Seismological Review of the July 16, 1936 Milton-Freewater Earthquake Source Region

Prepared for

Washington Public Power Supply System
3000 George Washington Way
Richland, Washington 99352

January 1980

Under the direction of

United Engineers & Constructors, Inc.
30 South 17th Street
Post Office Box 8223
Philadelphia, Pennsylvania 19101

Contract No. 52028, C.O. 11
Task No. WCC 1

Woodward-Clyde Consultants
Three Embarcadero Center, Suite 700, San Francisco, CA 94111

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January 31, 1980

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Attention: Mr. B. D. Redd
Project Engineering Manager

Subject: Final Report
Seismological Review of the July 16, 1936
Milton-Freewater Earthquake Source Region

Gentelmen:

We are pleased to enclose three (3) copies and one unbound photo ready master copy of our final report "Seismological Review of the July 16, 1936 Milton-Freewater Earthquake Source Region."

We have enjoyed working with you and Washington Public Power Supply System on this interesting project and hope we may be of further service if required.

Very truly yours,

Thomas Turcotte

Thomas Turcotte
Project Manager

TT:mf

Enclosures

cc: J. P. Thomas (3)
D. D. Tillson (20)

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1.0 SUMMARY

The instrumental epicenter, 46°12.5'N, 118°14.0W, of the July 16, 1936 earthquake determined in this study is in close agreement with that originally reported by the International Seismological Center and the U.S. Coast and Geodetic Survey. Critical evaluation of the reliability of the epicenter location determined in this study, and of S-P interval data from the seismograph station at Spokane, support the conclusion that this earthquake most likely occurred near Waitsburg, Washington rather than at an epicenter, defined by intensity data, near Milton-Freewater, Oregon as previously believed. The magnitude of this earthquake, previously listed as M=5-3/4, was reviewed and found to have an average value of M=6.1.

The high quality epicentral location solution computed for the April 8, 1979 earthquake indicates that this event occurred very close to the intersection of the Wallula and Hite fault systems, and at a shallow focal depth of about 5 kilometers. The fault plane solution derived for this earthquake is moderately well constrained and indicates either oblique, right-lateral, reverse motion on a fault striking N30°E, or oblique, left-lateral, reverse motion on a fault striking N40°W. Each of these fault planes is consistent with the strike of major fault systems that

have been identified by surface geological investigations (Shannon and Wilson, 1979). Only the N30^{o}E plane has a sense of motion in agreement with the reported geologic observations, however.

The alignment of the instrumentally located epicenter of the 1936 earthquake and the epicenter of the 1979 earthquake coincide with the strike of one of the 1979 earthquake fault planes. This coincidence supports the theory of a northeast-trending system as the source of both earthquakes. In addition, intensity data for the 1936 event indicate that the 1936 earthquake probably occurred near Waitsburg, Washington, close to the instrumental epicenter, and that rupture subsequently propagated to the southwest along the Hite fault system.

2.0 INTRODUCTION

The Walla Walla, Milton-Freewater area was the source area of a magnitude 5-3/4 earthquake on July 16, 1936 which was widely felt in the Eastern Washington - Oregon border region and which caused some damage in the zone of highest intensity (MM VII). Because of the geologic structural trends extending from the Milton-Freewater area northwest towards Wallula Gap and the continuing northwesterly trend of the Rattlesnake Hills, the

earthquake activity in this area has been of importance to the definition of a design earthquake for critical structures located in the region.

The location of the 1936 earthquake has been thought to be well constrained by the intensity data collected during the thorough studies conducted immediately following the event by B.H. Brown (1937) and by the U.S. Coast and Geodetic Survey (USGS, 1937). Isoseismal analyses of these data have placed the epicenter of the earthquake near Milton-Freewater at approximately 45°58'N, 118°18'W (Brown, 1937; Neumann, 1938). This epicentral location has been generally accepted.

In addition to the intensity data, the 1936 earthquake was instrumentally recorded at seismograph stations in the United States, in Canada and abroad. Using P-wave data from 25 of the stations reporting the event, the International Seismological Center (ISC) (1946) and the USCGS (1937) located the epicenter at 46.2°N, 118.2°W, northeast of Walla Walla, and approximately 30 km north of the felt epicenter. It is not uncommon for teleseismically located epicenters such as this to be in error by as much as tens of kilometers. This is especially true for earthquakes that occurred before the mid 1950's when the use of seismographs having low sensitivities and inaccurate timekeeping

were common. However, the instrumental data for the 1936 earthquake have been utilized only to a limited degree in past studies, and a complete reassessment of these data and an evaluation of the accuracy of the instrumental epicenter were judged to be worthwhile.

The historic record indicates that in general the rate of occurrence of earthquakes in the Walla Walla area appears to have been low. Long periods of quiescence have been punctuated by infrequent earthquakes, which include shocks of moderate magnitude, such as the 1936 event. In 1977, an eight-station microearthquake array deployed in the area did not record any local events during the three-month period of operation (WPPSS, 1977). The occurrence on April 8, 1979 of a magnitude 4.1M_L earthquake near College Place (Malone, 1979), therefore, was fortuitous. Not only did the well-recorded local data on this earthquake permit investigation of the causative mechanism of this event itself, but a comparative study of the two events was also possible.

