ANNUAL TECHNICAL REPORT: 1993

Name of Grantee:	**University of Washington**
Principal Investigator:	**R. S. Crosson** **Geophysics Program AK-50** **University of Washington** **Seattle, WA 98195**
Government Technical Officer:	**Dr. John Sims** **U. S. Geological Survey** **905 National Center** **Reston, VA 22092**
Short Title:	**Earthquake Hazard Research in the Pacific Northwest**
Effective Date of Grant:	**March 1, 1993**
Grant Expiration Date:	**Feb. 28, 1994**
Amount of Grant:	**$71,700.**
Date Report Submitted:	**Sept. 9, 1994**

Sponsored by the
U.S. Geological Survey
Grant No. 14-08-0001-G1803

CONTENTS

FIGURES

TABLES

APPENDICES

1. Recent Abstracts
2. Preprint: S.R. Dewberry and R.S. Crosson, "Source scaling and moment estimation for the Pacific Northwest Regional Seismograph Network using coda amplitudes", to be submitted to BSSA.

Summary

This is the final technical report for USGS grant 14-08-0001-1803, "Earthquake Hazard Investigations in the Pacific Northwest" during the period 2/1/92 - 2/28/93. The objective of our research is to investigate earthquake hazards in the Pacific Northwest including problems related to large scale plate interactions and possible large subduction earthquakes. Improvement in our understanding of earthquake hazards is based on better understanding of the regional structure and tectonics.

A primary source of our data is the Pacific Northwest Seismograph Network (PNSN; formerly known as the Washington Regional Seismograph Network), and our studies require cooperation and collaboration among a number of individuals and projects. Investigations by our research group include source moment estimation for Cascadia earthquakes, the Scotts Mills, Oregon earthquake sequence, and a study of crustal and upper mantle structure beneath Washington state from array analysis of short-period network data. Appendix 1 includes abstracts funded under this grant.

Source scaling and moment estimation using S-coda amplitudes

A manuscript entitled "Source Scaling and Moment Estimation for the Pacific Northwest Seismograph Network Using S-Coda Amplitudes" by Shawn R. Dewberry and Robert S. Crosson is included as Appendix 2. It has been submitted to the Bulletin of the Seismological Society of America. This paper proposes a way to estimate the seismic moment (and thus magnitude) of local earthquakes through amplitude measurements of the S-coda recorded on short-period vertical instruments.

Development of Analysis Software

Significant changes to our network support software have become necessary because of the addition of broadband stations to our regional network. First, the underlying digital trace-data format required revision so that we could flexibly incorporate data with differing dynamic ranges, time windows, and sample rates. In addition, three component support was needed. We accomplished this by designing revised trace-data formats, called UW-2, that are backward-compatible extensions of our existing data formats. UW-2 will become the standard trace-data recording format when our new Sun-based data acquisition system comes on-line (presently we can either convert the from the old format to the new, or use the backward-compatible features of the new format). Secondly, our "pickfile" extracted parameter data format was revised and extended to accommodate multiple phases, three-component analysis, and to provide other enhancements to our previous pickfile format.

We now have a working set of basic software analysis tools that utilize the new data and pickfile formats. These tools include: interactive manual and automated seismogram picking and analysis, earthquake location, focal mechanism fitting and plotting, record section and other plotting programs, and data management programs. This effort has come to fruition in the past few months, and we are only now making full use of the new capability.

The Scotts Mills, Oregon Earthquake Sequence

On Mar. 25, 1993 (1334 UT), a magnitude 5.6 earthquake occurred at a depth of about 15 km, approximately 40 km ENE of Salem, Oregon and 50 km south of Portland, Oregon. Various magnitude estimates ranging from 5.4 to 5.7 have been reported for this earthquake. The location is near the west margin of the Cascade Range of northern Oregon. The preliminary moment estimate is 2-3E24 dyne-cm (John Nabelek, pers. comm.). This earthquake was widely felt (there were even felt reports from Seattle at a distance of 290 km), and was the most significant earthquake to occur in the Pacific Northwest since the Elk Lake earthquake of Feb. 1981 (M 5.5). Dewey et al. (1994) report results of intensity questionnaires sent to Post Offices in the region, summarize the results of preliminary analysis of teleseismic records, and report on strong motion accelerograms obtained at 6 distinct sites. Intensity V shaking was reported in the Portland area, and Salem reported intensity VI. An extensive aftershock sequence followed the mainshock, and seismic activity in the region has remained above previous levels since the event over one year ago.

Soon after the mainshock, the USGS and other investigators operated digital portable seismograph stations with high dynamic range to record aftershocks. Our analysis of this earthquake sequence included assembling and merging data from the portable USGS instruments with the regional network (PNSN) data, as well as analyzing the sequence.

Data

Groups from USGS Denver and Golden operated 15 portable digital recorders, including 11 DR200 recorders, and 4 Reftek Passcal recorders for a period of 10 days beginning as early as about 18 hours after the mainshock (Carver, 1993). These instruments all had short period, three-component sensors. In addition, a USGS Menlo Park group operated 11 Geos instruments for a period of up to 20 days following the mainshock. Several analog recorders (MEQ's) were also operated by the University of Washington. Other groups, including Oregon State and U. of Oregon, operated broadband portable instruments for various periods of time in the region. The portable USGS instruments provide the only close-in digital recording of aftershocks for this earthquake. The nearest PNSN station, SSO (Fig. 1),

