WASHINGTON REGIONAL SEISMOGRAPH NETWORK

MAJOR SCIENTIFIC ACCOMPLISHMENTS

and

OPERATIONS

1990

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INTRODUCTION

It is impossible in the space of this short report to do more than mention the major scientific accomplishments to which the WRSN operation has contributed. In nearly 20 years of operation the WRSN has played a central role of the seismological and related research carried out by students, faculty, and staff at the University of Washington. In addition, numerous investigators from outside the University have acquired and used our data in earthquake hazard and other research.

At least 23 student theses (see publication list) have been completed using network data, and several more are currently in the process of completion. Some students have completed non-thesis programs in which publication of network research substituted for the thesis. All seismology students presently gain exposure to various phases of network operation. Thus the WRSN operation supports and is consistent with the University's basic educational mission.

Although they often come in increments, and are thus more difficult to discern, the gains that we have made in knowledge as a result of the network operation are truly significant. These gains have been made in a broad range of studies, from structure to seismicity, tectonics, and earthquake hazards. The network underpins advanced analysis, such as tomography of the deep subduction zone structure, as well as providing the data needed for rapid response to public inquiries about regional and local earthquakes. While there are many difficulties associated with network operation, and significant resources are required, these accomplishments could have been achieved in no other manner.

In the next section we list, with brief descriptions, the major scientific accomplishments that have been based on WRSN data. To keep this report brief, this list is not exhaustive, nor are the descriptions necessarily complete. Also for brevity, we have avoided formal references, or attribution of authors or investigators. The reference list of this report can be used for more complete documentation. The topics are not necessarily selected in order of priority or significance. Where appropriate, we mention possible future advances in research related to each topic.

MAJOR SCIENTIFIC ACCOMPLISHMENTS

Regional Seismicity

The nearly two decades of network operation has resulted in definition of the regional seismicity for western Washington and most of eastern Washington at the magnitude 1-5+ level. Prior to network operation, there was no detailed knowledge of small earthquake occurrence in Washington. In western Washington earthquakes are distinctly divided into intracontinental and intraslab groups, and provide much of our basic knowledge about subduction zone structure. Outside of the St. Helens region, which produces exceedingly large numbers of small earthquakes, the Puget Sound region of western Washington is the most active area with numerous small spatial clusters occurring in the crust to depths of 25-30 km, and subcrustal earthquakes occurring to depths of 70 km or more. Outside of the Puget Sound region, including eastern Washington, most earthquakes occur in the shallow crust at depths of 15 km or less, although a few subcrustal earthquakes occur in western Oregon and in western British Columbia.

The seismicity data base is the normal starting point for many studies such as tectonics, earthquake hazards and structure. Our data base is now sufficiently large that we can begin to study long-term changes in the patterns of earthquake occurrence, and to apply advanced analysis methods in assessing the hazard significance of the earthquake occurrence pattern.

Aftershocks and Earthquake Sequences

Numerous network-based studies of specific swarms or mainshock-aftershock sequences have been performed. In many cases these involved deployment of portable field instrumentation to supplement the network stations. The most recent example (past several months) is the swarm of earthquakes, many felt, in northwest Washington near the town of Deming. Past examples have included a persistent swarm near Seattle in the early 70s, mainshock-aftershock sequences at Elk Lake on the St. Helens seismic zone (SHZ), and in the Goat Rocks region southeast of Mt. Rainier, and study of several mainshock-aftershock sequences near Mt. Rainier. These studies have contributed to our understanding of regional seismicity, and in some cases affected our assessment of earthquake hazards. For example, the Elk Lake earthquake (M_L 5.5) sequence demonstrated the potential hazard of the SHZ, and helped delineate the active part of that zone.

Delineation of St. Helens Seismic Zone

The St. Helen seismic zone is worthy of special note as the only clearly linear feature in the regional seismicity picture for the Pacific Northwest. The occurrence of the Mount St. Helens eruption sequence, and the M_L 5.5 Elk Lake earthquake in 1981 both contributed major components to our understanding of this zone. Most earthquakes in the zone exhibit strike-slip mechanisms with one plane near the epicenter alignment direction. The zone is considered to be a possible terrane boundary experiencing strike-slip shear, although no evidence of surface faulting has been found. The identification of this zone arose in a straightforward way from network data analysis.

Focal Mechanisms and regional stress

Numerous studies have dealt with focal mechanisms and inferred stress and we cannot hope to summarize them all here. In the central Puget Sound region, several studies, including one using contemporary inversion methods, have shown that the focal mechanisms are consistent with crustal N-S compression. Both strike-slip and thrust mechanisms are observed from earthquakes distributed throughout the crust to depths of 25-30 km. Shallow crustal earthquakes in eastern Washington also appear to reflect N-S crustal compression. By contrast, intraslab earthquakes in western Washington have mechanisms consistent with tensional stress with a complex pattern in the plane of the slab. Mechanisms of dominantly strike-slip earthquakes in the St. Helens seismic zone have been interpreted to suggest some rotation of the crustal compression axes to the NE. Stress inversion and other considerations suggest a possible alternative explanation involving reactivation of an existing zone of weakness in a NS regional compressive stress field. Focal mechanism analysis based directly on network data has given us a first order idea of tectonic regional stress. We can expect significantly more progress from focal mechanism studies as stress inversion methods and data handling techniques are further advanced.

Definition of large scale plate geometry

Network data which allowed us to accurately locate intraslab earthquakes for the Cascadia subduction zone (CSZ), played a major role in improving our understanding of the large scale plate geometry. Hypocenter data defines the brittle upper part of the subducted slab, mainly beneath the Olympic Mts. and the Puget Sound region, indicating that the slab dips about 10° to the east-northeast. To the north and south, data from deep reflection experiments, receiver function analysis, and to a lesser degree hypocenter data suggest somewhat steeper slab dips. What has emerged is a picture of major slab warpage, probably in response to a change in trench strike. This understanding could not have emerged without the network operation, and has considerable impact on our notion of subduction zone earthquake hazards (e.g. segmentation and source proximity) and regional tectonics.

Recently we have discovered what we interpret to be evidence for channel (or waveguide) phases that arise from the subduction of oceanic crust riding on top of the subducted Juan de Fuca plate. If our interpretation is correct, these phases could provide a sensitive way to probe the plate geometry and relative locations of intraslab earthquakes to depths of 60-70 km using network data. Future studies should allow us to build quantitative, testable models of the 3-D subduction zone structure, leading to refinement of our models as new data are acquired.

Definition of major features of deep slab geometry of the CSZ

Geo-tomography using teleseismic direct P phases has given us our first direct imaging of the deep structure (to 500 km depth or so) of the subduction zone. These studies suggest that the slab penetrates to several hundred kilometers at a much steeper angle (50° or more) that the shallow portion of the slab where it is initially subducted. We are now attempting to refine the initial low resolution (due in large part to first order linear imaging) images by performing non-linear tomography with full ray tracing. This work was also the stimulus for a new method of cross-correlation analysis to obtain highly precise relative delays from teleseismic P-waves recorded with the regional network. This methodology should be applicable to other similar networks worldwide.

Crustal 3-D velocity variations

We have employed tomographic methods of velocity inversion with earthquakes in the central Puget Sound and St. Helens regions to delineate 3-D velocity variations in the crust. In the St. Helens region, known plutonic intrusions have been imaged, and the method holds promise for more detailed imaging of the magma system. In the Puget Sound region, major terranes such as the Crescent volcanics appear to be imaged, and the technique may provide further insight into the structure and composition at intermediate crustal depths. Several innovations such as the development of jack-knife procedures for error estimation and a new method of applying inversion constraints were developed in this research.

Development and application of structure inversion methods

We were among the earliest investigators to apply modern inversion methods to obtain structure and earthquake locations directly (and simultaneously) from earthquake arrival time data from a regional network. This work was directly motivated by needs arising from problems of network data analysis. The work resulted in reference layered earth models (both P and S velocities) which are still used for our routine locations. As noted earlier, we have extended this work to crustal geo-tomography. Much progress still remains to be made. Extension of the methodology to routine determination of 3-D reference structure, using simultaneous inversion and modern smoothing techniques, is an obtainable goal. Routine locations should now be carried out using 3-D structure. For example our recent investigations have shown that intraslab earthquake locations (subcrustal) are probably significantly biased by the 3-D structure resulting from the dipping slab. We expect that our group will continue to be major contributors to the refinement of structure inversion methods from travel time and other data. Without the stimulus of readily available network data, this work could not take place.

Advances in network data analysis procedures

In addition to the analysis efforts mentioned above, we have actively pursued other network data handling and analysis procedures where they are deemed important to support the overall operations-research-public service effort. We were among the first groups to digitize and automate the network data acquisition (under USGS support), in fact just in time for the major St. Helens activity. We have developed extensive manual/automatic acquisition and analysis procedures for the routine network operation (described elsewhere). In addition, we are pursuing the development of more fully automated analysis procedures, which will greatly enhance our ability to quickly do preliminary analysis of large volumes of data such as encountered in aftershock or swarm sequences. It is important to recognize that while the the tremendous advantages of digital data are clear to everyone, a very large investment in software development is required to make the data readily available and usable to the researcher. The procedures and programs that we have developed have been widely exported to other groups, just as we have also been on the receiving end. This interchange has resulted in a rapid increase in our overall ability, as a community, to take full advantage of modern digital data.

Regional Attenuation

Network data have been analyzed for coda Q, examining the effects of source location and depth. The initial regional coda Q model is now being used to define a network-specific self calibrating method of magnitude/moment calibration. This research should lead to improved automated methods of magnitude and moment determination for regional network data.

Regional P_n analysis

The WRSN has provided excellent opportunities to use P_n phases from regional earthquakes outside of the network in a modified time term analysis. These studies have documented an anomalously low upper mantle P velocity in western Washington (7.6 km/s) which we associate with an asthenospheric wedge above the subducted Juan de Fuca plate. East of the Cascade range, upper mantle P velocity is 8.1 km/s or greater. No significant regional slope to the Moho was found in either region, and upper mantle anisotropy is observed east of the Cascade range (beneath the Columbia Plateau) but not west of the Cascades. P_n data do not reflect the presence of the subducted Juan de Fuca slab beneath western Washington, however other studies have been used to identify and map the slab geometry.

Volcanic Hazard Monitoring

Our network operation has played a major role in using seismicity in volcano hazard monitoring. Eruption prediction methodology was developed based primarily on seismic network data in the post May 18, 1980 observation period. A number of eruptions subsequent to May 18 were predicted based on network data, and appropriate warnings and evacuations were issued. Monitoring of Cascade volcanoes other than Mount St. Helens is also important. For example, in 1975, steam venting at Mount Baker Washington caused concern, but a local seismic network showed there was no accompanying seismicity, providing negative evidence as to the eruptive potential. At Rainier, the local seismic network provides information about background seismicity, and also records rockfalls and mudflows. Volcano hazard monitoring at these and other Cascade volcanoes remains an ongoing network function.

Volcanic earthquake studies

Particularly since the St. Helens monitoring effort began in 1980, numerous studies of volcanogenic earthquakes have been based on network data. These have included source studies, attenuation studies, studies of low frequency volcanic earthquakes, tomography studies, and studies of focal mechanisms of volcanic earthquakes. The St. Helens portion of our network has provided an extensive new set of data for volcanic seismology that will continue to be used by investigators both within and outside of the University for many years.

Earthquake hazards.