This study, together with associated geological and geophysical studies, should provide information to aid in the eventual identification and assessment of earthquake source structures in the Walla Walla area. A secondary purpose of this study was to

investigate any relationship of the August 14, 1969 North Powder, Oregon earthquake (which occurred approximately 125 km southwest of Walla Walla) to the 1936 and 1979 events.

3.0 DATA ACQUISITION

A considerable effort was made to gather all available data from the United States and Canadian seismographic stations for the 1936, 1969, and 1979 earthquakes. The data search for the 1936 earthquake was based on the ISC and USCGS bulletins for the event. High quality copies of seismograms were obtained from all but 4 of the 22 United States and Canadian stations that recorded useful data. Photographic enlargements of the original records from selected stations were obtained to facilitate focal mechanism studies. In addition to the records themselves, original station reading sheets for the event and station bulletins were obtained when available. Particular attention was given to time corrections and sense of motion applicable to each of the records. Stations from which data on the 1936 earthquake are available are shown in Table 1.

The locations and operating authorities of all the stations likely to have recorded the 1969 and 1979 earthquakes were taken from the U.S. Geological Survey publications "Historical Survey

of U.S. Seismograph Stations" (Poppe, 1979), and "Seismograph Station Codes and Characteristics" (Poppe and others, 1978). Copies of all useful seismograms for these events were obtained. Seismograms from more distant stations in British Columbia, Alberta, Idaho, Montana, Utah and Oregon were also examined to ensure that no useful data had been overlooked.

4.0 APRIL 8, 1979 EARTHQUAKE

The April 8, 1979 earthquake was located from data recorded at stations of the University of Washington's eastern Washington network array shown in Figure 1 and listed in Table 2. Even though usable records are available from the northeast Washington stations and from more distant stations, the change in the crustal velocity structure from south to north across the Columbia Plateau results in a degradation of the quality of the hypocentral solution if these stations are included (Malone, 1979, personal communication). Except for the local stations, MFW and PEN, no usable records are available from stations to the east or south of the epicentral area. This earthquake was located using the local location program, HYPOELLIPSE (Lahr and others, 1978), the Eastern Washington "South" velocity model (Table 3), and station delays determined by the University of Washington (S.D. Malone, personal communication). The reading

precision of the P phase arrival times, obtained from S.D.Malone, is 0.025 seconds. As discussed below, several additional computer runs were made to investigate the sensitivity of the hypocentral location to variations in the velocity model in the earthquake source area and of variations in focal depth. The epicenter computed for the 1979 earthquake is plotted in Figure 1, and details of the computer solution are given in Table 2.

The directions of P-wave first motion shown in Table 4 were read from seismograms from the local and regional stations that clearly recorded the 1979 earthquake. As far as could be ascertained, the sense of motion on the records corresponds correctly with the direction of ground motion except at station NEW, where the sense of motion is reversed. A Schmidt equal area fault plane projection of the lower focal hemisphere was used in all solutions. Station azimuths and angles of incidence are calculated along with the hypocentral location of HYPOELLIPSE. P-wave first motions recorded at the distant stations that were not included in the hypocentral location computation were used to construct the fault plane solution because these data are not, in general, sensitive to regional variations in the velocity structure. However, first motions from stations west of the Cascades were found to be inconsistent

with the rest of the data and were rejected. This phenomenon is commonly observed on the University of Washington network data and is probably caused by large, abrupt changes in the crustal and upper mantle structure beneath the Cascades (Malone, 1979, personal communication). The fault plane solution for this event is shown in Figure 2, and the interpretation of the solution is given in Table 5. Because fault plane solutions can be particularly sensitive to the velocity structure in the source area and to earthquake focal depth, further fault plane solutions were constructed using the azimuths and emergence angles that resulted from hypocentral location runs using various source area models and with the focus constrained at different depths. Examples of fault plane solutions that resulted from two such trial runs are shown in Figures 3(a) and 3(b) and are discussed in a later section.

5.0 JULY 16, 1936 EARTHQUAKE

All of the stations listed in Table 1 were used to locate the July 16, 1936 earthquake. P-wave arrival times were carefully reread from seismograms for which time corrections were available and compared with those reported in the bulletins in order to check the precision of the original readings and to correct gross errors. In the majority of cases, reread arrival