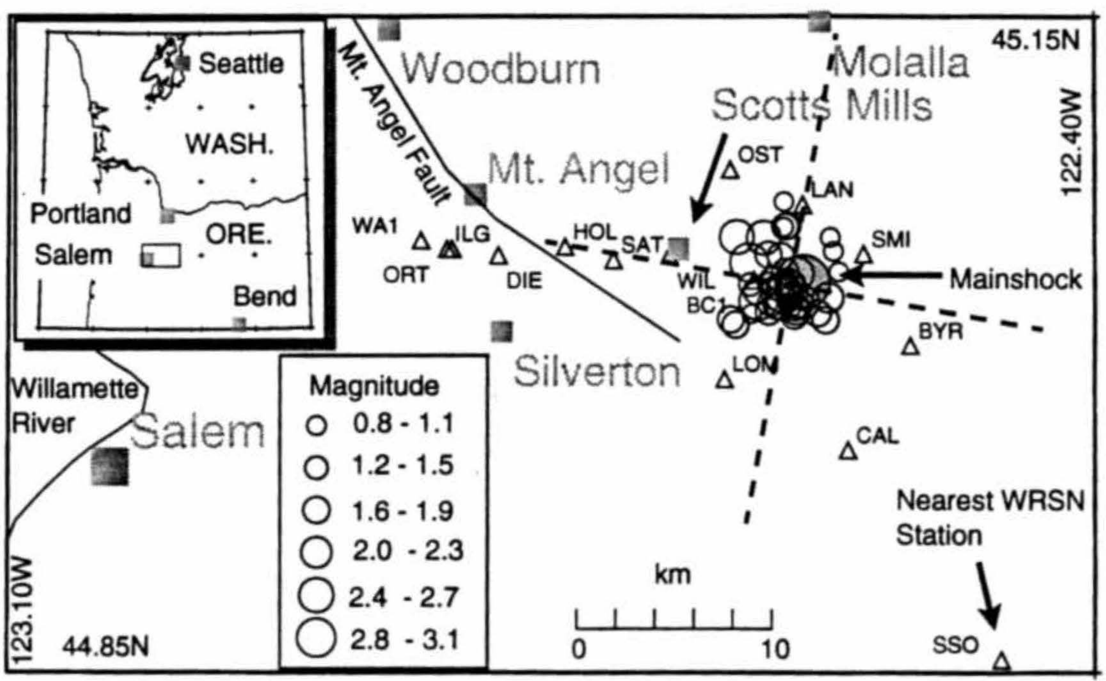

Fig. 1. Location map and aftershock epicenter map of Scotts Mills region of northern Oregon. The expanded region at right shows epicenters of 42 well located earthquakes used for determining the planar alignment of aftershocks discussed in the text. Portable station locations are indicated by small triangles and the single PNSN station that lies within this region is labeled. Dashed lines show the azimuths of cross-sections discussed later in the text. The trace of the Mt Angel fault has been extended somewhat further to the SE than originally indicated by Werner et al. (1991).

is at a distance of approximately 22 km from the mainshock epicenter; SSO and other regional net stations provide continued monitoring ability for the ongoing sequence of earthquakes in the region. No permanent near-in stations were established. The nearby portable stations used for aftershock recording are shown in Fig. 1. George Thomas, a UW graduate student, reformatted digital trace-data from the modified DR100 data format, used by the USGS for both DR200 and Reftek data, to UW-2 format. The merging of the Geos data remains to be completed, but this is a smaller part of the data set. The current merged trace-data set is about 250 Mb in size, and includes about 80 locatable earthquakes recorded during the period of aftershock monitoring with portable digital instruments. Station calibration and other important parameter data are stored with the merged data.

This data set is unique for Pacific Northwest earthquakes in both the quantity and quality of digital seismogram data. When merging of the Geos data is completed, this data will be made available in UW-2 format, with a conversion program to the widely used AH format. All PNSN analysis tools, which work with the UW-2 format, will also be available.

Aftershock Analysis

With the permanent PNSN network, we have recorded about 150 reliably located earthquakes in the Scotts Mills sequence through the end of February, 1994. A much larger number of small, unlocatable earthquakes have been detected with the network, either through triggering of the digital recording system or, more often, on continuous helicorder records at SSO and other nearby stations.

From the total data set, we selected a subset of 42 aftershocks that were well recorded on both the PNSN and the portable digital stations for further analysis. Fig. 1 shows epicenters of these aftershocks, including the mainshock. Also included on this figure are the locations of temporary stations used to record the aftershock sequence.

To gain better understanding of the regional background seismicity of the Scotts Mills region, we examined past locatable earthquakes in two regions: a larger region including Salem to Portland (44.5° to 46.0° N, and 121.5° to 123.5° W) which we call region A, and the immediate Scotts Mills region (44.85° to 45.15° N, and 122.4° to 123.1° W) which we call region B. Note that region B is identical to the region shown in Fig. 1. Fig. 2 shows histograms of earthquakes from the UW catalog for these two regions, with number of earthquakes plotted on the vertical axis against horizontal axes representing time and magnitude. Fig. 2a covers region A and Fig. 2b covers the smaller area of region B. In region A, seismicity prior to 1993 is dominated by a moderate swarm of earthquakes in 1991 at a depth of about 20 km in the Portland region. From early 1993 on, the Scotts Mills sequence dominates the activity. From Fig. 2b, it is clear that for region B, the 1993 Scotts Mills sequence represents a dramatic change of the activity pattern from the prior four years. Fig. 2c shows that after the immediate aftershock sequence decay (2-3 weeks after the mainshock), small earthquakes in the magnitude 2 to 3 range continued, producing a significantly higher level of background seismicity than before the mainshock.

