HIGH RESOLUTION EARTHQUAKE RELOCATION IN CASCADIA

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Investigations Undertaken

This report covers progress from October 1, 2002 through September 30, 2003, under USGS Grant 03HQGR0063. The purpose of this project is to obtain high-resolution relative locations of earthquakes in Cascadia using the double difference algorithm of *Waldhauser and Ellsworth* [2000]. The objective of this research is to increase our understanding of the relationship between seismicity, crustal faults, structure, and tectonic processes, with the ultimate goal of reducing earthquake hazards through greater understanding of where and how damaging earthquakes occur.

Results

It is difficult to directly associate earthquake activity in the Puget Lowland region of western Washington with known structural features. The structure of this region is complex, and surface mapping of faults is difficult, in part due to extensive shallow glacial deposits. Much of the crustal earthquake activity in this region lies in the mid-crust, from 15 to 30 km depth, making it particularly important to have good 3-D structure information to connect surface structure with activity at depth. From recent 3-D seismic structure studies, large seismic velocity variability is found in the crust of the Lowland, with velocity varying from 2 km/s or less in the shallower sedimentary basins, to over 7 km/s at moderate depths in the crust in rocks that may be of gabbroic composition. Large lateral variations in crustal velocity have a significant impact on conventional earthquake location methods that utilize laterally homogeneous crustal models. This structural complexity may contribute in part to the apparent dispersion of hypocenter patterns in this region.

We have set up the data and computer resources to apply the double difference earthquake location procedure, and have carried out initial analysis of three clusters of earthquakes. In these three cases, the method has provided apparent increased resolution in the relative hypocenter locations, and the results suggest possible fault associations. In the case of the sequence near Entiat and Lake Chelan, our results in combination with recent determination of the event epicenter by Bakun et al. [2002], suggest that a southwest dipping thrust fault may be the source of the 1872 M ~7 earthquake (the largest historic crustal earthquake in Washington). Based on our experience thus far, we believe that the improved spatial resolution resulting from use of the double difference methodology will allow us to define possible fault orientations of clusters (including aftershocks) which have not been previously identified. We also may be able to identify and study repeating earthquakes that are not apparent in routine network analysis. In this summary, we report on two of the three sequences that were relocated in our initial studies.

Bremerton Sequence

The Bremerton M 4.9 earthquake of June 1997 and its aftershocks provided one example of the application of double difference relocation to a small earthquake cluster. The Bremerton earthquake is one of the larger crustal earthquakes to occur within the PNSN. It is also of interest because it is in the general vicinity of the western part of the Seattle fault zone (SFZ). Although its relationship to the SFZ is not entirely clear, it may have important tectonic implications for the SFZ. *Blakely et al*. [2002] discuss this earthquake in relationship to their inferred fault structure for the Seattle fault, and conclude that either the Bremerton sequence is directly related to the observed surface displacements on a high angle fault, or that it reflects slip on a nearly horizontal plane near the base of the Seattle basin.

Initial routine network locations placed the mainshock of the Bremerton earthquake at a depth of 7.7 km with aftershocks distributed over a vertical depth range from about 11 km to the surface. Subsequent reanalysis and relocation of the sequence placed the mainshock at a depth of about 13-14 km, but the aftershocks were still distributed over a vertical range from 13 km to the surface using conventional network location procedures. Focal mechanisms for the mainshock and several aftershocks were constructed, with one possible slip surface a nearly vertical fault plane parallel to the regional trend of the SFZ (as defined by gravity measurements and tomography studies; the auxiliary plane was sub-horizontal). The initial relocation studies revealed that the depth control for this mainshock-aftershock sequence was actually quite poor using conventional location procedures, in spite of the fact that the sequence occurred near the center of the regional PNSN network. Based on the conventional network locations, the large vertical distribution of aftershocks for the Bremerton sequence is too great to reflect occurrence on or near the mainshock slip surface.