times agreed with the original readings to within 1 or 2 seconds, although some gross errors were corrected. An assessment of the estimated reading precision that is achievable on the records from each of the stations is included in Table 1. These estimates combine the precision with which times can be measured on the records and the accuracy of station clock corrections. Clock corrections were not available for the seismograms from stations SPO, UKI and DEN. Accurate, continuously kept clock correction records were available for all the Berkeley stations except FER (BRK, SFB, MHC, PAC, FRE), and all the C.I.T. stations (TIN, MWC, PAS, RVR, LJC). These records showed that a high degree of reliance can be placed on the time corrections applied to measured arrival times for these stations. Time corrections for USCGS stations (BZM, TUO, SIT, CMO) and for VIC were written directly on to the seismograms but continuous records were not available. Therefore, even though the time corrections applicable to arrival times read from seismograms from these stations appear to be precise, it is not possible to check their reliability. The "record qualities" listed in Table 1 refer to the clearness with which the earthquake was recorded at the stations, and hence, indicate the reliability with which P phases could be identified. Taking into consideration the achievable reading precisions, the confidence in the reliability of clock corrections, and the

legibility of the seismograms, enabled some assessment of the overall quality of the data to be made. The arrival times used to compute the 1936 epicenter are judged to be accurate to within 0.2 seconds at most of the Berkeley and C.I.T. stations, and to within 1 or 2 seconds at most of the other stations for which time corrections are available.

Arrival times at stations for which seismograms are not available and at foreign stations were taken from the ISC and station bulletins. Station locations were taken from Poppe (1979) and from Poppe and others (1978). The 1936 location of the Victoria station (VIC) was supplied by W. Milne, (Victoria Station director).

The 1936 earthquake was relocated using P phases only and the teleseismic location program, MEVENT (Dewey, 1971), together with the Herrin travel time tables for P phases (Herrin and others, 1968). This program, as it was used in this study, is essentially the same as the program, TELES (Bolt, 1961). Additional runs were made using different combinations of stations in order to assess the sensitivity of the solution to possible sources of error. The effects on the reliability of the location of the timing accuracy and reading precision at individual stations and groups of stations were also assessed

and are discussed in a later section. The relocation epicenter of the 1936 earthquake is plotted on Figure 1. Details of the final computer solution are given in Table 6.

Seismograms from all stations in the western United States and Canada that recorded the 1936 earthquake were examined for P- and S-wave data that could be used to constrain a fault plane solution. The results of this examination are shown in Table 7. The direction of P-wave first motion was determined from vertical component records from five stations and from the horizontal component records from VIC and SPO. Because these first motion readings are insufficient to constrain either fault plane of the solution, S-wave data were also used. The ratio of P- to S-wave amplitude at all the stations was determined and used qualitatively. The direction of S-wave first motion was determined at SEA. These data were plotted on a Schmidt equal area projection of the lower focal hemisphere.

In order to determine the angle of incidence of the ray leaving the earthquake focus, the 1936 earthquake was assumed to have occurred in a layer which has a P-wave velocity of 6.05 km/sec (Table 3). P-wave first arrivals at stations at epicentral distances of 12° or less were assumed to be the P_n phase, having a velocity of 8.2 km/sec. These rays, therefore, have an angle

of incidence of 48°. If it is assumed that the earthquake occurred in the basalt, which has a P-wave velocity of 5.15 km/sec (Table 3), then the angle of incidence for the P_n phase would be 39°, and most stations would be moved 10° towards the center of the fault plane solution, which is shown in Figure 4. The seismograms collected for the July 16, 1936 earthquake were also used to review the magnitude assigned to this event (5-3/4 PAS). Seventeen stations, listed in Table 8, were used to derive a revised magnitude based directly on Wood-Anderson records or on seismograms from mechanical type recorders converted to equivalent Wood-Anderson amplitudes. The data set included eleven standard Wood-Anderson equipped stations in the Berkeley and southern California networks. The data were reduced using Richter's nomogram derived for southern California, and incorporate the station corrections derived for the Berkeley network. The average magnitude value obtained from this data set was $M=6.1 \pm 0.2$ from data with a range of $5.5 \leq M \leq 6.4$.

6.0 DISCUSSION OF RESULTS

6.1 April 8, 1979 Earthquake

The hypocentral solution for the April 8, 1979 earthquake computed using the University of Washington "South" velocity model is judged to be good because good timing accuracy can be achieved in measuring arrival times on the records from the Hanford network and because the event was clearly recorded at many, relatively close stations. This location is in agreement with the University of Washington's solution (Malone, 1979). The distribution of stations around the epicenter is not ideal since no arrival times from stations to the east were available for use in the hypocentral solution and coverage to the south and southwest was limited to only two stations, MFW and PEN. Although these two stations, which were relatively close to the epicenter, do contribute accurate data, the use of these data in the hypocentral and focal plane solutions may be subject to some error arising from uncertainty in the shallow crustal velocity structure close to the Blue Mountain Front.

The University of Washington "South" velocity model (Table 3) is intended to be an average representation of the velocity structure of the Columbia Plateau south of latitude 47°N

(Malone, 1977). This model has been found to give good hypocentral solutions for earthquakes occurring in the central part of the area, especially for those that occur in the Pasco Basin. Therefore, the model adequately represents the structure underlying the majority of stations used to relocate the 1979 earthquake; that is, those situated in and close to the Pasco Basin. However, both the earthquake itself and stations MFW and PEN are located towards the southeastern edge of the Plateau. Neither the subsurface geologic structure nor the velocity structure of this area are known.