Much of the scientific progress that has resulted from our network operation provides basic information of importance for earthquake hazard analysis. Network data has been used directly to estimate the maximum magnitude earthquake possible from the St. Helens zone (assuming a single rupture event). Recent concern over the possibility of a major subduction earthquake on the CSZ has prompted a number of investigations, some directly or indirectly using network data. A significant observation that requires explanation is that we have never observed any earthquake, large or small, on the megathrust in spite of the undoubted network capability to observe such an event. If such events do occur, the network observational capability is essential for their study. Slab and megathrust geometry has been used to define the proximity to rupture for strong ground motion modeling calculations. These and other studies suggest that the network will play an increasingly important role in seismic hazard evaluation for the Pacific Northwest.

WASHINGTON REGIONAL SEISMOGRAPH NETWORK • OPERATIONS •

INTRODUCTION

The Washington Regional Seismograph Network (WRSN), operated by the Geophysics Program of the University of Washington has been in operation since late 1969. It consists of up to 128 short-period vertical component stations which telemeter their data in analog form to the University campus in Seattle for recording. The network currently covers the area roughly between 117° and 125° west longitude and 44° and 49° north latitude having grown and evolved over the years from a small 7 station network in the Puget Sound area in 1970 to the present 112 stations covering the whole state of Washington and much of northern Oregon.

Prior to 1980, telemetered signals from the remote stations were continuously recorded on four photographic Develocorders. Beginning in 1980, signals have been recorded digitally by an event triggered on-line computer system. The network went through significant expansion stages in 1975 to cover eastern Washington, in 1980 for detailed coverage of Mount St. Helens, and in 1981 and 1987 to cover northern and central Oregon. Other stations have been added or moved from time to time.

As of mid-1990 the network includes 35 stations in eastern Washington, 29 stations in the Puget Sound area, 19 stations in the Mt. St Helens area, 9 stations in the Olympic Peninsula, and 20 stations in northern Oregon. Figure 1 is a map of the currently operating seismograph stations showing the telemetry links back to the University which include VHF radio, telephone, and micro-wave circuits. At the University the seismic trace data as well as two time codes are recorded on a minicomputer in real-time using an event detection scheme. These events are then processed both automatically and manually off-line to determine locations, magnitudes, and other parameters for the recorded earthquakes. Catalogs, maps, and reports are then generated from these results as well as the data are used for a variety of scientific studies.

This document gives a brief introduction to the Washington Regional Seismograph Network (WRSN) and includes details of the seismic recording and analysis system, its history, its current operation and a summary of its output. It outlines the procedures for maintaining data integrity and quality control.

SEISMOGRAPH STATIONS AND INSTRUMENTATION

The standard University of Washington seismic telemetry station is modeled after the system developed by the U. S. Geological Survey for central California. Each station consists of a single-component, short-period vertical seismometer, a pre-amplifier/VCO, either a phone-line connection or a radio for signal transmission, and either batteries to power the equipment for at least 18 months or a solar panel and rechargable battery. The seismometers presently used are Mark Products L-4C 1.0 Hz geophones and Geotech S-13 1.0-Hz short-period seismometers. Before installation, they are adjusted to a damping of 0.8 critical and a velocity sensitivity of 100 v/m/sec. A variety of amp/VCO units are presently in use, including Emtel model 6202 and 6242 units, the USGS J302 and J402, and the Interface Technology VCO based on the design of Sean Morrissey.

The output of the VCO is transmitted to the University by low-power FM radio, voice-grade phone lines, micro-wave circuits provided by the Bonneville Power Administration or Puget Power and Light Co., or by some combination of these. About 70 stations are transmitter sites, but only 24 are radioed directly to the University. See figure 2 for a sketch of the various combinations of telemetry used. The total distance of our network telemetry is 10,225 km divided into 70 VHF radio links totaling 4,802 km, 17 microwave channels for 4,829 km, and 4 long-haul phone lines for 594 km.

Two stations have non-standard instrumentation. Seattle (SEA) operates two Wood-Anderson horizontals whose signals are recorded on a Helicorder by means of a photo-tube

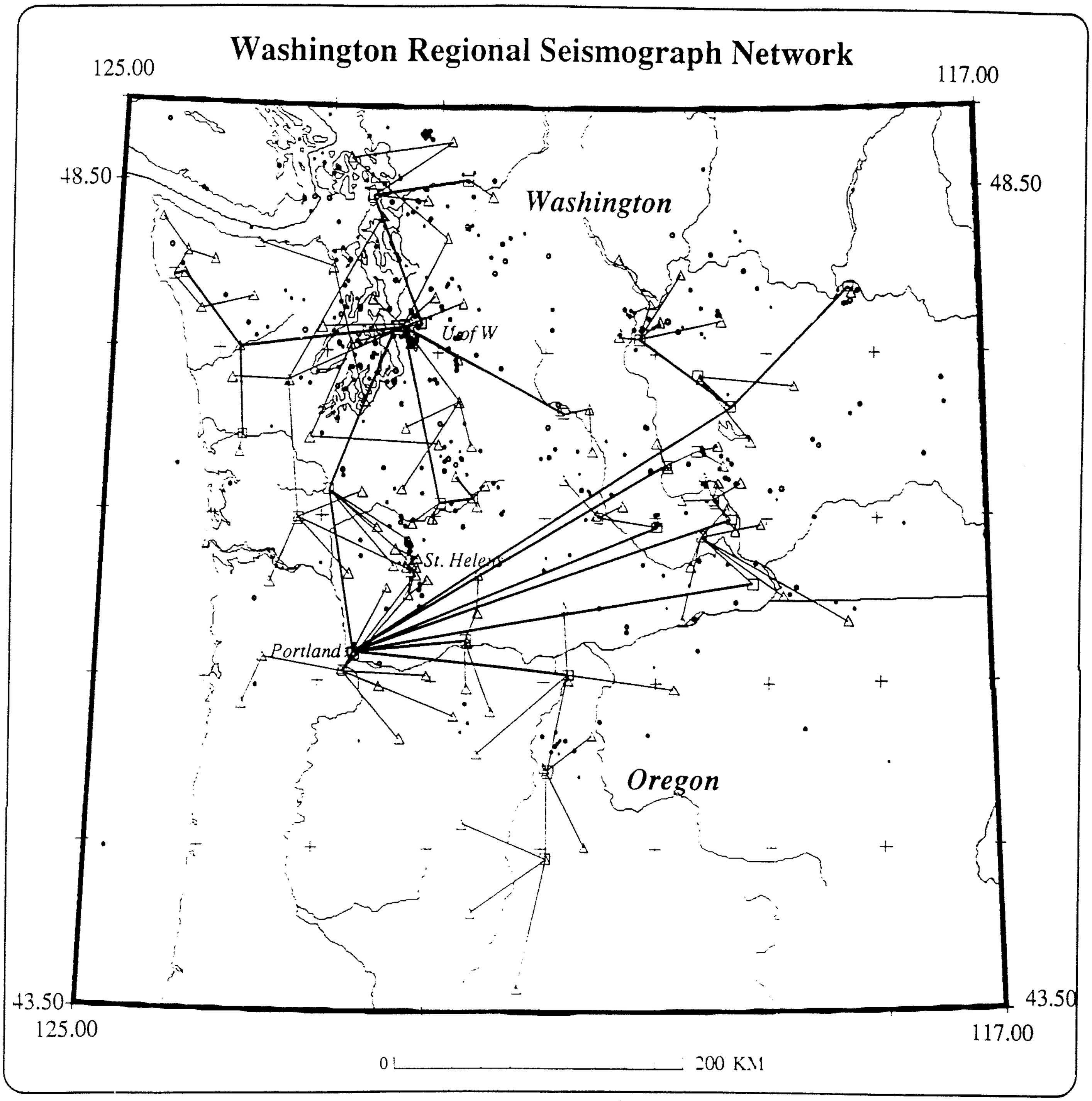


Figure 1. Map of the Washington Regional Seismograph Network showing seismograph stations (triangles), earthquakes larger than magnitude 3 from 1970-1990 (circles), and telemetry paths (thin lines are VHF radio, thick lines are micro-wave or leased telephone).

amplifier as well as two Geotech S-13 seismometers filtered to give a Wodd-Anderson response which are recorded on the on-line computer. Longmire (LON) is a World-Wide Standard Station which is now locally recorded digitally as part of the Digital World-Wide Standard Network. The long-period vertical seismometers and a 1.0 Hz Geotech S13 vertical component are telemetered to the University.

Maintenance

While the remote stations generally are solar powered or have battery capacity for two years unattended operation, most sites must be visited at least once a year for maintenance and calibration. Such visits generally are made in response to problems noticed at the University as a result of periodic telemetry channel and discriminator checks, output of a maintenance log on the recording computer, or as the result of the routine analysis of the seismic data. The technical staff makes several checks of the discriminator rack each week to ascertain that each station is functioning normally. However, since over half of the network is not recorded on a continuous basis but rather only during triggered events, intermittent problems may not be noticed except through checks of seismic data recorded by the on-line system. On-line triggers of teleseisms and the stronger local events are routinely examined in detail to verify correct operation and polarity. Data analysts report apparent malfunctions to the technical staff.

When malfunctions are noted, they are assessed for probable cause and a maintenance visit is scheduled. Priority for maintenance is made on the basis of the importance of the station, available manpower, and weather conditions. Many of the Cascade and Olympic Mountain stations are snowed-in most of the year, making maintenance difficult or impossible except during the summer months. Maintenance of 36 of the stations in eastern Washington is handled by a sub-contract technician who is stationed in the tri-cities area. The rest of the network is serviced by technicians stationed in Seattle or Vancouver, Washington. Overall up-time for the entire University of Washington network has been 91% over the past two years, varying from 88% at worst to 96% following several months of good field work conditions.

RECORDING AND ANALYSIS FACILITIES

The telemetered seismic data received at the University are discriminated, filtered, and recorded by several means. Fifteen stations and the Seattle Wood-Andersons are recorded on Helicorders. All telemetered data are digitized and used as input to an event-triggered on-line digital recording system, described later. The digital system is used for most data analysis, but the Helicorders serve as back-up in the event of a computer crash or failure to trigger, and to record late-arriving phases from teleseisms which may not trigger the digital system themselves. Film records were used for the Puget Sound network dating from 1969 and for the eastern Washington network from 1975. The recording of data on photographic film was terminated at the end of 1984 since the computer system had been well tested and proved to be quite reliable.

'HAWK' Real-Time System

The current on-line recording system is closely modeled after our previous on-line system called *TURKEY* which, in turn was closely modeled after the CEDAR system conceived and implemented at Cal Tech by Carl Johnson.[1] The code which we are running, called *HAWK*, is derived from the *RAVEN* system written by NEWT INC for Los Alamos National Lab's hot dry rock experiment and licensed to the University by NEWT INC. Because of its ease of modification it has changed and evolved since it first came up in the spring of 1988 to provide a complete, reliable and efficient integrated recording and processing system which can easily handle the load of our network.

[1] *CEDAR -- An Approach to the Computer Automation of Short-Period Local Seismic Networks.* Carl Johnson, California Institute of Technology Ph.D Dissertation, 1979.

