similarity of waveforms. If two earthquakes have similar waveforms, then they probably have similar focal mechanisms and hypocentral locations. Cross-correlation of the waveforms of two similar events, one which has a clear first arrival and one which has an unclear first arrival (due to noise, or smaller magnitude), will pick out the P-wave arrival on the second event. This is the essence of the technique. Its simplicity enhances its merit of leading to much better precision in the relative locations of the earthquakes of a cluster. Cross-correlation of two events at the same station as a function of frequency also yields information as to how close the events are to each other. The better correlated two events are at higher frequencies, the closer they are to each other. It is generally accepted (Geller and Mueller, 1980) that the highest frequency at which two earthquakes are well-correlated yields the maximum separation distance d between the two events by the relation

$$d = \frac{1}{4}\lambda = \frac{1}{4}\frac{v}{f}$$

where λ is the wavelength, v is the P- wave velocity, and f is the frequency.

In regard to the Darrington swarm, cross-correlating every event against every event at several stations as a function of frequency indicated that the swarm consisted of approximately seven discreet families of very similar events or multiplets. Based on the cross-correlation behavior at various frequencies, we estimated that the families occurred within an area roughly several hundred meters on a side. We set out to determine the relative locations of the families. The first thing we did was to assign each of the 25 earthquakes to a particular family. Details of this procedure are left for a later publication.

The seven families were clustered tight enough that at least adjacent families had similar enough waveforms that we could apply the cross-correlation technique to better pick the P-wave arrivals. For the relative locations of the families, we chose one representative event from each family.

Figure V-2 illustrates how cross-correlation can help pick out the first arrival. Two very similar events recorded at the same station are shown, together with their cross-correlation function. The offset of 0.07 s of the cross-correlation maximum from the alignment of the P- picks indicates that the second event was picked 0.07 s too early. Routine processing picked this first arrival on a compression which is actually a telemetry glitch. We cannot overemphasize that it was only by cross-correlation that this mispick was discovered. The true P- wave arrival is at the following dilatation, which corresponds to the first motion of the first event. We estimate our precision of picking by this method to be 0.01 - 0.02 s. Our sampling rate is 100 samples/s.

Results

In this manner we repicked the arrivals of the seven representative events at the stations shown in Figure V-1. Using a Cascade velocity model and P- waves only, we relocated each family relative to its most similar family. Results are shown in Figure V-3. The filled circles are the cross-correlation relocations of the representative earthquake of each family. The error bars are not true error bars but are estimates of the mislocation error due to the imprecision in picking, approximately 100 m in epicenter and 200 m in depth. With this precision, it is clear that with the possible exception of the two northern most events, none of the earthquakes co-located, and the relative positioning of the events cannot be argued.

In comparison, Figure V-4 shows the results of the standard locations and the master event relocations, together with the cross-correlation relocations. The standard locations were obtained using a slightly modified version of Crosson's Puget Sound velocity model and P- and S- waves. The master event and cross-correlation relocations both were obtained by using a Cascade velocity model more appropriate for the Darrington area and P- waves only. Error bars are estimated errors in location. Considering the large error bars for the standard locations, the earthquakes are not well located, neither their relative locations nor the cluster as a whole. The master event relocations improved the precision of the location of the cluster, however the relative locations of the events still are not determined. Only the cross-correlation relocations are able to resolve the relative locations of the events. It is interesting to note that the master event and cross-correlation relocations both located the cluster within the same area. If one were only interested in defining where the cluster occurred, the master event technique did just as good a job as the cross-correlation method, for a lot less work. However, it is clear that the relative locations of the hypocenters is resolved only by applying the cross-correlation technique.

The cross-correlation technique described above makes it possible to resolve the relative locations of earthquakes on the order of several 100 m apart by simply better picking the first arrivals. With this amount of resolution, determination of small scale geological structures is possible.

After completing analysis on the Darrington swarm, we plan to apply the cross-correlation technique to other event clusters. The seismicity of eastern Washington is largely characterized by swarm activity and offers many promising data sets. The Vantage swarm of 1984-85 and the continued seismicity south of Lake Chelan and in the Saddle Mountains are three obvious candidates. We believe that analysis of these earthquake sequences using the cross-correlation technique will help explain the occurrence of these earthquakes and contribute to the understanding of the tectonics of eastern Washington.

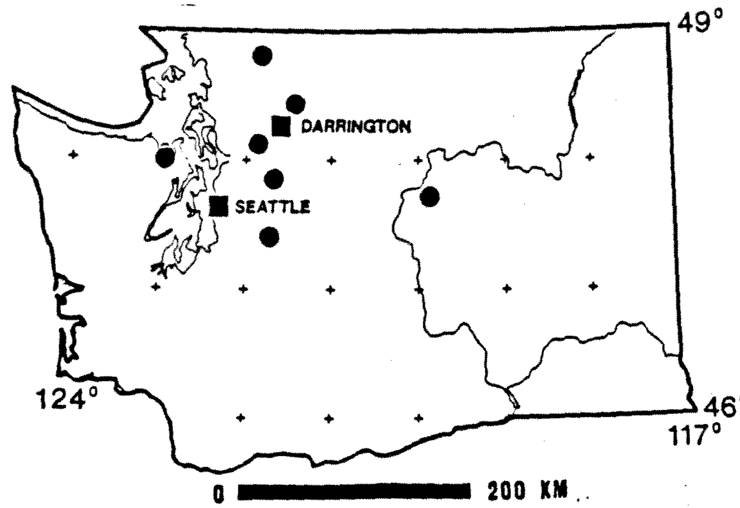


Figure V-1. Map showing the location of Darrington, the site of the earthquake swarm. The filled circles are the stations used for the cross correlation relocations.