The aftershock sequence in region B was accompanied by changes in b-values. Fig. 3 shows magnitude - cumulative frequency plots for several groups of earthquakes using coda duration magnitudes from the PNSN data. We find b-values of 0.75 for the first seven days following the mainshock, 1.05 for April-June 1993, and 1.10 for July-December 1993. These curves indicate that the detection sensitivity of the PNSN lies between magnitudes 1.8 and 2.0 for this region. No attempt has been made to normalize the curves to the same time period, so the curves cannot be compared directly for relative activity levels. The rate of activity in the Scotts Mills area before March 1993 was extremely low, and b-values were not determined for this period. A small "swarm" of earthquakes (6 were located) was detected and located in the vicinity of Woodburn in 1990, and these events were used by Werner et al. (1992) to infer that the Mt. Angel fault was active. Similar to many aftershock sequences, the immediate aftershock sequence appears to have a b-value lower than normal background. However, it is clear from the quality of fits on Fig. 3 that this difference is not great and may not be significant. The b-values for the later portions of the aftershock sequence agree well with typical b-values for crustal earthquakes in the Puget Sound region which are near 1.0. It will be possible to refine magnitudes for those aftershocks that were recorded on the portable instruments by using amplitude measurements on the calibrated 3-component stations.

Last year we speculated that aftershocks might lie on a NE dipping fault plane, based only on the changes in location for 10 aftershocks caused by including arrival time data from a single smoke-

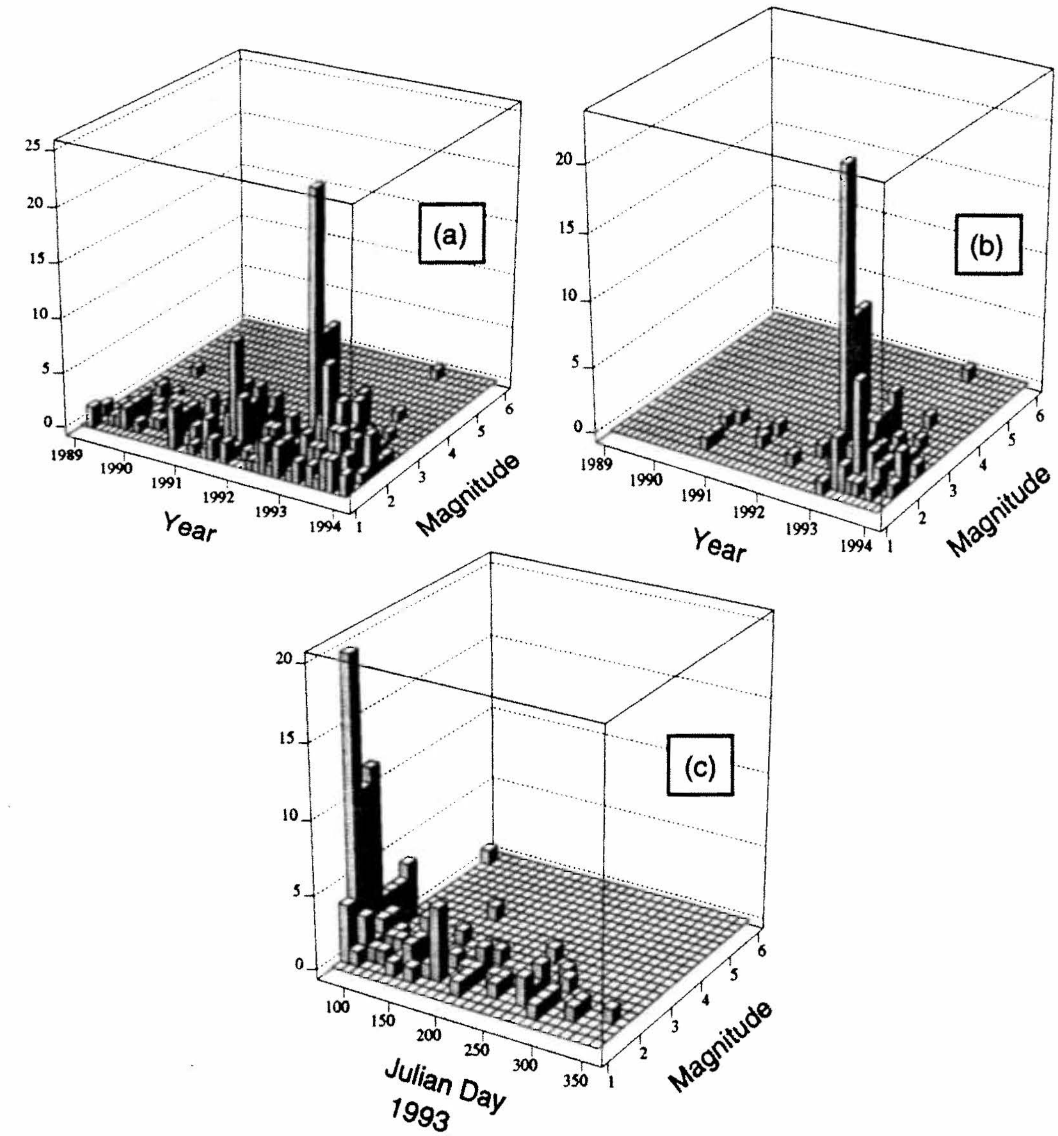

Fig. 2. Histograms of earthquake activity for (a) region A, the Salem-Portland region, bounded by 44.5° to 46.0° N and 121.5° to 123.5° W; (b) region B, the immediate Scotts Mills region bounded by 44.85° to 45.15° N and 122.4° to 123.1° W for time period 1989 through Feb. 1994; and (c) Scotts Mills aftershock sequence for region B, but from the time of the main shock to the end of 1993.