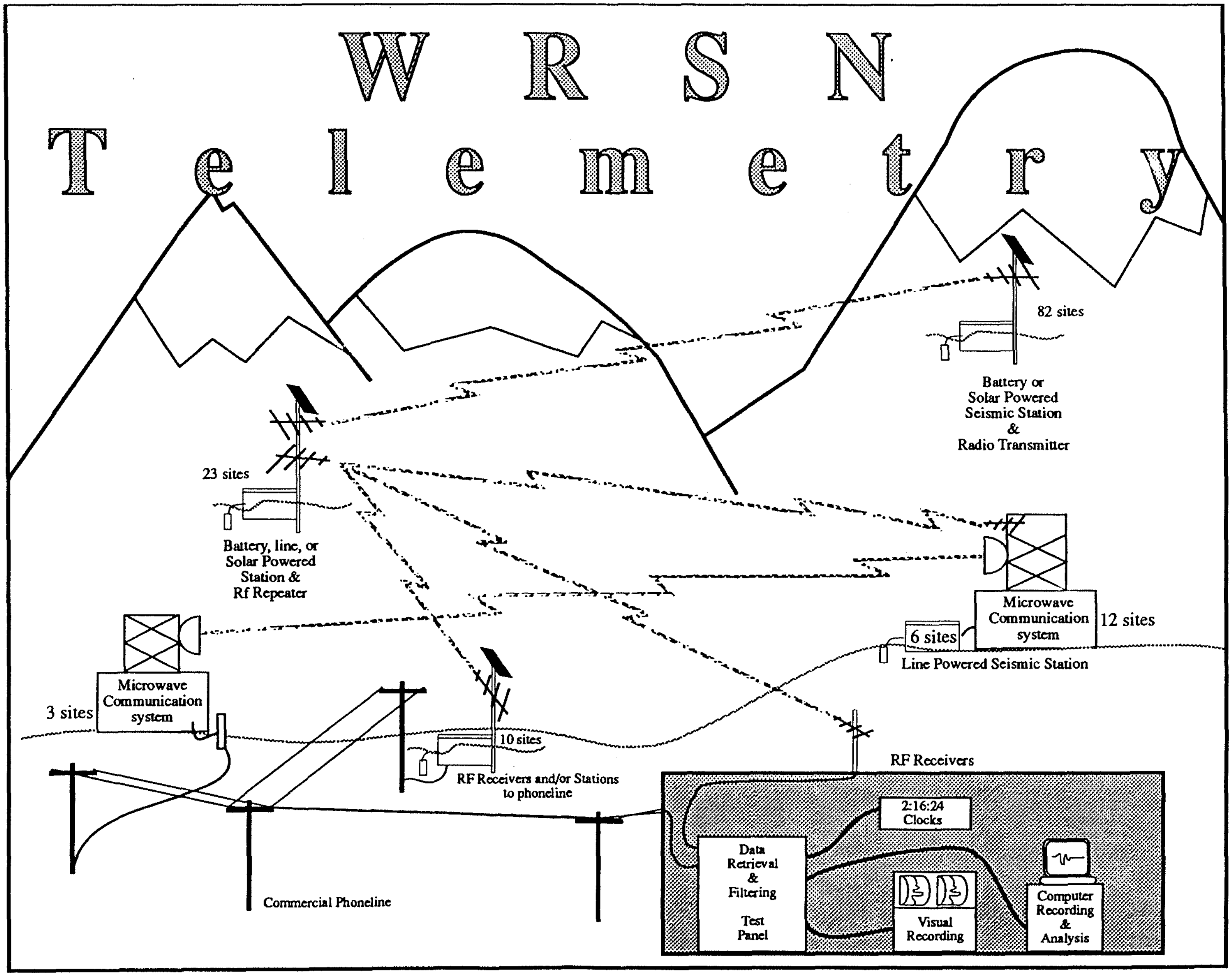


Figure 2. Sketch showing the different types of remote seismograph stations in the Washington Regional Seismograph Network, and the different combinations of telemetry used to bring the data back to the University for recording.

Refer to figure 3 for a detailed schematic diagram of the data analysis steps in the *HAWK* system. The basic concept of the real-time part of *HAWK* is one of saving all incoming seismic data digitized at 100 samples per second per channel and stored on a circular ring buffer disk file for a short period of time (nominally about 20 seconds). During this time the data are examined to see if a seismic 'event' is underway. If an earthquake, explosion, or other such transient seismic event is taking place, the data in the ring buffer are saved, rather than being over-written by new data. In this way the disk file acts as a delay line giving the computer time to look at enough data to make an intelligent decision about whether an event of possible interest is occurring or not. The beginning of the event is not lost since data are saved starting at the oldest in the ring buffer; some 20 seconds before the decision to save it was made.

There are several concurrently running tasks which are coordinated by the 'MAIN' task through a block of shared memory. The 'MAIN' task does all of the buffer management of the ring buffers and ultimately stores the event data in the *RAVEN* file-system, a first-in-first-out (FIFO) highly optimized file-system. This task also checks that the other tasks are healthy and produces a hardware 'heart-beat' pulse used by an external 'watch-dog' device capable of producing a variety of alarms in case the heart-beat stops.

The decision-making process, 'TRIG' analyses data from the ring buffer under command from 'MAIN. It involves two separate steps, one to evaluate individual channels of incoming data and the other to consider combinations of channels that form subnetworks. Four statistical parameters are formed for each data channel; long and short term averages of both the rectified and straight signals. By comparing the short term with the long term averages, a fluctuation in the signal of an individual channel can be quantified. When the fluctuation is large enough, a trigger on that channel is declared. Since there are many causes for such fluctuations other than seismic events of interest, it is not desirable to record and save the data when a single channel has an active trigger. The next step of the detection routine is to lump a number of channels together into subnets for which several channels must have a trigger active at the same time. When enough channels within a given subnet have active triggers, an 'event' is declared and 'MAIN' is informed that it should start saving data. Saving of data continues until some time after all subnet triggers have turned off. The length of time this lasts depends on the number of subnets that trigger. Thus, a large event which triggers many subnets will last much longer than a small event so coda information not lost.

The trigger sensitivity parameters are tuned for the network configuration to maximize recovery of useful data, and minimize recording of useless data. A number of adjustable parameters determine how sensitive the detection scheme will be. The 'INTERFACE' task provides real-time trace monitoring and parameter adjustment capability. Several seismic traces and trigger sensitivity variables may be displayed in real-time. We currently have 21 subnets with an average of 12 stations in each. Either three or four stations must be active at the same time for an event to be declared. Individual stations may appear in more than one subnet so that subnets effectively overlap. Individual station trigger thresholds, the minimum length of time a station triggers, as well as the minimum length of an event trigger are all adjustable. Currently most single station triggers remain active for at least 15 seconds, and the event trigger stays active for an additional 25 seconds so that the minimum recording time for even a small event is about 40 seconds.

After each seismic event has been detected and recorded, the 'LOGGER' task enters basic information about the event in a log-file and queues the event for automatic near real-time processing.

'HAWK' Near Real-Time Processing

Each recorded event is processed by two slightly different automatic processing routines. The first, called 'QUICKLOC' is designed to produce a very rapid estimate of an earthquake's size and location. It only runs on events for which many stations triggered; that is, a larger event. Its purpose is to provide an earthquake alarm, and preliminary size and location information for distribution to civil authorities and to the public. Trigger times at each station are used as arrival times in a quick location routine. The quality of the solution of both a teleseismic location routine

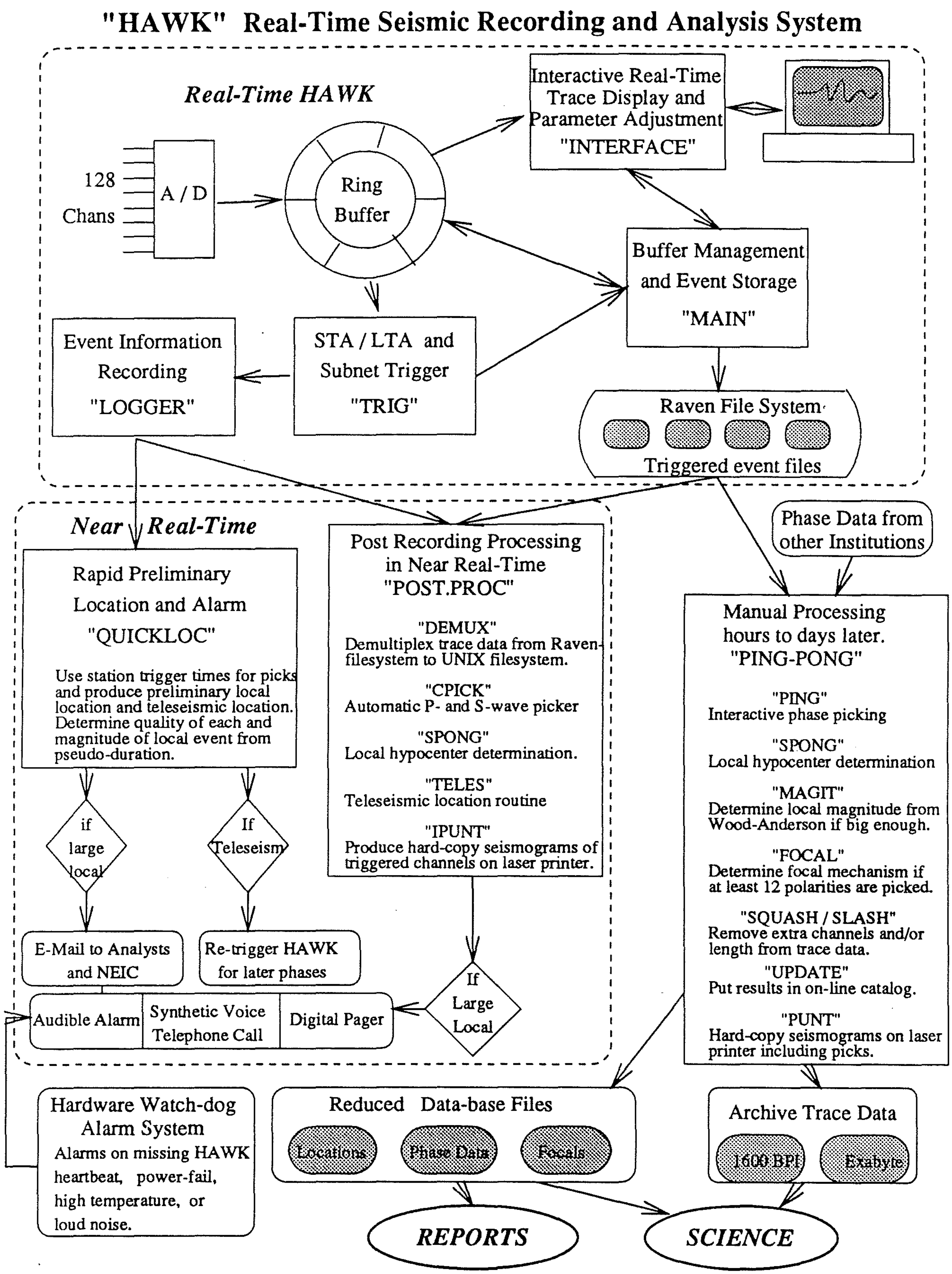


Figure 3. Schematic flow chart of the processing steps followed in the *HAWK* seismic recording and analysis system.

and a regional hypocenter determination are used to decide whether the event is a large local earthquake, a teleseism, or possibly a noise trigger. If the event is a large local earthquake, seismologists are notified in a number of ways. This includes an audible alarm, computer messages and E-Mail, and telephone calls are placed to a series of phone numbers with a synthetic voice, and a digital pager (carried by a seismologist at all times) is notified with the location and magnitude of the event. This all takes place within about 30 seconds of the event termination. If the event was determined to be a teleseism then a special travel-time calculation routine is used to predict arrival times of later arriving phases. Control signals are sent back to the real-time *HAWK* recording system to trigger at those times so that data from, even weakly arriving phases will be recorded.

The second automatic processing routine, a more detailed and time consuming is activated for all events, not just the large ones. This routine, 'POST.PROC' first demultiplexes the data from the *RAVEN* file-system to the regular UNIX file-system into the standard UofW 'PING' format which has been used for all digital data since 1980. An automatic phase detection and timing routine, 'CPICK' is run on all the triggered traces. Our standard hypocenter determination routines, 'TELES' and 'SPONG' are run on these arrival times. A one page hard-copy of the triggered traces is produced on a laser printer so that a permanent visual record is made of every triggered event. The digital trace data are also backed up onto an 8mm mass-storage system in a compressed form. Again, if any event is determined to be large and local the alarm system as mentioned above is activated.