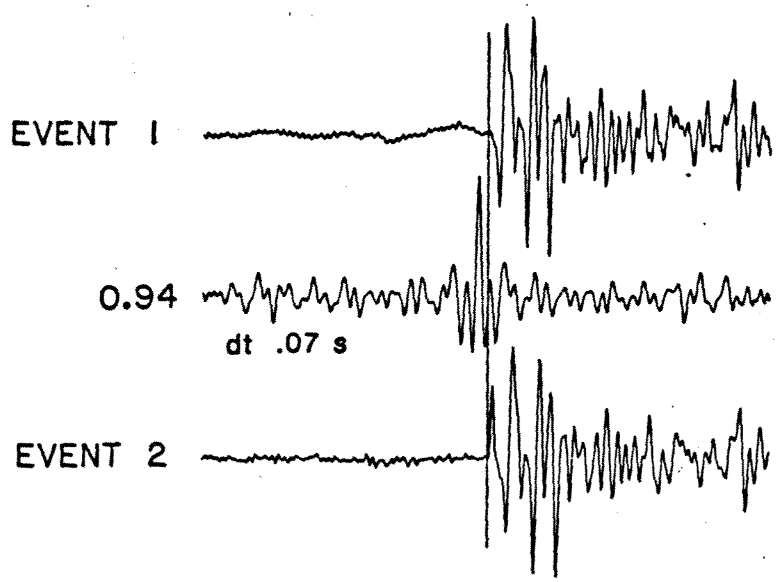


Figure V-2. Two very similar earthquakes (top and bottom traces) recorded at the same station, shown together with their cross correlation function. Illustrates how cross correlation can help pick out the first arrival. See text for explanation.

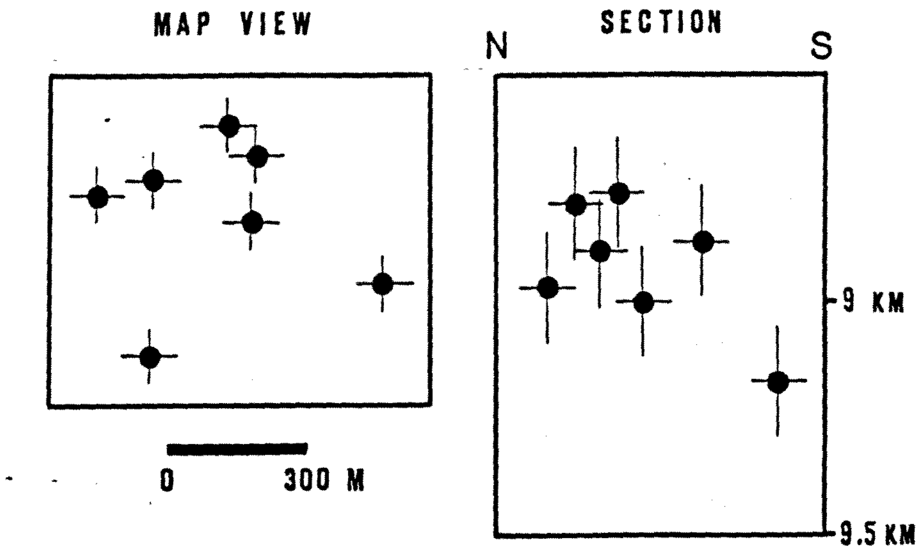


Figure V-3. Cross correlation relocations of the representative earthquake of each family. Error bars are estimated errors in location due to imprecision of picking. Map and section are plotted to the same scale.

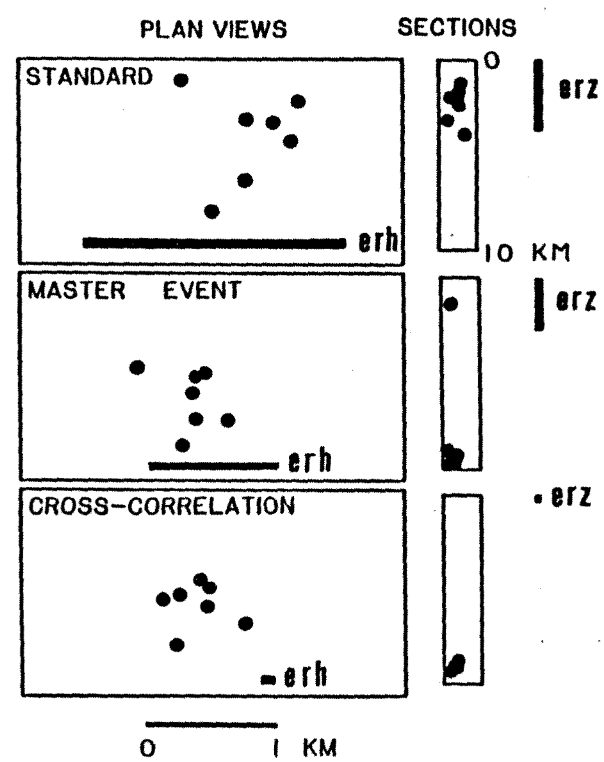


Figure V-4. Comparison of the three sets of locations. Error bars are the estimated errors in location. Note the different horizontal and vertical scales. See text for discussion.