drum recorder located just north of the aftershock zone. That prediction has turned out to be in agreement with refined locations of a number of aftershocks. To obtain aftershock locations, we started with a basic velocity model for western Washington and have made small changes to accommodate geologic information appropriate to the east side of the Willamette Valley. In this region, basalt lies within a few hundred meters of the surface, and the surface sediment cover is thin

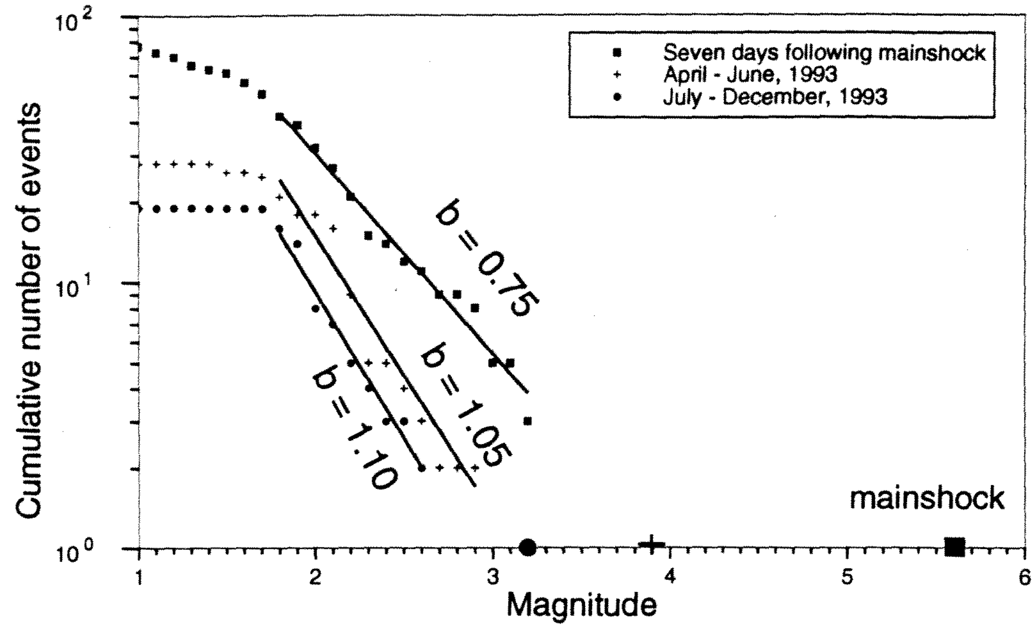

Fig. 3. Magnitude-frequency distributions for earthquakes in the immediate Scotts Mills region bounded by 44.85° to 45.15° N and 122.4° to 123.1° W. Squares are for events in the immediate aftershock period 7 days following the mainshock; pluses are for the ensuing aftershock period through June, 1993, and round dots are for July through December, 1993. The mainshock (M 5.6) is shown as a black square. Data are not normalized to the same time interval.

according to Werner et al. (1992). We have also generated a new set of stations corrections from the aftershock RMS time residuals.

Fig. 4 illustrates two cross-sections of hypocenters for a group of 42 aftershocks with high quality locations. The NNE trending cross-section clearly shows alignment on a plane dipping about 60° to the NE (dashed line). Although the mainshock lies off of this plane, uncertainty of the depth of the mainshock is great enough to account for this discrepancy. We determined the best fitting plane through the aftershock hypocenter distribution using both least squares and eigenvector decomposition of the location data; these two approaches yield similar results to within about 8°. From this alignment of hypocenters, we conclude that there is a high likelihood that most of these earthquakes lie on the rupture surface of the mainshock.

Last year, based on preliminary analysis, we also noted that the mainshock focal mechanism obtained with PNSN data was not in complete agreement with the mechanism obtained from

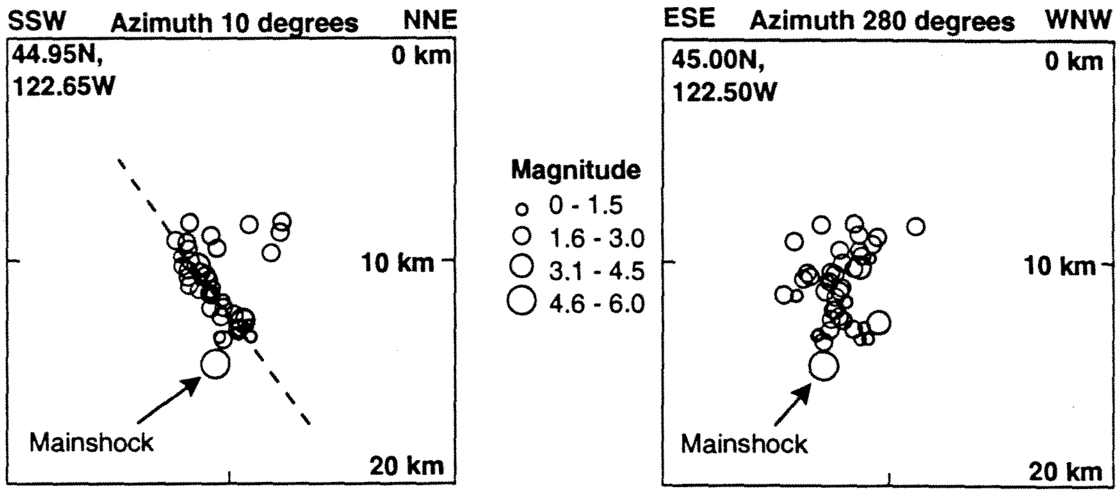

Fig. 4. Orthogonal cross-section plots of mainshock and 42 well located aftershocks (also see orientations shown on Fig. 1). The orientation along a 10° azimuth show nearly optimal alignment into a plane. The dashed line is the projection of a plane dipping 54° to the NNE. Note that the depth of the mainshock is not well constrained since portable station data were not available.