'HAWK' Manual Processing

All triggered events are reviewed by an analyst every day or two. The analyst decides if an event is of seismological interest, and discards the data for obvious noise triggers. The analyst then processes each event in a standard manner, finally adding the event to an on-line catalog. There are several steps that each event is taken through.

Interactive Trace Picking (PING). An interactive picking routine, 'PING' is used to obtain reduced data, such as arrival time information from the trace data. The analyst may review the picks produced by the automatic phase picker, or may start over and pick the event from scratch. 'PING' displays all trace data sorted by distance from the first arrival station and allows the operator to choose which channels are to be examined more closely. These channels are then displayed one at a time. Each may be scaled in either time or amplitude and band pass filtered to bring out subtle features. Both P and S arrival times can be 'picked' including weights and polarity.

The output is a *pickfile* which looks very much like old fashion phase cards. 'PING' can reread events already processed by the location routine and use the *pickfile* to show where picks have previously been made and their residuals.

Location Routine (SPONG). We are currently using a modified version of *fasthypo* written by Bob Herrmann at St. Louis University. It has been extensively modified in several ways. It uses a weighting scheme similar to that of the U.S.G.S. routine HYPO71. It uses damping techniques to speed convergence, and it is compatible with our *pickfiles*. Our version of this location routine is called *spong* which rewrites the *pickfile* with a new first line containing the location of the event, a line of error information, and time residuals for each station. (Note that one can go back and forth from picking an event to locating and back to picking in a ping-pong fashion.)

Magnitude determination (MAGIT). A coda-duration magnitude is produced for every local earthquake from the durations picked at the same time as the phases. For earthquakes of a large enough size to record on the simulated Wood-Anderson response traces at the University, a local magnitude is also determined. The amplitudes of the digitized Wood-Anderson traces are measured and converted to an equivalent amplitude and used along with the distance to determine a local 'Richter' magnitude.

Focal Mechanism (FOCAL). For any event which has at least 12 first motion polarities picked that are reasonably well distributed over the focal sphere, the program 'FOCAL' is used to determine a focal mechanism. This program uses the USGS program 'FPFIT' at its core but reads our *pickfiles* and produces a focal mechanism summary in our format to include in a catalog of focal mechanisms.

Final Hardcopy Plot (PUNT). After an event has been picked and located, a final hardcopy plot on a laser printer is made using 'PUNT' which includes all phase and location information along with plots of each picked station with a cross-hair marking each pick. This plot is used as the permanent visual record of the event and is convenient to access once the trace data for the event have been archived on tape and removed from the disk file system.

Data Compression and Archiving (SQUASH, SLASH) The trace data for our 112 station network are quite voluminous and would be cumbersome to try to keep in its entirety. For most earthquakes, *i.e.* smaller events, only a part of the seismic network will be close enough to detect the event. The data for stations which do not detect an event need not be kept. The program 'SQUASH' rewrites the data files using the *pickfile* to determine what data to keep. Stations for which phases have been picked as well as any other stations listed will be saved by 'SQUASH'. A companion routine, 'SLASH', will cut off the beginning and/or the end of a data trace file if there is no interesting information there. It also is used to decimate regional earthquakes and teleseisms for which a high sampling rate is not needed. Typically a compression factor of from 5 to 10 is possible. This means that the number of events available for rapid retrieval from the data disk increases from about 100 to over 600. Ultimately the trace data are stored on standard archived (tar) 1600 BPI tapes as well as a copy on an 8mm Exebyte high capacity tape. Each 1600BPI tape usually contains all the events for a week to ten days while the 8mm tape contains the data for a whole year. These tapes are duplicated and a copy stored in another building to protect against loss.

Catalogs, Maps, and Reports. This computer catalog is kept in files by year. As errors are detected in older data, or supplementary data becomes available the pickfiles are modified, the hypocenters relocated, and the master catalog updated. The pickfiles for all 20 years of the network operation are kept on-line and available for review and research projects. We publish quarterly technical reports containing the quarter's catalog for events processed by the system as well as details of the network operation and a summary of significant seismic activity. This report is mailed to a mailing list of 33 recipients who have expressed interest in having the information. We also publish, every few years, through the State Department of Natural Resources, a comprehensive bulletin which contains a complete catalog, maps, and discussions of the seismicity and its significance for the period.

Quality Control

Maintaining uniform and high quality data is one of the most important aspects of this processing system. There are a number of checks which are periodically performed on parts of the system and staff members routinely check each others' work to try and maintain a uniform system of picking arrivals. Maintenance and calibration of the field equipment and telemetry lines is carried out by the Geophysics Program technical staff. The principal investigators of the sponsoring grants and contracts are oversee the technical staff and routinely review all processing and scan the various hard copy output for data integrity. The chief analyst reviews the state of the network with the research staff to isolate problems, improve efficiency, and set priorities for work to be done. A record analyst reviews all helicorder records daily for any earthquake activity within the network. A list of events from these records is compared to the on-line system triggered times to make sure no significant events are being missed. A data manager is responsible for the integrity of the computer systems and their data files. Every other night, backup tapes are made of all data and software on the system. Checks are performed to make sure files are not inadvertently lost or modified which would compromise the completeness or accuracy of the data. Backups of all trace data tapes are kept in a separate building in case of loss or damage to our primary tapes.

NETWORK HISTORY AND SUPPORT

The Washington Regional Seismograph Network (WRSN) has changed and evolved over the twenty years since it began. Operational support for the network has similarly changed. Figure 4 illustrates several aspects of these changes including the number of stations operating and earthquakes recorded over the years as well as the source and amount of financial support for operations. In all of the following discussions the amount and source of funding refers to operational costs only. In many grant and contract proposals operational costs are detailed separately from those costs related to research objectives. For those contracts in which there has been no explicit separation, an attempt has been made to estimate the operational support separate from the research support.

Prior to 1970, three locally recording seismograph stations were operated in the Puget Sound area for a number of years by University staff. A WWSSN station at Longmire, near Mount Rainier has been operating since 1962. The WRSN began in early 1970 with a Science Development Grant from the National Science foundation. The initial 7 station telemetry network established in the Puget Sound area in 1970 was expanded to 12 stations in 1972 under NSF operational support. In 1974 the U.S. Geological Survey took over responsibility for regional network operation support and has funded, at least part of the WRSN since then.

The U.S. Geological Survey established a small seismic network in eastern Washington in 1969 with support from the Atomic Energy Commission for monitoring seismicity around the Hanford facilities. This network was repeatedly expanded over the next several years. The operation and data analysis for this network was handled by the USGS during the first 5 years of its operation; however, all of the reduced data have been transferred to the University of Washington and are now included as part of the WRSN data base. Operation of the eastern Washington network was transferred to the University of Washington in the summer of 1975 and it has been a part of the WRSN since then. The AEC and then the Department of Energy has funded the operation of most of the eastern Washington portion of the WRSN for the entire 20 years.

Minor changes in the network configuration took place during the late 1970s under support from several different groups including the National Science Foundation, Puget Power, Washington Public Power Supply System, and the USGS volcanic hazards program because of possible volcanic activity at Mount Baker. In 1979, the USGS directly provided two Digital Equipment Corp. computer systems for the recording and analysis of network data. These systems operated from early 1980 until the spring of 1988 when they were replaced by a single Masscomp 5600 computer, again provided directly by the USGS, which does the recording and analysis functions today.

The volcanic activity at Mount St. Helens starting in the spring of 1980 required a rapid network expansion into that area. Because of the speed with which this occurred, much of the support for this expansion was in the form of direct help by USGS personnel and USGS equipment primarily from the Volcanic Hazards and Geothermal Energy branch At about the same time the network was expanded into the Olympic peninsula and in the following year into northern Oregon. This major increase in stations and coverage (from 63 in 1979 to 123 station in 1981) caused the network operation cost to peak in 1981 at almost $800K per year. Operational costs remained high during much of the 1980s even though the network did not significantly expand. Extra support was needed for the additional personnel to process the large amount of seismic data due to the larger network and the high activity at Mount St. Helens and to respond to public and government officials' inquiries whose geophysical 'awareness' was greatly heightened by the eruption. Also, between 1982 and 1986 the cost of telephone telemetry increased by a factor of three. In 1987 most of the long line telemetry was switched to the BPA microwave system which has reduced these costs from almost $150K per year to less than $50K per year.

Through the 1970s the state funded the position of 'State Seismologist' whose duties were primarily related to assisting the public, government agencies, and the press with questions regarding earthquake hazards. Norm Rasmussen held this position and used data from the seismograph network to provide information to others. He helped with the actual operation of the network only in a minor way. In the early 1980s, due to severe budget cut-back, the state support for this

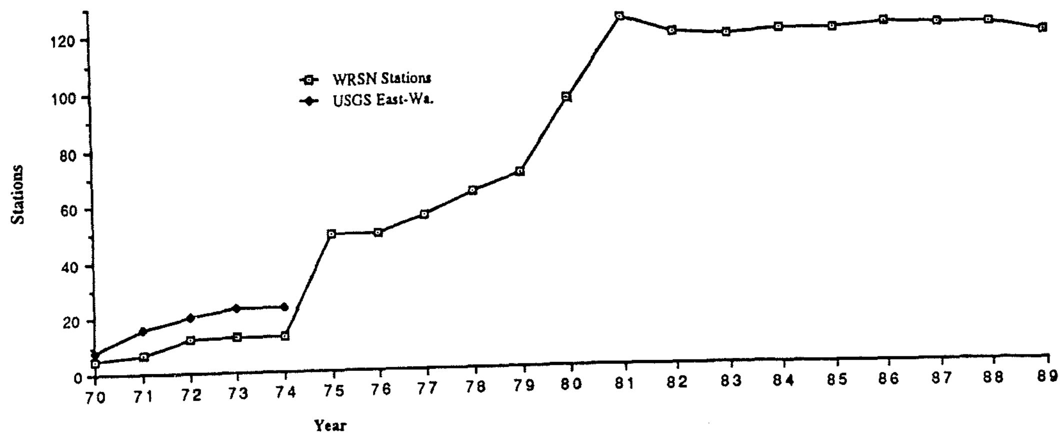
Figure 4. History of the Washington Regional Seismograph Network from 1970 to 1989.

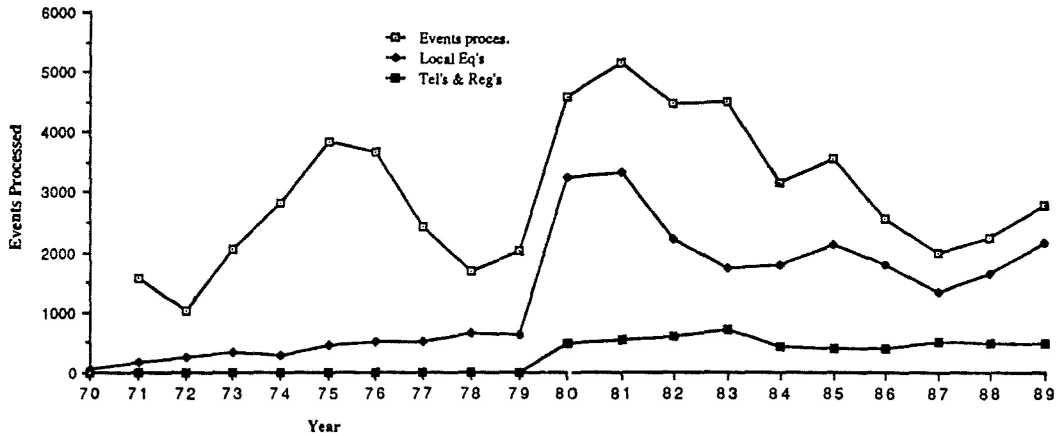
A. Average number of stations operating each year (squares), Number of stations operated in eastern Washington by the U.S.G.S (solid circles).