Lack of knowledge of how the basalts thin towards the edge of the Plateau is of particular relevance to this study. Several alternatives are possible: For example: (1) if the Blue Mountains Front represents the edge of the Pasco Basin, then the basalt here would form a thin layer and the top of the underlying basement would dip relatively steeply to its maximum depth near Pasco; (2) if the basalt layer remains thick well to the southeast of the Front, then a gentle basement dip could exist; or (3) if the basalt remains thick to the south and basining is abrupt, then the basalt could be as thick at the edge of the Blue Mountains as it is near Pasco.

If alternative (1) above is applicable, the shallow velocity

structure near the Blue Mountains Front would consist of a thin basalt layer (velocity 4.5 to 5.2 km/sec) underlain by the basement (velocity 6.05 km/sec). Between Milton-Freewater and Pasco, this structure would have to undergo an abrupt lateral change to the structure given by the "South" model. A further complication to the first alternative is that it is not known whether the average basement velocity (6.05 km/sec) would be appropriate to the first few kilometers of material underlying the basalt, or whether this material consists of slower sediments (Malone, personal communication). If alternative (3) is applicable, then the "South" model may be valid all the way to the Blue Mountains Front.

Even though it is impossible to choose between the above alternatives at present, the approximate effect of possible velocity structures on the hypocentral location and fault plane solution was investigated. This was done by relocating the earthquake using a variety of hypothetical velocity models that could approximate the alternative structures discussed above. The results computed using the "South" model (Table 2), are used as a standard with which to compare the results of the trial runs. The sensitivity of each of the earthquake hypocentral coordinates and of the focal mechanism to variations in velocity structure was assessed and is discussed below.

The most significant effect on the hypocentral location resulting from a change in the velocity model is a change in the focal depth. This is because the focal depth is largely constrained by the closest stations. Therefore, this parameter is not only significantly influenced by a change in crustal structure at the source, but also by changes in the crustal structure at the depth-constraining stations, especially at MFW.

Various hypothetical models were used to compute travel paths to stations MFW and PEN. The "South" model was used for the remaining stations. These trials included, for example, source area models having a single basalt layer ranging in thickness from 1 to 5 km and with velocities from 4.0 to 5.15 km/second overlying the deeper structure given by the "South" model. Other models incorporated up to 3 layers between the surface and the basement at a depth of 4 or 5 km, and had velocities similar to those in the "South" model.

The overall effect of these trials was to drive the hypocenter to shallower depths. In all cases but one, however, the quality of the solution was degraded. In all runs using a thin (1 km) basalt layer, depth control was lost as the focal depth became too shallow, and the program had to constrain the focal depth in order to converge to a solution. The one velocity model that

improves the quality of the solution has a 1.2 km, 4.5 km/sec upper layer overlying a 5.15 km/sec intermediate layer which extends to the 6.05 km/sec basement at 5 km. The focal depth resulting from this model is 1.75 km, and the solution has horizontal and vertical spatial errors of 1.4 and 1.6 km, respectively.

The methods used can only crudely represent the situation described in alternative (1); they probably cannot account for the implied lateral discontinuity in the velocity structure of the uppermost crust as it affects ray paths from a very shallow earthquake to stations in the Pasco Basin. What is of note is the consistently shallow (less than 5 km) focal depth. This is significant because it tends to indicate that the earthquake occurred within the basalt rather than in the underlying basement. In an attempt to further investigate this, relocating the earthquake using the "South" model, but with the focal depth fixed below the assumed basalt/basement interface was examined for its effect on the quality of the solution. The results of these trials are inconclusive. The best solution is obtained using a focal depth of 8 km. However, even though the spatial error estimates are improved to 1.5 km horizontally and 1.4 km vertically, the RMS of the residuals is increased to 0.2 seconds, indicating that this solution is less consistent than the

accepted solution.

The epicentral location shown in Figure 1 is judged to be reliable within the given horizontal error limits (Table 2). No significant migrations of the epicenter resulted from any of the trial runs described above.

In summary, no significant improvement in the quality of the hypocentral location of the April 8, 1979 earthquake, was achieved as a result of using a variety of hypothetical alternative models designed to account for possible changes in the upper crustal structure in the earthquake source area. The epicentral location derived using the regional model is considered to be accurate to within 2 km. The quality of the focal depth determination, as indicated by the vertical error in the solution, also appears to be good. However, the uncertainty of the crustal structure in the source area, and the interplay between this uncertainty and the focal depth of the earthquake in the attempted trial runs, do not allow for a definite conclusion as to whether the earthquake occurred within the basalt or in the basement.

The fault plane solution for the 1979 earthquake, shown in Figure 2 and described in Table 5, was constructed from P-wave

first motion data from 28 local and regional stations. The fit of the solution to the data is good since there are only three inconsistent stations within one of the quadrants. The constraint on the solution, however, is only moderate and is governed by the following features:

(1) The majority of clearly recorded first motions at local stations fall into one dilatational quadrant. There are no data in the opposite dilational quadrant.