As a test, we applied the double-difference algorithm to a set of 11 well-recorded earthquakes in the 1997 Bremerton sequence (using the program hypoDD). The 11 events comprise the mainshock and 10 aftershocks, with magnitudes ranging from 1.9 to 4.9. The events were all relocated with hypoDD using the standard central Puget basin 1-D velocity model. Whereas the routine network locations placed most of the aftershocks at depths less than two kilometers, with only 4 events deeper than 2 km, in the double-difference results all of the aftershocks “collapsed” into a tight circular cluster about 1.5 km in diameter at a depth of about 14.5 km. The plane of this cluster strikes NW and the cluster defines a nearly vertical plane in space that corresponds well with to orientation of the high-angle plane of the mainshock first-motion focal mechanism. This agreement allows us to assert with some confidence that the rupture plane is likely to be the nearly vertical plane: oblique slip with the northeast side block moving upward and eastward relative to the southwest side block.

Both routine network and double-difference solutions place the mainshock about 1 km SW of the map-view aftershock lineation. The reason for this displacement remains unclear. The offset is not the result of a single station anomaly – we investigated that possibility in our preliminary analysis. The aftershocks may occur on a subsidiary fault that was activated by the mainshock. Another possibility is that the difference in signal strength between the mainshock and the aftershocks, as a result of their size difference, resulted in different phases (different arrival “paths”) being picked as first arrivals between the main and aftershocks. For example lateral refractions associated with the SFZ may be observed in the mainshock signals, but have amplitudes too low to be observed in the smaller amplitude aftershocks signals. The observed strong lateral variation in velocity from the Seattle basin southward across the Seattle fault zone could contribute to such effects. Further careful study may reveal the nature of this location difference.

Moving the Bremerton mainshock hypocenter from 8 km depth to 14 km depth places it within rocks of the Crescent formation, well below the sediments of the Seattle basin and consistent with regional background seismicity which is found to occur dominantly within the Crescent. The north-side-up character of the Bremerton earthquake, even at a depth of 14 km, suggests that fault displacement resulting from repeated earthquakes might ultimately reach the surface in the vicinity of the SFZ.

Entiat-Chelan Sequence

The Entiat-Chelan region of eastern Washington, near the boundary between crystalline rocks of the north Cascades and the basalt flows of the Columbia Plateau, is a seismically active region on the eastern flank of the Cascade Range. This region is of particular interest because it is a possible source zone of the December 1872 M ~7 earthquake, widely regarded as the largest crustal earthquake in the historic record for Washington. *Bakun et al.* [2002] recently reanalyzed the felt reports for this earthquake, and concluded that the 1872 earthquake was a shallow (crustal) event, and that the epicenter coincides almost exactly with the hypocentroid (effectively mean position) of the contemporary instrumental hypocenters in the region.

To see if any evidence of the fault plane of the 1872 event might be identified in the contemporary hypocenter distribution, we applied the double difference relocation technique to this sequence. We initially selected a group of 1198 earthquakes ranging in magnitude from 0 to 3.5, and in depth from the surface to about 15 km (a few outliers were at greater depth). The time window was from 1980 through 2001, and all quality levels were included in the initial selection. Only hand picked first arrival data in the PNSN phase catalog were used in this initial study.