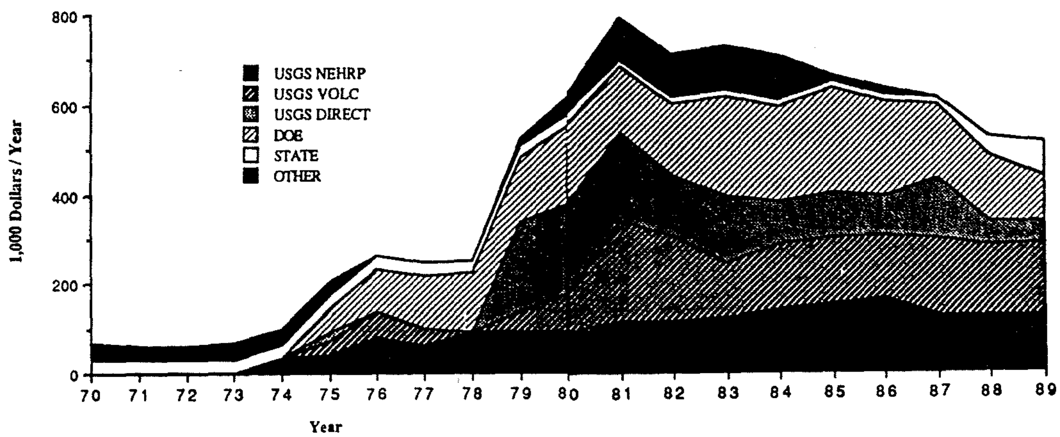
B. Number of seismic events detected by the network. During the 1970s these are events detected by scanning the film records, during the 1980s these are events triggering the computer system (open squares). The number of earthquakes located within or near the network (closed circles), and the number of teleseisms and regional earthquakes located using network data. No earthquakes outside the network were typically located using the film records during the 1970s (closed squares).

C. Support for the operation of the WRSN shown divided by funding agency over the past 20 years. 'USGS NEHRP' is funds from the USGS Earthquake Hazard program comming through the external grants program. 'USGS VOLC' is funds from the USGS Volcanic Hazards and Geothermal Research programs. 'USGS DIRECT' is approximate value of personnel, services, and equipment supplied directly to network operations from the USGS. An average of 83% of this has come from the Volcanic Hazards and Geothermal Research programs and 17% from the Earthquake Hazards program. 'DOE' is funds for the eastern Washington portion of the network. 'STATE' is funds provided for network operations from the state of Washington. 'OTHER' includes funding from NSF, WPPSS, NRC, and other very minor sources.

D. A tabulation by year of phone calls requesting information about earthquakes or volcanic activity logged from government agencies, primarily USGS (open squares), press (closed circles), public, mostly curious individuals (closed squares) and public and private institutions such as schools, universities, consulting firms, and insurance companies (open circles).


WRSN Stations
USGS East-Wa.
Stations
Year
0
20
40
60
80
100
120
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89


Events proces.
Local Eq's
Tel's & Reg's
Events Processed
Year
0
1000
2000
3000
4000
5000
6000
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89


USGS NEHRP
USGS VOLC
USGS DIRECT
DOE
STATE
OTHER
1,000 Dollars / Year
Year
0
200
400
600
800
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
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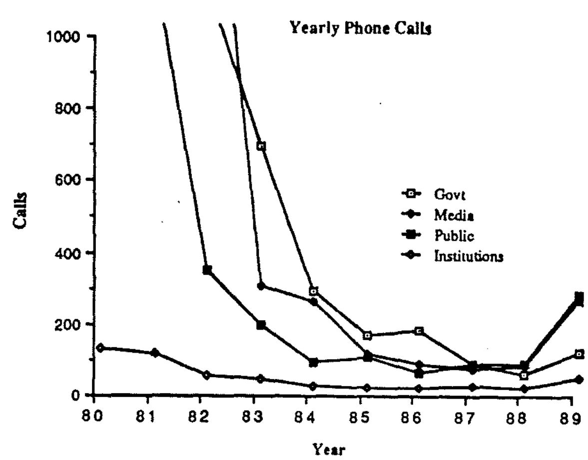
Yearly Phone Calls
Govt
Media
Public
Institutions
Calls
Year
0
200
400
600
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1000
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position was drastically reduced. About this time Linda Noson took over acting as the 'State Seismologist'; which only funded part of her salary. In 1988 the state agreed to not only fully fund the 'State Seismologist' position, currently held by Dr. A. Qamar, but to contribute significantly to the operation of the Network. By 1989 the state had increased its contribution to network operations from $15K to $75K per year and this support is expected to increase in the future. In addition to the 'State Seismologist' position, the state also pays parts of the salaries of a seismic analyst, a data technician, and two staff seismologists.

The U.S. Geological Survey remains the major source of funds for network operations. The Department of Energy contribution was reduced with the termination of the Basalt Waste Isolation Program in 1988; however its contribution remains significant. Even though the U.S.G.S. contribution to network support is more than half, the majority of this support comes from the Volcanic hazards and Geothermal branch of the U.S.G.S. rather than from the Earthquake hazards program. Currently only 28% of the network support comes from the USGS Earthquake Hazard program. Table 1 lists the personnel associated with current network operations, their percent effort on network operations and the source of funds to cover these activities.

TABLE 1. WRSN Network Operation Personnel

Person and Position	Network Ops*	Source of Funds
Dr. Robert Crosson Professor (PI)	8%	8% state
Dr. Steve Malone Research Professor (PI)	30%	20% state, 5% USGS, 5% DOE
Dr. Tony Qamar State Seismologist (PI)	80%	80% state
Ruth Ludwin Staff seismologist	80%	50% state, 30% USGS
Rick Benson Seismic analyst	70%	20% state, 30% USGS, 20% DOE
Chris Trisler Data technician	80%	20% state, 30% USGS, 30% DOE
Laurence Engels Electronics technician	100%	100% USGS
Jim Ramey Electronics technician	90%	50% USGS, 40% DOE
New Hire Field technician	100%	100% USGS
2 Graduate Assistants General Duties	50% each	50% USGS, 50% DOE

* This is amount of persons time spent on network operations

FUTURE PLANS

We feel that the WRSN provides important data for scientific investigations as well as student training and public information. Maintaining quality and uniformity of such data are important. A goal of our standard operating procedures is to assure the continuity of data acquisition and processing. Changes in network configuration or analysis procedures are made with this goal in mind. The location and distribution of stations are such to maximize the recovery of useful data while minimizing the cost. Stations are moved or removed only when this will not hurt the sensitivity and completeness of the network.

We have plans to upgrade the network coverage as well as the quality of the recorded data. There are two evolutionary changes we currently have planned for the WRSN. The first is an expansion into the central Oregon Cascade mountains and coast range. This expansion has been planned for the past two years; however, it has not been done because of the lack of telemetry channels back to the University. During that time an agreement between the USGS and the BPA was being worked on to extend two of our BPA micro-wave links from Portland down the Willamette and Deschutes valleys to receive radio telemetry signals from stations in the neighboring mountains. We have now given up waiting on this agreement, and have worked out our own arrangement with the Oregon Department of Transportation to use their micro-wave system. We currently have one circuit installed and will be installing the first two new stations in mid August. By the end of the year we plan to have six additional stations in the western Oregon Cascades and Coast Range. This will substantially fill in the large gap in station coverage between the WRSN and the seismic networks of northern California. We plan to provide signals from up to eight of the Oregon seismic stations to a drop on the University of Oregon campus so that the geology department there can receive these signals.

The second network upgrade we have immediate plans for is to install a prototype broad-band, high-dynamic range, digital seismograph station which can be integrated smoothly into our analog telemetry network. This system is planned to have three components with a dynamic range of at least 92db over a bandwidth of 0.05 to 30 Hz. It will record locally with dial-up data retrieval capability. Our experience building the *GOPHER* system for IRIS convinces us that continuous digital telemetry is not necessary or, maybe even desirable. We will use the near real-time analysis part of *HAWK* to call and retrieve data from the broad-band system for events of interest. If this prototype system works as well as we hope, we plan to gradually install additional such stations, until our network is a hybrid of low-cost, low-quality stations and high quality, but much more expensive stations. However, the data telemetry costs for these new stations should not be a major factor since telephone connect time will be only for a fraction of what continuous telemetry requires.

We anticipate that funding support for the network will continue in much the same way as in the past. We expect the State of Washington to gradually increase their share of the support. They currently have committed to cover almost 20% of the operational costs and also pay for some capital improvements. For example, the state has ordered an uninterruptible power supply system to power our seismic electronics and computer system. They also are providing shaking restraints and other efforts to prevent loss of network function in a large earthquake.

PRODUCTS OF NETWORK OPERATIONS

Data from the WRSN is used for a variety of purposes. Obviously one of the most important uses is as input to many different research projects and as training for students. Many such projects have been complete at the University of Washington as well as at other Universities and institutions. The results of such research are typically published in formal scientific journals and reports, but are also disseminated to the public by more informal means. Data from the network are provided to anyone requesting it and are available in a variety of forms. This includes something as simple as checking if an earthquake occurred at a time someone felt something shake to a special catalog and/or map produced for a special purpose. Table 2 gives a list of examples of responses to significant requests for network data by people outside the University. Typically each of these requests requires, at least modest staff effort to generate a response.

Visiting Scientists. A number of Geophysists from other countries have visited our laboratories for periods from two weeks to over a year to use our data and cooperate on research projects. We typically provide them with office space, and access to our data and computer facilities. They always come with their own travel and salary support. Research projects involving the visiting scientist using our network data and interacting with the staff or students from the Geophysics Program usually results in scientific papers being published.

Routine Earthquake Notification. Emergency response to a large or unusual earthquake is part of our standard operating procedure. We routinely report significant earthquake information to the NEIC, Washington Department of Emergency Services, Cascade Volcano Observatory, Westinghouse Hanford Co., National Park Service, and the press, We also provide a dial-in computer bulletin board for information on all significant recent local and world-wide earthquakes. We regularly exchange phase data with NEIS, Pacific GeoScience Centre (Canada), Montana

Bureau of Mines and Geology, Idaho Geological Survey, Idaho National Engineering Laboratory, Oregon Department of Geology and Mineral Industries, University of Oregon, and Oregon State University. We also answer requests for teleseismic data, either seismograms or arrival times, from various universities as large earthquakes occur.

Hypocenter and Phase Data Distribution. We provide up-to-date catalogs of seismic activity for geotechnical firms to do risk estimation and other studies. For each calendar quarter, we produce (usually within 30 days) a preliminary catalog of events which includes maps of all located earthquakes and blasts within the network area. This quarterly catalog also details station operational problems, and includes a discussion of significant earthquake activity during the quarter. In addition to the contracting agencies, it is distributed to other agencies and individuals who have requested it, such as the BPA, local power companies, the Army Corps of Engineers, the Nuclear Regulatory Commission, National Forests, other colleges and universities, and geotechnical consulting firms. Annual catalogs (1980 and 1981) and five year catalogs (1982-1986) produced by the WRSN have been published by the Washington State Department of Natural Resources.

Technical Network Information. Operating a hundred seismometers in the field, telemetering their signals, detecting and triggering on seismic signals, and recording and analyzing the data demands a wide variety of technical expertise, and we are often called upon to provide technical information or consulting on network operations. These requests range from questions regarding dates of operation of individual seismometer sites, through operational questions (about individual station components; solar panels, batteries, antennae, telemetry, computer processing etc.), to questions regarding the many facets of the digital recording, detecting and processing of seismic signals. In the early 1980s copies of our complete computer recording and analysis programs were sent to seven other Universities where these programs were used to record and analyse data from their networks. Some of this code is still running at a few places today.