(2) Only two close stations (MFW and PEN) recorded compressional first motions. Therefore, constraint on the solution is dependent on less well recorded data from distant stations. The records from very distant stations, such as SES and HHM, had barely readable first motions.

(3) Control to the east is limited to one distant station (MSO). Control to the south is limited to stations MFW and PEN, for which the azimuths and emergence angles are somewhat uncertain, as discussed below.

The chief purpose of the trial relocations discussed above was to investigate the degree of sensitivity of the focal mechanism to uncertainties in the crustal structure in the source area. Because local changes in the source area velocity structure and in earthquake focal depth of the scale conceivable here have, in

general, little effect on the ray paths to more distant stations, the majority of the data points remain essentially unchanged. The effect on raypaths to close stations, such as MFW, PEN, EUK, and WGW, can be considerable. Therefore, because the constraint of the fault plane solution is heavily dependent on the compressions recorded at MFW and PEN and on the weak dilation recorded at EUK, the effects of local structure were investigated in detail.

It was found that the fault plane solutions that resulted from all the trial runs described previously were similar to the solution computed using the standard "South" model (Figure 2). Differences were negligible between the solutions that were computed using velocity models having shallow (1 km) basalt layers and the given solution. Figures (3a) and (3b) show the extreme results of the trials. Although the closer stations migrate appreciably in each of these examples, the solution remains essentially unchanged. The first motion pattern resulting from constraining the focal depth below the basalt/ basement interface also allows a pure strike-slip fault plane solution to be inferred. In all cases, the compressive stress field implied by the focal plane solution was oriented east-west, in contrast to the general north-south direction of compressive stress associated with the western Columbia Plateau and adjacent

Cascades.

6.2 July 16, 1936 Earthquake

The relocated epicenter for the July 16, 1936 earthquake, shown in Figure 1 and described in Table 6, is close to the original epicenter computed by the ISC and USCGS (ISC, 1946). In terms of the standards applicable to teleseismic locations in general, the fit of this solution to the observed data is good, as shown by the relatively small standard error of the travel time residuals (1.75 seconds). The residuals are distributed around a zero mean. However, the location could still be subject to systematic errors.

Major systematic errors could arise from two main sources. The first of these is the inability of the travel time tables used for teleseismic location computations to account for local and regional heterogeneities in the crust and mantle along the path between the earthquake source and the receiving stations. The travel time tables represent the velocity structure of the whole earth in a gross, smoothed manner, whereas the crustal structures through which seismic waves travel to reach different localities may differ considerably. The effect on seismic travel times of crustal heterogeneity is greatest for stations

close to the epicenter because seismic energy travelling to nearby stations is largely confined to the crust and upper mantle. Energy travelling to more distant stations spends a larger portion of its travel time in deeper earth layers which are more adequately represented by the global travel time tables. Because the crustal structure between the epicenter and each of the nearby regional stations is not known in detail, it is difficult to account for the effect of heterogeneities on travel time data from these stations. Therefore, if there are sufficient data, only arrival times from stations at greater epicentral distances (usually beyond 20°) should be used except for those source areas where the local crustal structure is completely known.

It was not possible in this study to use only stations at distances greater than 20° because this would have meant rejecting over 75 percent of the available data, including those of the highest relative accuracy, and losing the constraint on the solution to the south. Therefore, in an attempt to investigate the effect of this potential source of systematic error, the earthquake was relocated using only stations at epicentral distances greater than 9°. The result of this trial was to move the epicenter only 1 minute (2 km) in both latitude and longitude. Therefore, the epicenter does

not appear to be particularly sensitive to systematic mislocation resulting from crustal heterogeneity.

A second possible major source of systematic error can be the distribution of stations around the epicenter. Ideally, stations should be equally distributed, both in azimuth and distance. If one of the four quadrants surrounding the epicenter is empty, the solution will lack control in this direction. In order to minimize the effect of this azimuthal biasing, the location program utilizes an azimuthal rotation of axes and weighting system that attempts to minimize the effects of poor station distribution.

In Table 1, it can be seen that the majority of stations for which seismograms can be read with good precision (better than 0.5 seconds) are concentrated to the south of the epicenter, within the distance range 7° to 14° (Table 6). Stations to the north and northeast are all distant (greater than 70°). Because seismograms have not been obtained from these stations and the accuracy of their timing is not known, it is not possible to assess the quality of the data from them; the earthquake was probably not well recorded at these distances, so the accuracies of the arrival times are probably not good. Stations to the northwest are concentrated within two distance ranges

(3° to 4°, and 15° to 25°). All but SEA had achievable timing precisions of approximately 1 second. There are no stations to the west. The distance distribution of stations to the east and southeast is fairly good, although the arrival time at DEN is grossly inaccurate, as evidenced by the large residual for this station. Estimated achievable reading precisions are approximately 1 second at BZM, FLO and SLM and approximately 0.1 second at TUO.