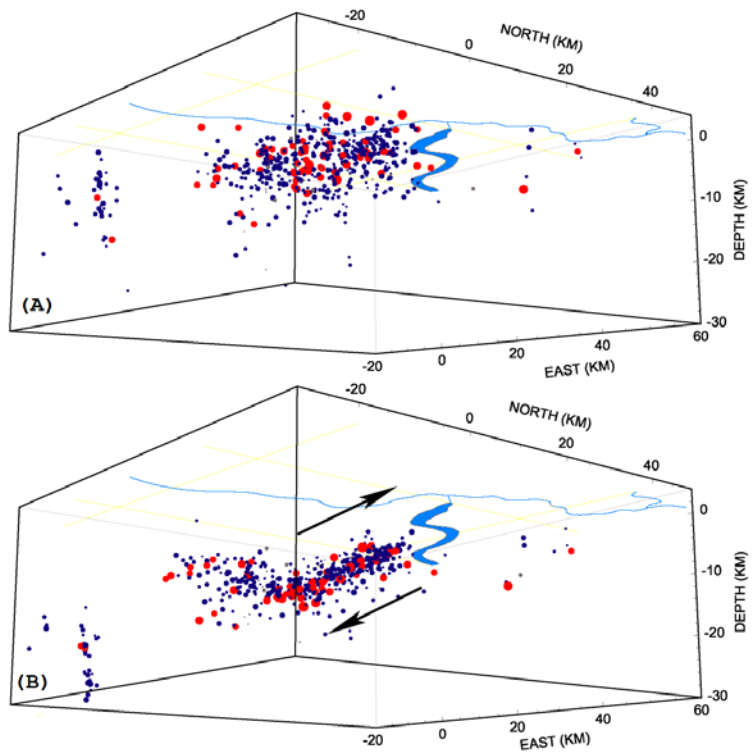

Figure 1. Identical 3-D views of 577 earthquakes that were relocated in the Entiat region of eastern Washington. (A) initial locations using conventional (Geiger's method) locations, and (B) relocations using double-difference (hypoDD). Size scaling is used for these plots, with linear scaling over the magnitude range from 0 to 3.5 . The "underside" of Lake Chelan is the sinuous feature on the upper surface of each plot. For plot (B) the full distribution is a sub-circular disk viewed from the side. The arrows in (B) show the sense of motion indicated by focal mechanism analysis.

After relocation using hypoDD, the number of events successfully relocated was 577. Many events were deleted from the relocation due to insufficient numbers of picks and insufficient cluster density. However we observed a dramatic change in the hypocenter distribution from the initial conventional locations to the double difference relocations. This difference is illustrated in Figure 1 which shows the same 577 hypocenters in a 3-D view from the same viewing position: (A) the conventional locations and (B) the hypoDD relocated positions. The view point was chosen to optimally "flatten" the hypocenter distribution in the hypoDD results. The original locations produced a featureless cloud of hypocenters with no discernable structure. However the hypoDD results show a clear sub-circular planar hypocenter distribution dipping to the southwest at an angle estimated to be 15-20° with depths typically from 5 to 15 km.

Although there is no clearly mapped surface expression of a fault or other features that might correspond to the thrust plane it is interesting that the projection of this plane to the surface coincides roughly with the average (linear) position of Lake Chelan. However, it is important to note from the hypocentral depths that the conjecture by *Bakun et al.* that the 1872 event may have occurred on a blind thrust is consistent with our analysis.