Special Catalogs. On request we prepare special catalogs, maps, or brief reports on seismicity within our network. These requests typically involve a particular geographic area, sometimes near an engineered structure such as near a dam or power plant, and usually come from geotechnical firms or public agencies.

Consulting on Seismicity. In connection with special catalogs or maps, geotechnical companies may need help with interpretation or background. We often write either letters or short reports on request to make sure that the network data are properly used and that the public receives the latest research results.

General Public Information. We respond to many public inquires each year. There are typically between 16 and 36 felt earthquakes within our network each year, and these generate interest proportional to their intensity. In addition, large and great earthquakes anywhere in the world which cause significant damage (Mexico City, Armenia, Iran, Philippines, Loma Prieta) usually attract media attention. In the early 1980s when Mt. St. Helens came to life, we fielded several thousand telephone calls each year; both from the press and public. Although the number of calls has now decreased, public awareness of earthquake and volcanic hazards in Washington and Oregon is very high. We continue to receive substantial numbers of calls. The increased public awareness is due in part to press coverage of the potential hazard of a subduction zone earthquake along the Washington-Oregon Coast, and to recent disastrous earthquakes and volcanic activity worldwide; most recently the damage inflicted on California by the Loma Prieta earthquake. In addition to the hundreds of phone calls, dozens of live or taped press interviews and appearances on TV and radio talk shows, we provide 6 or 7 laboratory tours and lectures per month for school and recreational groups. One measure of the demand for earthquake information in Washington is the requests for *Washington State Earthquake Hazards*, Information Circular 85, produced in late 1988 by the Washington State DNR in cooperation with the University of Washington. Nearly 3,500 copies have been distributed to businesses, corporations, schools, hotels, hospitals, scientists, libraries, and the general public. This bulletin is now in its second printing.

TABLE 2 PARTIAL LIST OF ORGANIZATIONS REQUESTING INFORMATION

Visiting Scientist:

- Jens Havskov, University of Bergen, Norway
- Marie-Jo Fremont, Univ. Sc. de Grenoble, France
- John Latter, Geophysics Div., New Zealand
- Conrad Lindholm, University of Bergen, Norway
- Hiroki Miyamachi, Usu Volcano Obs., Japan
- Giancarlo Neri, Univ. of Messina, Italy
- Roberto Scandone, Osservatorio Vesuviano, Italy
- Roberto Scarpa, University de Roma, Italy
- Moto Ukawa, Nat. Res. Cen. for Dis. Prev., Japan

Routine Earthquake Notification:

- Cascade Volcano Observatory
- DOGAMI
- National Park Service
- NEIC
- the press
- Wash. Div. of Emergency Services
- Westinghouse Hanford Co.

Hypocenter and Phase Data Distribution:

- DOGAMI
- Geophysics Div., New Zealand: John Latter
- Idaho Geol. Survey
- INEL
- Montana Bureau of Mines and Geology
- NEIS
- Oregon State
- Pacific GeoScience Centre (Canada)
- Saint Louis U.: Bob Hermann
- Terra Corp: M. Niasi
- U. of Oregon
- USGS: Dave Carver
- Woodward-Clyde Consultants: Dave Cole

Technical network information:

- C.I.R.E.S.: Sharon Kubecheck
- Cactus Foundation: Rachel Rosenthal
- Data Automation, Israel: Danny Ravid
- Faculty of Sci., Hokkaido U.: Motonori Suenaga
- Failure Analysis Assoc.: Gerald Fitzpatric
- Geomatrix: Dave Lapp
- Geophysics Div, New Zealand: John Latter
- Georgia Tech: Ted Habermann
- U. of Mexico: Servando de la Cruz Reyna
- Pacific Tsunami Warning Center: Gorden Burton
- Perkin-Elmer, England: Elizebeth McClintock
- Peterson Instruments: Dave Shotkey
- Puget Power & Light: Bill Hartzell
- Puget Power & Light: Jim Nolan
- Sierra Geophysics: Steve Ihnen
- Soil Dynamics Consulting: Michel Feves
- US Bureau of Land Management: Chris Woods
- U. of Alaska Geophysics: Nirin Biswas
- U. of Oregon: Eugene Humphreys
- Virginia Technical Inst.: Arthur Snoke
- Woodward-Clyde Consultants: Paul Summerville
- Woodward-Clyde Consultants: Woody Savage

Special Catalogs and/or Maps:

- American States Insurance: Barbara Jones
- Army Corp of Engineers: Dick Galster
- Army Corp of Engineers: Don Ballentine
- Battelle Northwest Labs: Nancy Doran
- Bureau of Reclamation: Roland LaForge
- Conforth Consults: Saleem Farooqui
- Dept. of Geol., Oregon State U.: Dick Couch
- E.G.G, Idaho: Dick Smith
- Ebasco Services: Umesh Chandra
- Embasco Consulting: Jim Dolittle
- Geomatrix: Kevin Copper-Smith
- Geomatrix: Steve Brewer
- Kamchatsky Inst. of Volcanol.: V.M. Zobin
- Mark Shaffer Consulting: Mark Shaffer
- Northwest Geological Service: Rick Keinle
- Oregon Emergency Management: Colleen Byran
- Oregon State Disaster Planner: Scott Bassette
- Pacific Geoscience Centre: Garry Rogers
- Puget Power & Light: Lynne Mills
- Sierra Club: Denise Antolini
- Sierra Geophysics: Dave Hadley
- Sweet-Edwards/EMCON Consulting: Rod Reeve
- Terra Corp: Larry White
- Terra Corp: M. Niasi
- UC Santa Cruz: Glenn Nelson
- US Soil Conservation Service: Ed Stearns
- USGS: Bob Engdahl
- USR Blume Assoc.: Norm Owens
- USR Blume Assoc.: Roger Greensfelder
- U. of British Columbia: Bob Ellis
- Wash. Dept. of Highways: Joan McVey
- Wash. Dept. Nat. Res.: Josh Logan
- Wash. State Geol. Dept.: Richard Thiessen
- Wenatchee City Geologist: Doug McFarlan
- Woodward-Clyde Consultants: Ivan Wong
- Yakima Indian Nation: Steve Armstrong
- Yale U.: Mark Brandon

Consulting on Seismicity:

- Battelle Northwest Lab.: Dan Hegadorn
- Bureau of Reclamation: Roland LaForge
- E.G.G, Idaho: Dick Smith
- Geomatrix Inc.: Steve Brewer
- Mark Shaffer Consulting: Mike West
- Northwest Geological Serv.: Rick Keinle
- Oregon Nat. Resource Council: Rita Runega
- Oregon State Disaster Planner: Scott Bassette
- Puget Power & Light: Bill Hartzell
- Puget Power & Light: Lynne Mills
- Sierra Club: Denise Antolini
- Utah Research Inst.: Howard Ross
- Wash. Dept. of Highways: Joan McVey
- Wash. State Highway patrol: Alan Hull
- Wenatchee City Geologist: Doug McFarlan

REFERENCES

The following list enumerates publications which have used data from the WRSN. Abstracts have not been included, nor have the annual technical reports or semi-annual summaries of technical reports prepared for the USGS as part of the contract requirements. The publications have been divided into several categories; papers and journal articles, annual catalogs and reports, maps and special reports, and theses; for the convenience of the reader.

Papers and Journal Articles

Barker, S.E. and S.D. Malone, "Magmatic system geometry at Mount St. Helens modeled from the stress field associated with post-eruptive earthquakes", JGR, 1990 (submitted).

Chou, C.W. and R.S. Crosson, "Search for time-dependent seismic P travel times from mining explosions near Centralia, Washington", GRL, v. 5, pp. 97-100, 1978.

Crosson, R.S., "Small earthquakes, stucture, and tectonics of the Puget Sound region", BSSA, v. 62, no. 5, pp. 1133-1171, 1972.

Crosson, R.S., "Crustal structure modeling of earthquake data 1. Simultaneous least squares estimation of hypocenter and velocity parameters," JGR, v. 81, no. 17, pp. 3036-3046, 1976.

Crosson, R.S., "Crustal structure modeling of earthquake data 2. Velocity structure of the Puget Sound region, Washington," JGR, v. 81, no. 17, pp. 3047-3054, 1976.

Crosson, R.S., E.T. Endo, S.M. Malone, L.L. Noson, and C.S. Weaver, "Eruption of Mt. St. Helens: Seismology", Nature, v. 285, pp. 529-536, 1980.

Crosson, R.S. and D. Frank, "The Mt. Rainier earthquake of July 18, 1973 and its tectonic significance," BSSA, v. 65, pp. 393-401, 1975.

Crosson, R.S. and J.W. Lin, "A note on the Mt. Rainier earthquake of April 20, 1974," BSSA, v. 65, pp. 549-556, 1975.

Crosson, R.S. and T.J. Owens, "Slab geometry of the Cascadia subduction zone beneath Washington from earthquake hypocenters and teleseismic converted waves", GRL, v. 14, pp. 824-827, 1987.

Endo, E.T., S.D. Malone, L.L. Noson, and C.S. Weaver, "Locations, magnitudes, and statistics of the March 20-May 18 earthquake sequence", in The 1980 Eruptions of Mount St. Helens, Washington, USGS Prof. Paper 1250, ed. P.W. Lipman and D.R. Mullineaux, pp. 93-107, 1981.

Fremont, M. and S.D. Malone, "High precision relative locations of earthquakes at Mount St. Helens, Washington", JGR, vol.92, pp 10,223-10,236,1986.

Grant, W.C. and C.S. Weaver, "Earthquakes near Swift Reservoir, Washington, 1958-1963: Seismicity along the southern St. Helens seismic zone", BSSA, v. 76, pp. 1573-1587, 1986.

Grant, W.C., C.S. Weaver, and J.E. Zollweg, "The 14 February Elk Lake, Washington earthquake sequence", BSSA, v. 74, pp. 1289-1309, 1984.

Havskov, J., S. Malone, D. McClurg, and R.S. Crosson, "Coda-Q for the State of Washington", BSSA, v. 79, pp. 1024-1038, 1989.

Johnson, P.A., "Central Washington evidence for a reactivated buried continental rift and northwest trending structural zones, GRL, v. 16, pp. 1325-1328, 1989.

Kohler, W.M., J.H. Healy, and S.S. Wegener, "Upper crustal structures of Mt. Hood, Oregon as revealed by time-term analysis", JGR, v. 87, pp. 339-355, 1982.

Lees, J.M. and R.S. Crosson, "Bayesian ART versus conjugate gradient methods in tomographic seismic imaging: an application at Mount St. Helens, Washington", in AMS-SIAM: Conf. on Spatial Statistics and Imaging, 1989. (in press)

Lees, J.M. and R.S. Crosson, "Tomographic inversion for three-dimensional velocity structure at Mount St. Helens using earthquake data," JGR, v. 94, pp. 5716-5728, 1989.

Lees, J.M. and R.S. Crosson, "Tomographic imaging of local earthquake delay times for three-dimensional velocity variation in western Washington", JGR, v. 95, pp. 4763-4776, 1990.

Lees, J.M. and J.C. VanDecar, Seismic tomography constrained by Bouguer gravity anomalies, with application to western Washington, U.S.A., PAGeophys1990 (in press).

Ludwin, R.S., C.S. Weaver, and R.S. Crosson, Seismicity of Washington and Oregon, in: Slemmons, D.B., E.R. Engdahl, D. Blackwell and D. Schwartz, editors, Decade of North

American Geology associated volume CSMV-1; Neotectonics of North America, 1990 (in press).

Ma, L., R.S. Crosson, and R.S. Ludwin, "Regional tectonic stress in western Washington from focal mechanisms of crustal and subcrustal earthquakes", JGR, (in prep.)