broadband data by John Nabelek's group at Oregon State University (OSU). Subsequent refinement of both solutions has eliminated any significant difference, so we are confident that the mainshock mechanism is well constrained. Our preferred mainshock fault plane strikes N 66° W and dips about 58° N. This result is also in reasonable agreement with the mechanism found by Dewey et al. (1994) using teleseismic data. Slip is partitioned on this plane nearly equally between strike-slip (right lateral) and thrust. This plane is within about 10° (angular displacement of poles) of the plane defined by the aftershock hypocenters. Considering the planar nature of the aftershock zone and the focal mechanism of the mainshock, our current working model is that the mainshock fault plane is a NE dipping oblique thrust.

Thomas et al. (1993) found that there was a systematic change in aftershock focal mechanisms from thrust for aftershocks deeper than about 13 km, to strike-slip for aftershocks shallower than 13 km. These differences do not appear to arise from location error. Although the mechanisms of aftershocks vary, virtually all mechanisms are consistent with NS compressive stress acting on pre-existing faults. This result confirms previous investigations of earthquake focal mechanism and well breakout studies that also show a dominance of NS compressive tectonic stress for western Washington and western Oregon (e.g., Crosson, 1972; Ma et al., 1991; Werner et al., 1991; Magee and Zoback, 1992). The Mt. Angel Fault Zone (MAFZ) (Werner et al., 1992) is shown as a NW-striking line just west of the earthquake sequence in our location map of Fig. 1. In the vicinity of the Scotts Mills epicenters, it appears to be rotated counterclockwise relative to its orientation further to the NW. Werner et al. extended the fault northwestward from the vicinity of Mt. Angel using seismic reflection data. They also considered the earlier occurrence of a small earthquake sequence near Woodburn that occurred in 1990. The MAFZ is viewed by Werner et al. as an important regional structure with mainly vertical displacement (NE side up), with reverse motion (i.e., dipping to the NE). This sense of displacement is consistent with our focal mechanism results. The fault is of Pliocene to Miocene age, and was inferred by Werner et al. (1992) to be currently active based on the earthquake occurrence. Surface geology does not currently provide much added insight into potential earthquake sources in this region.

Although the earthquake sequence occurred at a depth of 10 to 15 km and lies NE of the MAFZ, there is significant likelihood that it is related to the MAFZ because of the hypocenter distribution, fault plane solutions, and sense of displacement. If we project the plane defined by the aftershock zone to the surface, it forms a line subparallel (15° to 20° counterclockwise difference in strike) to the SE extension of the MAFZ. There is less than 5 km horizontal separation between the traces of these two planes in the vicinity of the aftershock zone. These differences are probably not significant in light of the uncertainty of both (a) the extension of the MAFZ to the depth of the aftershock zone, and (b) the dip of the fault plane based on aftershock locations and focal mechanisms. Therefore our preliminary conclusion is that the MAFZ is the same or a related manifestation of the mid-crustal fault zone which gave rise to this earthquake. The base of the aftershock zone at about 14 km may be at the depth of the brittle-ductile transition in this region. By contrast, near Portland, hypocenters extend to depths near 20 km (e.g., Yelin and Patton, 1991). One explanation for this difference in maximum depths is a decrease in the brittle-ductile transition depth as we approach the Cascade crest. Blackwell et al. (1990) give an extensive review of the thermal characteristics of the

Cascades of Oregon, and they describe a steep gradient in heat flow across the Cascade range front just east of the Scotts Mills earthquake epicenter which may be consistent with this interpretation.

The MAFZ or a related mid-crustal fault in the vicinity of Scotts Mills is clearly a seismically active structure - possibly an older shear zone reactivated under current NS compressive stress. There is no reason to believe that earthquakes of magnitude 6 or larger cannot occur on this structure, possibly northwest of the current sequence and closer to population centers in the Willamette Valley. Therefore this structure must be included in in regional earthquake hazard models. Of perhaps even greater concern are faults in the vicinity of metropolitan Portland such as the Portland Hills fault which has a NW trend similar to the MAFZ. Even a magnitude 5.0 crustal earthquake in the immediate vicinity of Portland would be damaging, and we have little basis at this point to assume that Portland Hills is fundamentally different from the MAFZ.

We expect to have the Scotts Mills data in a form for wider distribution within a period of several months from this writing. A manuscript on our preliminary analysis will be prepared during the current funding period. Further work on this aftershock sequence is proposed here, including refinement of the velocity model for the aftershock region, stress-drop and moment studies, and refined mechanism studies using the digital waveform data. The work that we have done to date on the Scotts Mills earthquake has been carried out by the PI and one graduate research assistant (George Thomas).

Crustal and upper mantle structure beneath Washington state from array analysis of short-period network data

Since 1980 digital data have been recorded by the PNSN, including over 5,000 teleseisms. This wealth of data, although limited by vertical component, short-period instrumentation, should provide a sufficient number of waveforms such that small amplitude phases generated by near-receiver structure can be enhanced and identified. We initially hoped to identify P-wave multiples originating from major boundaries within the crust or upper mantle, such as the continental moho, or the oceanic moho in the subducted Juan de Fuca slab. As the study developed, we found that deep reflected multiples can be identified at only a fraction of the network stations. In addition, some stations show phases that we interpret as multiples from shallow impedance contrasts, either alone or in combination with reflections from deeper horizons.