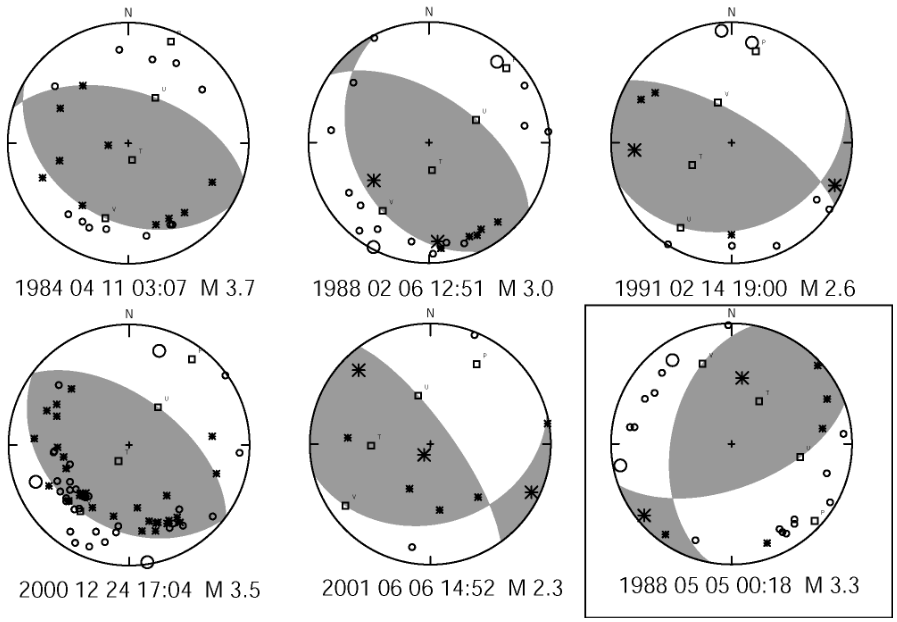

Figure 2. Focal mechanisms of 6 events within the relocated Entiat-Chelan sequence. Dates and magnitudes are indicated below each plot. These are lower hemisphere equal area plots, with compressional quadrants shaded. Symbols are: (*) for compressional observations and (0) for dilatational observations. Large symbols have takeoff angles in the upper focal hemisphere, and small symbols have takeoff angles in the lower focal hemisphere. Further work in refining the crustal velocity structure in this region may significantly improve our ability to determine focal mechanisms.

Since this hypocenter distribution suggests a possible thrust plane, we examined focal mechanisms of 6 events that had reasonably well distributed observations. The first arrival mechanisms for these events are shown in Figure 2. To obtain the mechanisms we approximated the local velocity structure by a linear velocity function, recognizing that more work needs to be done to refine the local velocity structure. Five out of the 6 events have mechanisms that are closely consistent with low angle thrust planes dipping to the southwest or south. The P axes for these mechanisms are typically NNE, generally consistent with the sense of compression observed in western Washington, and elsewhere in the Columbia basin. The arrows of Figure 1 (B) show the sense of motion indicated by the choice of the SW dipping fault planes. The sixth event, shown in the box, is consistent with thrust or reverse motion, but with the P axis oriented approximately 90° to the dominant solutions.

Although more detailed analysis may be required to confirm these preliminary results, we suspect that we may be observing activity associated with the structure that gave rise to the 1872 earthquake. The details of crustal structure in this region are not well known. However, based on the located event depths, it is reasonable to believe that most if not all of the earthquakes in the Entiat-Chelan cluster occur in the crystalline basement rocks of the N. Cascades. As reviewed in detail by *Bakun et al*., there are no good known candidates for surface mapped faults in the region that could provide surface control for thrust faulting. The Entiat fault, the largest fault in the area (about 20 km SW of the earthquake cluster), appears to be a strike slip fault that has been inactive since the Eocene. The general sense of compression (NE-SW) expressed for example in the Yakima fold belt south of Entiat, is definitely consistent with the P axis orientation of the dominant focal mechanisms. Thus, there is reason to believe that both the earthquakes and surface deformation reflect regional tectonic stress. Our results, in combination with the recent findings of *Bakun et al.,* will contribute to improved understanding of the crustal earthquake hazard for this region.

Data Availability: Results from relocations of earthquakes in the Entiat region of eastern Washington are available as interactive web displays at: http://faculty.washington.edu/crosson/RESEARCH/ENTIAT. This display shows before and after applying high-resolution relocation to the regional earthquake data near Entiat, WA.

Non-Technical Summary

Identifying faults in the seismicity patterns in Washington is difficult owing in part to uncertainty in earthquake locations. Recent advances in earthquake location technology allow us to overcome some of the difficulties that inhibit our ability to identify fault patterns using seismicity. In this study, we are applying these new techniques to obtain higher precision relative earthquake locations. Initial results suggest that we may be able to better identify and characterize faults using this new methodology. Alignment of earthquake locations in the Entiat region of eastern Washington may pinpoint the location of the large earthquake that struck this region in 1872.

Reports published:

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