Malone, S.D., "Volcanic earthquakes: Examples from Mount St. Helens", in Earthquakes: Observations, Theory and Interpretation, ed. H. Kanamori and E. Boschi, pp. 436-455, Elsevier/North Holland, Amsterdam, 1983.

Malone, S.D., C. Boyko, and C.S. Weaver, "Seismic precursors to the Mount St. Helens eruptions in 1981 and 1982", Science, v. 221, pp. 1376-1378, 1983.

Malone, S.D., E.T. Endo, C.S. Weaver, and J.W. Ramey, "Seismic monitoring for eruption prediction", in The 1980 Eruptions of Mount St. Helens, Washington, USGS Prof. Paper 1250, ed. P.W. Lipman and D.R. Mullineaux, pp. 803-813, 1981.

Malone, S.D. and D. Frank, "Increased heat emission from Mount Baker, Washington, Cover article", EOS, v. 56, p. 10, 1975.

Malone, S.D. and D. Frank, "Monitoring Mount Baker Volcano", Earthquake Information Bulletin 8, p. 20, 1976.

Malone, S.D., G.H. Rothe, and S.W. Smith, "Details of microearthquake swarms in the Columbia Basin, Washington", BSSA, v. 65, no. 4, pp. 855-864, 1975.

McCollom, R.L. and R.S. Crosson, "An array study of upper mantle velocity in Washington State", BSSA, v. 65, no. 2, pp. 467-482, 1975.

Michaelson, C.A. and C.S. Weaver, "Upper mantle structure from teleseismic P wave arrivals in Washington and northern Oregon", JGR, v. 93, pp. 2077-2094, 1986.

Neri, G. and S.D. Malone, "An analysis of the earthquake time series at Mount St. Helens, Washington, in the framework of recent volcanic activity", Jour. Volcan. Geother. Res., 1989. (in press)

Peters, D.C. and R.S. Crosson, "Application of prediction analysis to hypocenter determination using a local array," BSSA, v. 62, no. 3, pp. 775-788, 1972.

Qamar, A., W. St. Lawrence, J.N. Moore, and G. Kendrick, "Seismic signals preceding the explosive eruption of Mount St. Helens, Washington, on 18 May 1980", BSSA, v. 73, pp. 1797-1813, 1983.

Rasmussen, J. and E. Humphreys, "Tomographic Image of the Juan de Fuca plate beneath Washington and western Oregon using teleseismic P-wave travel times", GRL, v. 15, pp. 1417-1420, 1988.

Richins, W.D, J.C. Pechmann, R.B. Smith, C.H. Langer, S.K. Goter, J.E. Zollweg, and J.J. King, "The 1983 Borah Peak, Idaho, earthquake and its aftershocks", BSSA, v. 77, pp. 694-723 ,1987.

Scandone, R. and S.D. Malone, "Magma supply, magma discharge, and readjustment of the feeding system of St. Helens during 1980", J. Volcanol. Geotherm. Res., v. 23, pp. 239-262, 1985.

Shemeta, J.E. and C.S. Weaver, "Seismicity accompanying the May 18, 1980 eruption of Mount St. Helens, Washington", in Mount St. Helens: Five Years Later, ed. S.A.C. Keller, Eastern Washington University Press, 1986.

Swanson, D.A., T.J. Casadevall, D. Dzurisin, R.T. Holcomb, C.G. Newhall, S.D. Malone, and C.S. Weaver, "Forecasts and predictions of eruptive activity at Mount St. Helens, USA: 1975-1984", J. Geodynamics, v. 3, pp. 397-423, 1985.

Swanson, D.A., T.J. Casadevall, D. Dzurisin, S.D. Malone, C. G. Newhall, and C.S. Weaver, "Predicting eruptions at Mount St. Helens, June 1980 through December 1982", Science, v. 221, pp. 1369-1376, 1983.

Taber, J.J. and B.T.R. Lewis, "Crustal structure of the Washington continental margin from refraction data", BSSA, v. 76, pp. 1011-1024, 1986.

Taber, J.J. and S.W. Smith, "Seismicity and focal mechanisms associated with the subduction of the Juan de Fuca plate beneath the Olympic Peninsula, Washington", BSSA, v. 75, pp. 237-249, 1985.

Thompson, K.I., Seismicity of Mt. Rainier - a detailed study of events to the west of the mountain and their tectonic significance, BSSA, 1990 (in preparation).

U. W. Geophysics Program, "Eruption of Mt. St. Helens: Seismology", Nature, v. 285, no. 5766, pp. 529-536, Washington U., Jun 1980.

VanDecar, J.C. and R.S. Crosson, Determination of teleseismic relative phase arrival times using multi-channel cross correlation and least squares, BSSA, V. 80, pp. 150-169, 1990.

Weaver, C.S. and G.E. Baker, "Geometry of the Juan de Fuca plate beneath Washington and northern Oregon from seismicity", BSSA, v. 78, pp. 264-275, 1988.

Weaver, C.S., W.C. Grant, S.D. Malone, and E.T. Endo, "Post-May 18 seismicity: volcanic and tectonic implications", in The 1980 Eruptions of Mount St. Helens, Washington, USGS Prof. Paper 1250, ed. P.W. Lipman and D.R. Mullineaux, pp. 109-121, 1981.

Weaver, C.S., W.C. Grant, and J.E. Shemeta, "Local crustal extension at Mount St. Helens, Washington", JGR, v. 92, pp. 10170-10178, 1987.

Weaver, C.S., S.M. Green, and H.M. Iyer, "Seismicity of Mount Hood and Structure as determined from teleseismic P wave delay studies", JGR, v. 87, pp. 2782-2792, 1982.

Weaver, C.S. and S.D. Malone, "Mt. St. Helens seismic events: volcanic earthquakes or glacial noises?", GRL, v. 3, pp. 197-200, 1976.

Weaver, C.S. and S.D. Malone, "Seismic evidence for discrete glacier motion at the ice-rock interface" J. Glaciol., v. 23, pp. 171-184, 1979.

Weaver, C.S. and S.D. Malone, "Overview of the tectonic setting and recent studies of eruptions of Mount St. Helens, Washington", JGR, v. 92, pp. 10149-10154, 1987.

Weaver, C.S., and C.A. Michaelson, "Seismicity and volcanism in the Pacific Northwest: Evidence for the segmentation of the Juan de Fuca plate", GRL, v . 12, pp. 215-218, 1985.

Weaver, C.S. and S.W. Smith, "Regional Tectonic and Earthquake hazard implications of a crustal fault zone in southwestern washington", JGR, v. 88, pp. 10371-10383, 1983.

Weaver, C.S., J.E. Zollweg, and S.D. Malone, "Deep earthquakes beneath Mount St. Helens: Evidence for magmatic gas transport?", Science, v. 221, pp. 1391-1394, 1983.

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, 1990 (in press).

Wu, C. and R.S. Crosson, "Numerical investigation of dilatency biasing of hypocenter locations," GRL, v. 2, pp. 205-208, 1975.

Yelin, T.S. and R.S. Crosson, "A note on the south Puget Sound basin magnitude 4.6 earthquake of 11 March 1978 and its aftershocks", BSSA, v. 72, pp. 1033-1038, 1982.

Yelin, T.S. and H.J. Patton, "Seismotectonics of the Portland, Oregon region", (1990, submitted to BSSA).

Zervas, C.E. and R.S. Crosson, "P_n observations and interpretations in Washington", BSSA, v. 76, pp. 521-546, 1986.

Zollweg, J.E., and Johnson, P.A., "The Darrington seismic zone in northwest Washington", BSSA, v. 79, pp. 1833-1854, 1989.

Zollweg, J.E. and R.S. Jacobson, "A Seismic zone on the Oregon-Idaho border: the Powder River Earthquakes of 1984", BSSA, v. 76, p. 985-999, 1986.

Annual Catalogs and Reports

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., S.D. Malone, L.L. Noson, and J.E. Zollweg, Washington Earthquakes 1980, in U.S. Earthquakes, National Earthquake Information Service,1982.

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, 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, 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, 1977, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1979.

Ludwin, R.S., S.D. Malone, and R.S. Crosson, Washington Earthquakes 1983, in U.S. Earthquakes 1983, National Earthquake Information Service, 1985.

Ludwin, R.S., S.D. Malone, and R.S. Crosson, Washington Earthquakes 1984, in U.S. Earthquakes 1984, National Earthquake Information Service, 1985.

Ludwin, R.S., S.D. Malone, R.S. Crosson, A.I. Qamar, Washington Earthquakes 1985, in U.S. Earthquakes, National Earthquake Information Service, 1990 (in press).

Ludwin, R.S., S.D. Malone, R.S. Crosson, A.I. Qamar, Washington Earthquakes 1986, in U.S. Earthquakes, National Earthquake Information Service, 1990 (in press).

Ludwin, R.S., S.D. Malone, R.S. Crosson, A.I. Qamar, Washington Earthquakes 1987, in U.S. Earthquakes, National Earthquake Information Service,1990 (in press).

Ludwin, R.S., S.D. Malone, R.S. Crosson, A.I. Qamar, Washington Earthquakes 1988, in U.S. Earthquakes, National Earthquake Information Service,1990 (in preparation).

Noson, L.L., R.S. Crosson, S.D. Malone, and J.E. Zollweg, Washington Earthquakes 1981, in U.S. Earthquakes, National Earthquake Information Service,1982.

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, Washington Dept. of Natural Resources, Geology and Earth Resources Division, 1985.

Qamar, A., R. Ludwin, R.S. Crosson, and S.D. Malone, Earthquake hypocenters in Washington and northern Oregon - 1982-1986, Washington Dept. of Natural Resources, Division of Geology and Earth Resources, 1987.

Qamar, A., A. Rathbun, R. Ludwin, R.S. Crosson, and S.D. Malone, Earthquake hypocenters in Washington and northern Oregon - 1980, Washington Dept. of Natural Resources, Division of Geology and Earth Resources, 1986.

Qamar, A., A. Rathbun, R. Ludwin, L.L. Noson, R.S. Crosson, and S.D. Malone, Earthquake hypocenters in Washington and northern Oregon - 1981, Washington Dept. of Natural Resources, Division of Geology and Earth Resources, 1987.

U.W. Geophysics Program, Annual Technical Reports on earthquake monitoring in western Washington, Geophysics Program, University of Washington, 1970-89.

U.W. Geophysics Program, Annual progress report on micro-earthquake monitoring of the Hanford Region, Geophysics Program, University of Washington, 1976.

U.W. Geophysics Program, Annual Technical Reports on earthquake monitoring of the Hanford region, eastern Washington, Geophysics Program, University of Washington, 1977-81.

U.W. Geophysics Program, Annual Technical Reports on earthquake monitoring of eastern and southern Washington, Geophysics Program, University of Washington, 1982-85.

U.W. Geophysics Program, Annual Technical Reports on earthquake monitoring of eastern Washington, Geophysics Program, University of Washington, 1986-88.

Special Reports and Maps

Crosson, R.S., "Review of seismicity in the Puget Sound region from 1970 through 1978," in Proceedings of Workshop XIV, Earthquake Hazards of the Puget Sound Region, Washington, USGS Open File Rept. 83-19, ed. J.C. Yount and R.S. Crosson, pp. 6-18, U.S. Geol. Survey, 1983.

Crosson, R.S., "Seismological setting of the Puget Sound region," in Proceedings of Conference

XXXIII, A Workshop on "Earthquake Hazards in the Puget Sound, Washington Area", USGS Open-File Rept. 86-253, ed. W.W. Hays and P.L. Gori, pp. 46-51, 1986.

Crosson, R.S., "Seismicity and structure of the Cascadia subduction zone," in Minutes of the National Earthquake Prediction Evaluation Council, April 2 and 3, 1987, USGS Open File Report 88-37, ed. C.S. Shearer, pp. 91-110, 1988.