The technique is summarized as follows: Well recorded teleseisms in the distance range of 40° to 95° are selected. Vertical component seismograms at individual stations for a given event are source-deconvolved for each event. An estimate of the source "time" function for each event is made by stacking high signal-to-noise traces for the event aligned on the direct-P arrival. This enhances waveforms common to all stations, namely all phases with the same apparent velocity as the direct-P arrival. Selecting events with depths greater than 75 km ensures that depth phases (pP and sP) arrive outside of the time window of interest. The source estimates are normally time-limited to 10 seconds or less, and are similar to the results found by Vidale and Houston (1993) who investigated the source time functions of deep focus events with the same stacking technique, using data from three short-period regional seismic networks in Washington and California. Others have performed similar time-domain stacking techniques using short-period data (Houard and Nataf, 1992; Vidale and Benz, 1992; Bostock and VanDecar, manuscript) and broad-band data (e.g., Paulssen et al., 1993).

The deconvolved seismograms recorded by a single station for many different events are grouped in narrow backazimuth windows. We examine both record sections and slant stacks based on model predictions using simple dipping interface receiver structures. Record sections provide a means to identify obvious dependence of the secondary arrivals on distance or incidence angle. For example, we have found that often secondary phases are observed for events only in certain distance ranges. This could be the result of rapid lateral variation in the receiver structure. Slant stacks can be used to enhance secondary arrivals and determine their moveout when there is adequate signal in the record sections. Forward modeling with simple plane interface models provides a guide to interpretation of the slant stack results. With adequate distance and backazimuth coverage, the depth, dip and strike of simple reflecting interfaces may be modeled.

To date we have analyzed nearly 100 earthquakes from backazimuths centered at 130° and 305°. Distance ranges for the events are nominally 40°-95°, though we have a concentration in the distance range 75°-90°. Both record sections and slant stacks for 85 stations have been studied.

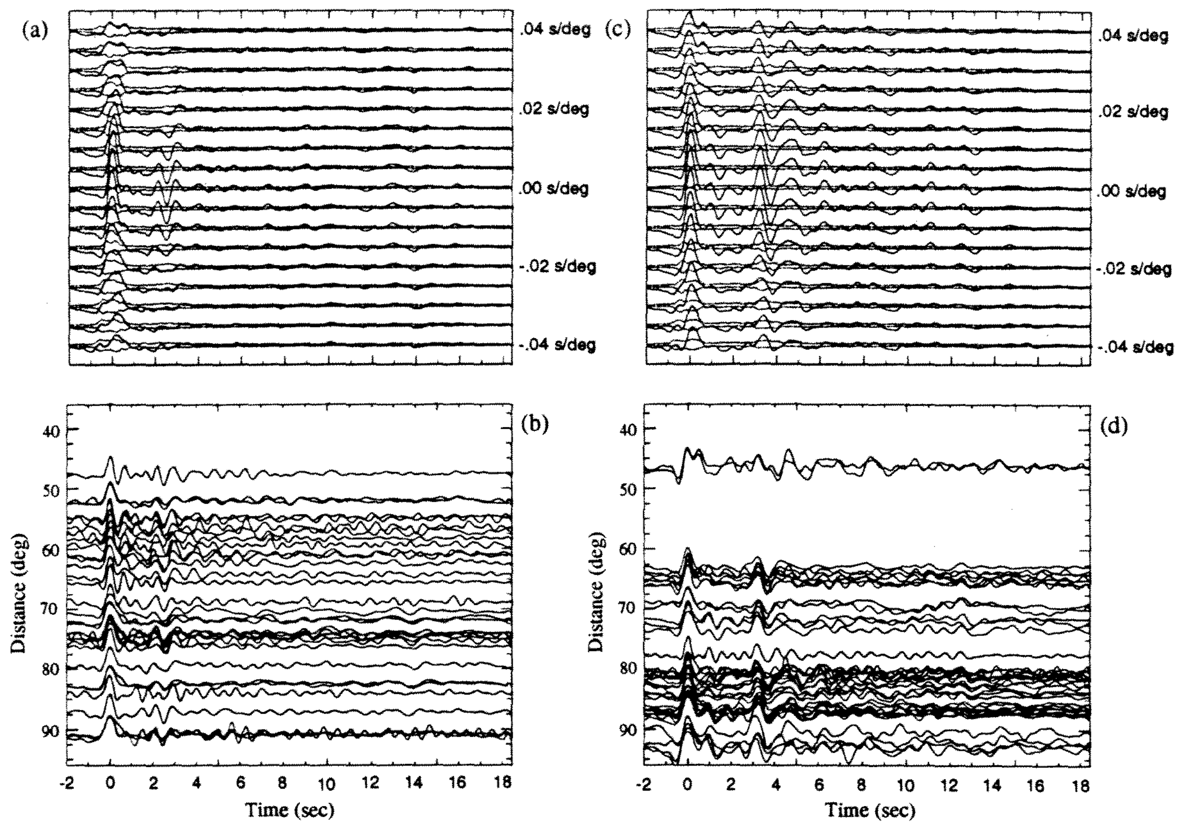

Fig. 5. Slant-stacks and record sections for station MBW with data from two backazimuths, 305 degrees, (a) and (b), and 130 degrees, (c) and (d). Each solid curve in the slant stack suite is the mean stack for a given differential ray parameter; dashed lines are the associated 95% confidence intervals. A large, shallow crustal phase is clear at 2-4 seconds in both record sections and slant stacks. A smaller, deeper phase at 13-14 seconds is brought out by the slant stacks. The time and the negative polarity are consistent with P-multiples from the continental moho at a depth of ~45 km.