From the above description of station distribution, it appears that the epicentral solution is moderately well constrained in the northwest-southeast direction because there are approximately the same number of stations in these opposite quadrants at similar distances. Control to the north, northeast and east is judged to be poor. However, good control in the north-south direction is provided by the numerous stations to the south that showed relatively clear arrivals and good timing precision. Therefore, no obvious reason for severe azimuthal biasing is evident. This is supported by examining the azimuthal distribution of travel time residuals, which appears to be random, without clustering of positive or negative residuals at any azimuth. The poorest control on the solution is in the east-west direction, as is reflected in the orientation of the 90 percent confidence ellipse (Table 6).

The sensitivity of the epicentral solution to the azimuthal distribution of stations was investigated by relocating the earthquake using the arrival times at stations selected to give as close to equal azimuthal distribution as possible. In order to minimize the possible effects of crustal heterogeneity, all the stations used were at epicentral distances of approximately 9° or greater. All of the stations selected, except those to the northeast, had achievable reading precisions of 1 second or better. This trial resulted in the epicenter migrating 10 km to the west-southwest, which tends to indicate that the solution is not subject to gross azimuthal biasing. However, because the trial relocation used only nine stations, this conclusion is not definitive.

To estimate the spatial error of the location is difficult. The 90 percent fiducial confidence ellipse (Table 6) provides some indication of the size and orientation of the maximum and minimum errors, but an exact interpretation is difficult (Evernden, 1969). One check on the reliability of the location is provided by the record from Spokane (SPO). This record has very clearly recorded P- and S-wave arrivals, which enabled an accurate S-P time interval to be measured. The S-P interval versus distance relationship for this epicentral azimuth and distance was derived from the measured S-P interval on the

Newport (NEW) record of the April 9, 1979 earthquake, the epicenter for which is relatively accurately located. The epicentral distance to SPO, calculated from the S-P interval, agrees with the distance from the computed epicenter to this station to within 2 km.

Based on the consistency of the epicentral solution, the apparent lack of sources of gross systematic errors, the size of the 90 percent fiducial confidence ellipse, and especially, the good agreement of the SPO epicentral distance calculated from the S-P interval, the computed epicentral location is conservatively estimated to be accurate to within 20 km. The orientation of the maximum spatial error is judged to be east-west. Although the earthquake appears to have occurred at a shallow focal depth of a few kilometers, it is not possible to compute a more exact depth estimate from the available data. The given epicentral solution was computed with the earthquake constrained to the surface. In location runs when the depth was allowed to vary, the program attempted to drive the hypocenter to increasingly shallower depths; this resulted in the focal depth becoming increasingly poorly controlled. In these runs, the program itself constrained the focus to the surface in order to converge to a meaningful solution.

The instrumentally derived epicenter is approximately 30 km north-northeast of the epicenter defined by the area of maximum intensity, 45°58'N, 118°18'W (Neumann, 1938), which has been the accepted location of the 1936 earthquake. This epicenter was deduced from the isoseismal map reproduced in Figure 5; a similar location was implied by a reanalysis of the intensity data (WPPSS, 1974), which resulted in the isoseismal map reproduced in Figure 6. Even if the instrumental epicenter is mislocated by as much as the conservatively estimated maximum error given above, it would still be located north of Walla Walla, and certainly not as far south as Milton-Freewater.

It is not uncommon for an earthquake location that is taken as the center of the zone of maximum intensity to be considerably displaced from the true epicenter that has been reliably located instrumentally (Richter, 1958). This displacement can result from factors other than the closeness of a site to the epicenter that determine the intensity experienced at the site. One of the chief factors affecting site intensity is the nature of the ground surface at the site. Higher intensities are generally experienced at locations underlain by unconsolidated materials than at sites on competent rock. Ground conditions vary considerably from site to site, especially in an area, such as that surrounding Walla Walla, which is intersected by numerous

rivers and streams and their associated unconsolidated fluvial deposits. The shapes and orientations of the isoseismal lines are also influenced by the population distribution within the felt area. The instrumental location may, to some extent, be supported by intensity data. The main-shock maximum intensity was experienced south and southwest of Walla Walla, in the vicinity of Freewater, Umapine, and State Line. The report of the main-shock from Freewater states that about 20 aftershocks were felt the first night. The report from Umapine mentions that 38 aftershocks were felt the first night and that aftershocks continued "for some time" (Neumann, 1938). However, most of the specific reports of individual aftershocks that occurred during the two days immediately following the main shock are from Waitsburg and Walla Walla, and not from the area of maximum intensity. Apart from two isolated reports from Athena, Oregon, on July 15 at 2337 (PST) and July 16 at 0430 (PST), specific aftershock reports from the area of maximum intensity are not mentioned until July 18. No reports from Waitsburg are mentioned after July 16. It is possible that aftershocks were felt so frequently in the area of maximum intensity during the first two days that the investigators did not feel it was worthwhile to detail reports of individual shocks. However, the mention of specific reports from Waitsburg and Walla Walla may be significant in that those aftershocks may have been felt

particularly strongly at those locations. It may also be significant that reports from Waitsburg cease after July 16.