Crosson, R.S., "Seismicity of Puget Sound and sourthern British Columbia", in Proceedings of Conference XLVIII: 3rd Annual Workshop on Earthquake Hazards in the Puget Sound, Portland Area , USGS Open File Report 89-465, pp. 31-32, 1989.

Davis, G.A., Tectonic evolution of the Pacific Northwest precambrian to present. Subappendix 2R C, Preliminary Safety Analysis Rept., Amend. 23, Nuclear Project #1, Wash. Public Power Supply System, p. i-2R C-46

Engdahl, E.R. (compiler), Seismicity map of North America 1:5,000,000, prepared by W.A. Rinehart; National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, CO. for The Decade of North American Geology, The Geological Society of North America, 1988.

Gower, H.D., J.C. Yount, and R.S. Crosson, Seismotectonic map of the Puget Sound region, Washington, 1985. Dept. of Interior, U.S. Geological Survey, Miscell. Invest. Series Map I-1613

Hawkins, N. and R.S. Crosson, "Causes, characteristics, and effects of Puget Sound Earthquakes", in Proc. U.S. National Conf. on Earthquake Engineering, pp. 104-112, 1975.

Kelly, S.M. and R.S. Crosson, "Seismicity, 1970-1979, Sheet 11," in Western North America Continental Margin and Adjacent Ocean Floor off Oregon and Washington, Atlas 1, Ocean Margin Drilling Program, Regional Atlas Series, ed. L.D. Kulm and others, Marine Science International, 1984.R

Ludwin, R.S., "Earthquake occurrence and hazards in Washington and Oregon", in Proceedings of Conference XLVIII: 3rd Annual Workshop on Earthquake Hazards in the Puget Sound, Portland Area , USGS Open File Report 89-465, pp. 128-140, 1989.

McCrumb, D.R., R.W. Galster, R.S. Crosson, R.S. Ludwin, D.O. West, W.E. Hancock, and Lawrence V. Mann, "Tectonics, Seismicity, and Engineering Seismology in Washington", in Engineering Geology in Washington, Vol. II, ed. R.W. Galster, Washington Division of Geology and Earth Resources, Bulletin 78, 1989.

Noson, L.L., A.I. Qamar, and G.W. Thorson, Washington State Earthquake Hazards, Washington Division of Geology and Earth Resources, Information Circular 85, 77 p., 1988.

Puget Sound Power & Light Company Skagit Nuclear Power Project, units 1 and 2. Project No. 514 Status Review, 1979 13 September.

Rohay, A.C. and Malone S.D., "Crustal Structure of the Columbia Plateau Region, Washington", Rockwell Hanford Operations RHO-BW-SA-289 P, 1983.

Swanson, D.A., T.S. Casadevall, D. Dzurisin, S.D. Malone, C. G. Newhall, and C.S. Weaver, "Forcasts and predictions of Mount St. Helens, U.S.A.: 1975-1983", International Geology Conference, Moscow, USSR, 1984.

Weaver, C.S., and K.M. Shedlock, "Potential subduction, probable intraplate, and known crustal earthquake source areas in the Cascadia subduction zone", in Proceedings of Conference XLVIII: 3rd Annual Workshop on Earthquake Hazards in the Puget Sound, Portland Area , USGS Open File Report 89-465, pp. 11-26, 1989.

Washington Seismic Safety Council, Washington Seismic Safety Council policy recommendations: Washington Seismic Safety Council, 2 v., 1986.

Zollweg, J.E. and W.D. Richins, "Later aftershocks of the 1983 Borag Peak, Idaho earthquake and related activity in central Idaho", in Proceedings of Workshop XXVIII on the Borah Peak, Idaho, earthquake, R.S. Stein and R.C. Bucknam, editors, USGS Open File Report 85-290, pp. 345-367, 1985.

Theses

Barker, S.E., Magma body geometry at Mount St. Helens inferred from the stress field associated with post-eruptive earthquakes, University of Washington, 1988. M.S. Thesis

Bor, S.S., Scaling for seismic source spectra and energy attenuation in the Chelan Region, University of Washington, 1977. M.S. Thesis

Glover, D.M., Crustal Structure of the Columbia River Basin, Washington from borehole and refraction data, Univ. of Washington, 1985. M.S. Thesis

Hesser, D.H., Linear predictive processing and pattern recognition for automated classification of local seismic events, Univ. of Washington, 1982. M.S. Thesis

Johnson, P.A., Cluster analysis of eastern Washington Seismicity, 86 pp., University of Washington, 1989. M.S. Thesis

Leaver, D.S., Mixed stochastic and deterministic modeling of the crustal structure in the vicinity of Mount Hood, Oregon, p. 180pp., Univ. of Washington, 1984. Ph.D. Thesis

Lees, J.M., Seismic tomography in western Washington, p. 173pp, Univ. of Washington, 1989. Ph.D. Thesis

Lin, J.W., A study of upper mantle structure in the Pacific Northwest using P waves from teleseisms, pp. 1-98, University of Washington, 1974. Ph.D. Thesis

Ma, L., Regional tectonic stress in western Washington from focal mechanisms of crustal and subcrustal earthquakes, p. 84pp, Univ. of Washington, Seattle, Washington, 1988. M.S. Thesis

McClain, K.J., A geophysical study of accretionary processes on the Washington margin, p. 141, Univ. of Wash., Seattle, November 1981. Ph.D. Thesis

McClurg, D.C., Coda-Q analysis at Mount St. Helens and its implications for volcanic seismology, University of Washington, 1987. M.S. Thesis

McCollom, R.L., An array study of upper mantle seismic velocity in Washington state, Univ. of Wash., Seattle, 1972. M.S. Thesis

Michaelson, C.A., Three-Dimensional Velocity structure of the crust and upper mantle of Washington and Oregon, University of Washington Geology Dept., 1983. M.S. Thesis

Rasmussen, J., The seismic P-wave velocity structure of the upper mantle between Washington and western Oregon, University of Oregon, 1989. M. S. Thesis

Rohay, A.C., Crust and mantle structure of the North Cascades Range, Washington, University of Washington, 1982. Ph.D. Thesis

Rothe, G.H., Earthquake Swarms in the Columbia River Basalts, Univ. of Washington, 1978. Ph.D. Thesis

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

Weaver, C.S., Seismic events on Cascade Volcanos, University of Washington, 1976, Ph.D. Thesis

Wu, J.C., Inversion of travel-time data for seismic velocity structure in three dimensions, University of Washington, 1977. Ph. D. Thesis

Wu, S.W., Earthquake mislocation due to lateral heterogeneity, Univ. of Washington, 1983. M.S. Thesis

Yelin, T.S., The Seattle earthquake swarms and Puget Basin focal mechanisms and their tectonic implications, Univ. of Washington, 1982. M.S. Thesis

Zervas, C.E., A time term analysis of P_n velocities in Washington, Univ. of Washington, 1984. M.S. Thesis

Zuercher, H., A study of the crust in Puget Sound using a fixed seismic source, Univ. of Wash., Seattle, 1975. M.S. Thesis

APPENDIX 3

Publications supported fully or partially under these operating agreements

Articles and Reports:

Barker, S.E. and S.D. Malone, (in press), Magmatic system geometry at Mount St. Helens modeled from the stress field associated with post-eruption earthquakes, JGR

Ludwin, R. S., S.D. Malone, R.S. Crosson, A.I. Qamar, and R. Benson (in preparation), Washington Earthquakes 1989, in U.S. Earthquakes, National Earthquake Information Service.

Ludwin, R. S., S.D. Malone, R.S. Crosson, A.I. Qamar, and R. Benson (in preparation), Washington Earthquakes 1988, in U.S. Earthquakes, National Earthquake Information Service.

Ludwin, R. S., S.D. Malone, R.S. Crosson, A.I. Qamar, (in press), Washington Earthquakes 1987, in U.S. Earthquakes, National Earthquake Information Service.

Ludwin, R. S., S.D. Malone, R.S. Crosson, A.I. Qamar, (in press), Washington Earthquakes 1986, in U.S. Earthquakes, National Earthquake Information Service.

Ludwin, R. S., S.D. Malone, R.S. Crosson, A.I. Qamar, 1990 (in press), Washington Earthquakes 1985, in U.S. Earthquakes, National Earthquake Information Service.

Ludwin, R. S., C.S. Weaver, and R.S. Crosson, (in press), Seismicity of Washington and Oregon, in: Slemmons, D.B., E.R. Engdahl, D. Blackwell and D. Schwartz, editors, Decade of North American Geology associated volume CSMV-1; Neotectonics of North America.

Ma, Li, R.S. Crosson, and R.S. Ludwin, (submitted), Preliminary Report on Focal Mechanisms and stress in western Washington, (submitted to USGS Professional Paper)

Malone, S.D., 1990, Mount St. Helens, the 1980 re-awakening and continuing seismic activity, Geoscience Canada, V. 17, N. 3, pp. 146-150.

Thompson, K.I., (in preparation), Seismicity of Mt. Rainier - a detailed study of events to the west of the mountain and their tectonic significance

Univ. of Wash. Geophysics Program, 1990, Quarterly Network Report 89-D on Seismicity of Washington and Northern Oregon

Univ. of Wash. Geophysics Program, 1990, Quarterly Network Report 90-A on Seismicity of Washington and Northern Oregon

Univ. of Wash. Geophysics Program, 1990, Quarterly Network Report 90-B on Seismicity of Washington and Northern Oregon

Univ. of Wash. Geophysics Program, 1990, Quarterly Network Report 90-C on Seismicity of Washington and Northern Oregon

Weaver, C.S., R.D. Norris, and C. Jonientz-Trisler, 1990, Results of Seismological Monitoring in the Cascade Range, 1962-1989, earthquakes, eruptions, avalanches, and other curiosities, Geoscience Canada, V. 17, N. 3, pp. 158-162.

Abstracts

Johnson, P.A., and S.D. Malone, (in press), Cluster analysis of eastern Washington seismicity; a new algorithm, results and geological correlations, SSA meeting, 1991.

Jonientz-Trisler, C., C. Driedger, and A. Qamar, 1990, Seismic signatures of debris flows on Mt. Rainier, WA, EOS, Vol. 71, No. 36, p. 1068.

Jonientz-Trisler, C., and C. Driedger, 1990 (in press), Seismic evidence of historic debris flows and dry season floods on Mount Rainier, Washington, 1961-1990, EOS, V. 71, N. 41, p. 1145.

Malone, S.D., A.I. Qamar, and C. Jonientz-Trisler, (in press), Recent Seismicity studies at Mount Rainier, Washington, SSA meeting, 1991.

Malone, S.D., (in press) The Hawk seismic data acquisition and analysis system, SSA meeting, 1991.

Moran, S. C., and S.D. Malone, 1990, Pre-1980 seismicity at Mt. St. Helens: is the past the key to the present, EOS, Vol. 71, No. 36 p. 1067.

Moran, S. C., and S.D. Malone, 1990, Focal mechanism solutions from recent earthquakes in the deeper magmatic system at Mt. St. Helens, EOS, V. 71, N. 41, p 1145.

Moran, S. C., and S.D. Malone, 1990, Recent micro-seismic activity at Mt. St. Helens and

its implications for the evolution of the deeper magmatic system, EOS, V. 71, N. 43, p. 1693.

Nabelek, J., K. Werner, R. Yeats, and S. Malone, 1990 (in press), The August, 1990, Woodburn, Oregon earthquake sequence: constraints from broadband regional recording and geological implications, EOS, V. 71, N. 41, p. 1145.

Qamar, A. and J. Zollweg, 1990 (in press), The 1990 Deming Washington earthquakes: a sequence of shallow thrust earthquakes in the Pacific Northwest, EOS, V. 71, N. 41, p. 1145.