Synthetic seismograms generated using simple two-layer models indicate that P-multiples from the continental or subducted plate moho should arrive in the time window 8-15 seconds after the direct-P arrival, with amplitude about 10% of the direct-P.

For the 85 stations studied, only 13 show arrivals which persist over a range of ray parameters and fall in the appropriate time window for moho-generated P-multiples. Most of these stations are found in western Washington. A total of 23 stations show significant secondary arrivals that we interpret as reflections from intra-crustal reflecting boundaries. Table 1 lists the stations where these signals are observed. Figs. 5 and 6 show example record sections and slant stacks for stations MBW and OFK respectively (see also Table 1). Station MBW is in the north Cascade Range of Washington, and station OFK is near the coast west of the Olympic Mts. Station OFK has clear secondary

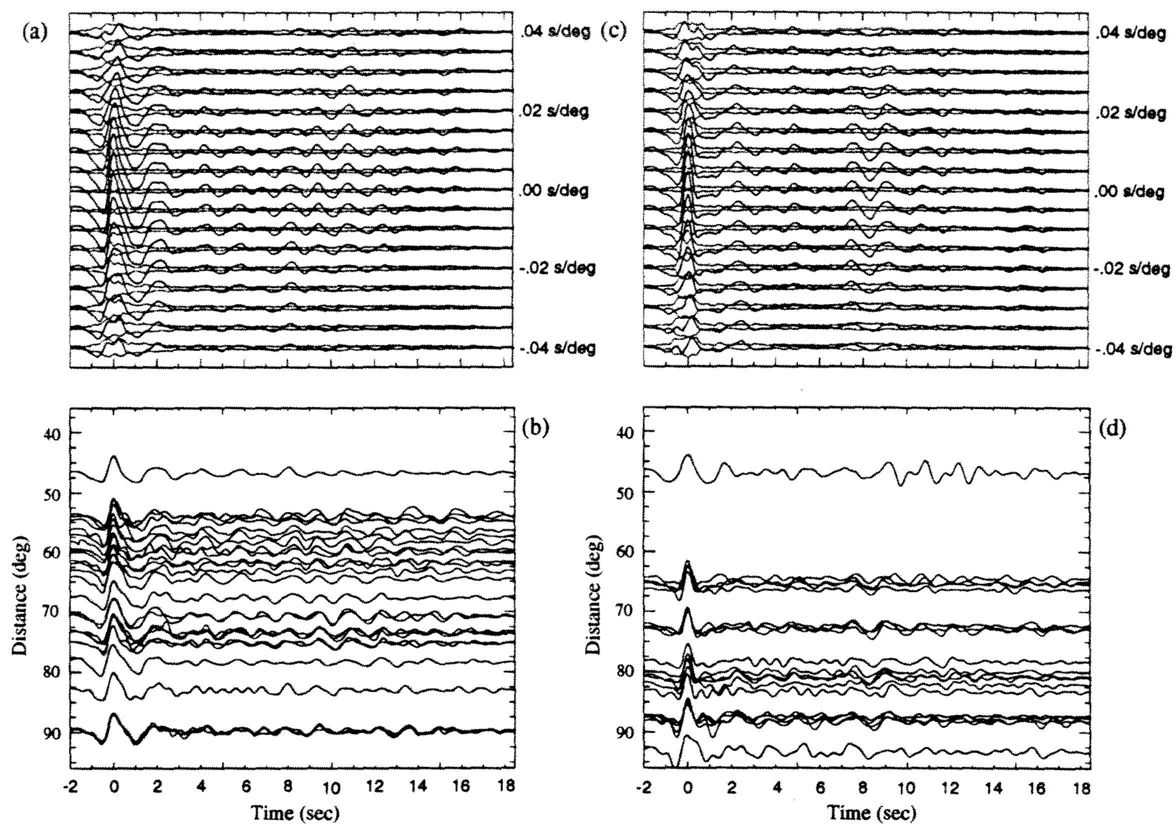

Fig. 6. Slant stacks and record sections for station OFK with data from two backazimuths, 305 degrees, (a) and (b), and 130 degrees, (c) and (d). The prominent negative polarity phase near 8 seconds seen in (c) and (d) can be modeled as a P-multiple from the oceanic moho at a depth of ~25 km. The data from the northwest, (a) and (b), show many coherent phases at 7-10 seconds, however these are not easily modeled using simple planar dipping models.

arrivals at lapse times appropriate for multiples from an oceanic moho at a depth of about 25 km. Station MBW exhibits both a strong shallow depth phase and a depth phase at lapse times appropriate for multiples from a continental moho at a depth of about 45 km. Preliminary results from this study were presented by Dewberry and Crosson (1993) at the Fall AGU meeting.

While using simple models with dipping planar boundaries has been illuminating as a first step, they are inadequate to explain the rapid lateral variations in the receiver structure suggested by the data. Surprisingly, stations within only a few kilometers of one another show remarkably different receiver waveform structure. For example, station WAT in the north-central Columbia Plateau shows what appears to be strong continental moho reflections, whereas stations within 30 km of WAT show no evidence of the same reflections. To complete this project, we are in the process of incorporating

Station	Crustal	Moho	Station	Crustal	Moho
ASR	X	X	OFK		X
BOW		X	ONR	X	
CMM	X	X	OOW		X
FMW	X		RPW	X	
GLK	X		SMW		X
GSM	X		SPW	X	
HDW	X		STW	X	
HTW	X		TBM	X	X
JCW	X		VBE	X	
LO2	X		VCR	X	
LVP	X		VLL	X	X
MBW	X	X	VTH	X	
MTM	X	X	WAT	X	X
NAC		X	WPW	X	
OBH		X			

Table 1. List of stations with intra-crustal and/or moho reflected phases as discussed in text.

more realistic models into the interpretation. These include models with topographic irregularity and boundary curvature. We are investigating the use of Gaussian beam methods and possibly other modeling techniques to interpret these data.