It does appear possible, therefore, that the aftershock pattern in time and space is defining the limits of the rupture zone, with the rupture having been initiated near Waitsburg and extending to the southwest to near the zone of maximum intensity. The apparent migration of aftershocks in a northwest-southeast direction has been noted in a previous report on a detailed intensity study of the 1936 earthquake (WPPSS, 1974). This report also states that "the felt reports indicate that the zones of maximum structural damage during the main shock were also basically aligned along a northeast-southwest trend". A statement in this report that the aftershocks migrated "back and forth" is probably based on reports of earthquakes being felt at Waitsburg on August 4, 1936 and on September 3, 1936 [Waitsburg Times,1936(a), 1936(b)], which are not included in the USCGS compilations. Aftershocks were instrumentally recorded only at SPO but these records are too small to enable S-P intervals to be determined.

It is also perhaps significant that intensity VI was assigned to Waitsburg, although Walla Walla, which was closer to the area of maximum intensity, was assigned intensity V. Selective site

amplification could, as discussed above, explain those effects, but they could also be associated with the initiation and termination of rupture.

Because sparse, generally poor quality data are available to constrain the fault plane solution for the 1936 earthquake, several different approaches were considered. The fault plane solution of an earthquake can be obtained from seismic waves in several independent ways. The simplest method is to use the direction of first motion of P-waves. The next simplest method is to use the direction of first motion, or at least the polarization angles of S-waves. The fault plane solution can also be obtained from the radiation pattern of surface waves. Because the latter method requires the measurement of ground motion amplitudes, it entails a much more detailed analysis than the other two methods, is subject to many sources of error and often does not constrain the solution very well. For this reason, and after examining the recorded data, it was decided to use only body (P and S) waves to determine the fault plane solution for the 1936 earthquake.

The P-wave first motion data listed in Table 7 and shown in Figure 4 are not sufficient to constrain either fault plane. However, S-wave information of two types constrains the solution.

First, at stations in southern California and at Tucson (TUO), the amplitudes of S-waves are very small (no larger than the P-wave amplitudes on horizontal components), indicating that this region is near an S-wave node and a P-wave lobe. Secondly, the direction of first motion of S-waves at Seattle points away from southern California, indicating that Seattle is in the other compressional quadrant. (It is assumed that Seattle is in the same compressional quadrant as neighboring Victoria.)

The fault plane solution shown in Figure 4 was drawn to satisfy these two criteria. The tension axis centered in the compressive quadrant is close to the direction of the southern California station, and the S-wave first motion at Seattle points away from the intersection of the two fault planes. The solution shown is consistent with all of the observations. However, in view of the sparsity of first motion data and the qualitative nature of the S-wave constraints used to obtain the solution, it is not possible to have very high confidence in the solution. The strikes and dips of the planes could be varied by as much as 30° without giving rise to any inconsistency. By choosing to ignore only one first motion observation, a large variation in the solution might be allowed. For example, if the S-wave first motion observation at SEA is ignored, it is then permissible to draw a purely thrust solution with one plane dipping steeply to

the northeast, and the other with a shallow southwestern dip. These considerations notwithstanding, the solution shown in Figure 4 is preferred because it is consistent with all of the observations. The orientation of the north-east striking fault plane for the 1936 earthquake solution is close to that of the same plane for the 1979 earthquake. The sense of motion on the planes agree in each case, with both mechanisms indicating a roughly equal partition between thrust (dip-slip) and strike-slip motion.

The identity of the fault plane of a double-couple mechanism cannot be determined from first motion data. Adequate data do not appear to exist to identify the fault plane from "directivity", that is, the effect of rupture propagation on wave amplitudes. Thus, the identity of the fault plane of the July 16, 1936 earthquake remains unresolved from this analysis.

6.3 Joint Interpretation

The results of the April 8, 1979 and July 16, 1936 earthquake investigations appear to be consistent. Although neither of the results discussed above provide much of a basis for identifying a causative structure for either earthquake, combining the results does allow interpretation of a possible source structure.

This interpretation, however, is based on minimal data and must be regarded as somewhat speculative.

The moderately well constrained solution for the 1979 earthquake (Figure 2) allows either oblique left-lateral, reverse motion on a southwest-dipping fault striking N40°W, or an oblique right lateral, reverse motion on a northwest-dipping fault striking N30°E. The strikes of these fault planes are roughly the same as the strikes of the two major fault systems which intersect to the south of Milton-Freewater; that is, the Wallula fault system striking west-northwest and the Hite fault system striking north-northeast. No choice can be made between these fault planes based on the 1979 earthquake solution alone, because this earthquake was located very close to the intersection of the two fault systems. However, the 1979 and 1936 epicenters are aligned along an azimuth of 34°, which is the same as the strike of one of the fault planes. Therefore, assuming that the relocation of the 1936 earthquake is accurate, it is possible that both earthquakes occurred on the same north-northeast-striking fault. The similarity between the fault plane solutions supports this hypothesis. Also, the possible north to south migration of felt aftershocks that has been discussed above could have occurred on a fault striking in this direction. The instrumental data are insufficient to enable this hypothesis

to be further investigated.