Publications funded under this grant

Articles

Chiao, L.-Y., and K.C. Creager, in preparation, Geometry and Lateral Membrane Deformation Rate of the Subducting Cascadia Slab, to be submitted to JGR

Dewberry, S.R., and R.S. Crosson, in preparation, Source scaling and moment estimation for the Pacific Northwest Seismograph Network using S-coda amplitudes, to be submitted to the BSSA.

Ma, L., R.S. Crosson, and R.S. Ludwin, 1991, Focal Mechanisms of western Washington earthquakes and their relationship to regional tectonic stress, USGS Open File OF-91-441-D, will also be published in a USGS Professional Paper - "Assessing and Reducing Earthquake Hazards in the Pacific Northwest")

Mundal, I., M. Ukawa, and R.S. Crosson, 1991 (in preparation), Normal and anomalous P phases from local earthquakes, and slab structure of the Cascadia Subduction zone, BSSA

VanDecar, J.C., R.S. Crosson and K.C. Creager, (in preparation), Travel-time inversion for subduction zone structure: I. The effect of three-dimensional ray tracing on resolution analysis, to be submitted to JGR.

Abstracts

Dewberry, S.R., and R.S. Crosson, 1993, Crustal and upper mantle structure beneath Washington state from array analysis of short-period network data, EOS, V. 74, N. 43, p. 201.

Schultz, A.P. and R.S. Crosson, 1993, A 2-dimensional P-wave velocity profile across the Cascade Range of Washington State using earthquake sources and regional network observations, EOS, V. 74, N. 43, p. 202.

Thomas, G.C., R.S. Crosson, S. Dewberry, J. Pullen, T. Yelin, R. Norris, W.T. Bice, D. Carver, M. Meremonte, D. Overturf, D. Worley, E. Sembera, and T. MacDonald, 1993, The 25 March, 1993 Scotts Mills, Oregon earthquake: aftershock analysis from combined permanent and temporary digital stations, EOS, V. 74, N. 43, p. 201.

VanDecar, J.C., Bostock, M.G., R.S. Crosson, and K.C. Creager, 1993, How does a subduction zone die?: Reconciling the dynamic and kinematic observations of Cascdia tectonic evolution, EOS, V. 74, N. 43, p. 92.

Acknowledgments

Work under this grant could not be carried out without the data collected by the Pacific Northwest Seismographic Network; we recognize the contribution of the electronics technicians, data analysts, and seismologists of the PNSN.

REFERENCES

Blackwell, D.D., J.L. Steele, M.K. Frohme, C.F. Murphey, G.R. Priest, and G.L. Black, Heat flow in the Oregon Cascade Range and its correlation with regional gravity, curie point depths, and geology, *G. Geophys. Res., 95*, 19,475-19,493, 1990.

Bostock, M.G. and J.C. VanDecar, The influence of crust and upper mantle heterogeneity on short period waveform distortion, *Phys. Earth Planet. Sci. Int.,* Submitted,.

Carver, D., D. Worley, and T. Yelin, Digital recordings of aftershocks of the March 25, 1993 Scotts Mills, Oregon earthquake, *Open-File Report 93-535,* U.S. Geol. Survey, 117 pp., 1993.

Crosson, R.S., Small earthquakes, stucture, and tectonics of the Puget Sound region, *Bull. Seis. Soc. Am., 62*(5), 1133-1171, 1972.

Dewberry, S. and R.S. Crosson, Crustal and upper mantle structure beneath Washington State from array analysis of short-period network data (abstract), *EOS, 74*, 201, 1993.

Houard, S. and H.C. Nataf, Further evidence for the "Lay discontinuity" beneath northern Siberia and North Atlantic from short-period P waves recorded in France, *Phys. Earth Planet. Sci. Inter., 72*, 264-275, 1992.

Ma, L., R.S. Crosson, and R.S. Ludwin, Focal mechanisms of western Washington earthquakes and their relationship to regional tectonic stress, *Open-File Report OF-91-441-D,* U.S. Geological Survey, 1991.

Magee, M. and M.L. Zoback, Wellbore breakout analysis for determining tectonic stress orientations in Washington State, *Open-File Report 92-715,* U.S. Geological Survey, 56pp. pp., 1992.

Paulssen, H.J., J. Visser, and G. Nolet, The crustal structure from teleseismic P-coda: I. Method, *Geophys. J. Int., 112*, 15-25, 1993.

Vidale, J.E. and H.M. Benz, A sharp and flat section of the core-mantle boundary, *Nature, 359*, 627-629, 1992.

Vidale, J.E. and H. Houston, The depth dependence of earthquake duration and implications for rupture mechanisms, *Nature, 365*, 45-47, 1993.

Werner, K.S., E.P. Graven, T.A. Berkman, and M.J. Parker, Direction of maximum horizontal compression in western Oregon determined by borehole breakouts, *Tectonics, 10*, 948-958, 1991.

Werner, K.S., J. Nabelek, R. Yeats, and S. Malone, The Mount Angel Fault: Implications of seismic-reflection data and the Woodburn, Oregon, earthquake sequence of August 1990, *Oregon Geology, 54*, 112-117, 1992.

Yelin, T. and H.J. Patton, Seismotectonics of the Portland, Oregon, region, *Bull. Seis. Soc. Am., 81*, 109-130, 1991.