7.0 AUGUST 14, 1969 NORTH POWDER EARTHQUAKE

A magnitude 3.6, August 14, 1969 earthquake occurred in the Powder River Valley, Oregon, approximately 130 km south-southeast of Walla Walla, Washington. Because one of the major fault systems in the area of interest trends roughly north-south, it is possible that this earthquake and those in the Walla Walla area may have occurred on related structures. Therefore, a brief, preliminary evaluation of the location and fault plane solution of the 1969 earthquake was carried out, and the results of this evaluation were briefly compared with those from the 1936 and 1979 earthquake investigations.

The 1969 earthquake had previously been studied by Couch and Whitsett (1969), who located the event at 44°59'N, 117°45'E, at a depth of 32 km. Couch and Whitsett estimated that the mechanism of this earthquake was strike-slip, with right-lateral motion on a northwest-southeast trending fault, or left-lateral motion on a northeast-southwest trending fault, in contrast to the sense of motion obtained from the Walla Walla region.

The earthquake was relocated using the P-wave arrival times

reported by Couch and Whitsett, plus arrival times read from seismograms from a few stations that recorded the event but that were not included by Couch and Whitsett. The program HYPOELLIPSE was used, together with the velocity model used by Couch and Whitsett (1969). The event was also relocated using velocity models based on the University of Washington "South" model.

Poor quality hypocentral solutions were obtained from this reevaluation; all the epicentral locations computed are in approximate agreement with Couch's solution, but the focal depths are much shallower (less than 20 km) and poorly constrained because all but one of the stations used are distant and the majority are concentrated to the north of the epicenter.

Seismograms from all the stations that recorded the event were obtained, but only nine have readable first motions. Of these, six are from stations of the Hanford array which are all at roughly the same azimuth and distance from the epicenter. The fault plane solution for this earthquake is, therefore, effectively constrained by only four data points. The solution agrees with the mechanism suggested by Couch and Whitsett; right-lateral motion on a plane striking approximately N20°W, or left lateral motion on a nearly vertical plane striking roughly N70°E, with the southeast side having a 40° downward direction

of motion to the east-northeast. This solution does not resemble the solution for the April 8, 1979 earthquake. The strikes of the fault planes are significantly different in each case, and the directions of the maximum and minimum stress axes are unrelated.

The results of this preliminary evaluation of the 1969 North Powder earthquake are of limited value because the earthquake was poorly covered by stations to the east, south and west. It is probably that some improvement in the hypocentral solution could be achieved by using the records already collected, by carefully rereading arrival times, and by refining the velocity model used. The focal mechanism, however, does not appear to be particularly sensitive to changes in the velocity model or focal depths and would remain poorly constrained.

8.0 CONCLUSIONS

In gathering together the data, every effort was made to ensure that no source likely to contain useful data was overlooked. Therefore, although the conclusions that can be drawn from the studies are in some aspects not definitive, they are based on a careful evaluation of what is believed to be the most comprehensive data set now available, and probably represent the

limits of reasonable interpretation of those data.

The epicenter computed for the April 8, 1979 earthquake is judged to be reliable to within approximately 2 km; this location is not significantly sensitive to possible variations in the crustal velocity structure near the source or to variations in the focal depth of the earthquake. The focal depth determined using the regional velocity model is also well constrained. The focal depth, however, is moderately sensitive to possible variations in the crustal structure of the source area. Although trial locations using reasonable hypothetical velocity models indicate that the earthquake occurred at a shallow depth, probably at depths less than 10 km and probably within the Columbia River Basalts, the possibility that it occurred in the underlying basement cannot completely be ruled out.

A consistent, moderately well constrained fault plane solution was constructed for the 1979 earthquake, which does not appear to be significantly sensitive to uncertainties in the source crustal structure or to the focal depth of the earthquake. The fault plane solution indicates either reverse faulting with some horizontal, right lateral component of motion on a fault striking N30°E, dipping 68°NW, or predominantly left lateral, strike-slip motion on a fault striking N40°W, dipping 48°NE.

The orientation of the compressive stress field indicated by this solution is east-west, at variance to the north-south axis of compression found in the western Columbia Plateau and Cascades. The orientation of the fault planes agrees with the strikes of the two predominant fault systems in the area (the Wallula and Hite fault systems). The sense of motion expressed by the fault plane solution is consistent with observed geologic observations on the Hite fault system and not with the Wallula system.

The relocated epicenter for the July 16, 1936 earthquake agrees with the original ISC and USCGS instrumental location, near Waitsburg, Washington. The discrepancy between this location and the felt epicenter for the event that has hitherto been generally accepted appears to be real because there is no obvious reason to suspect that the earthquake is mislocated by as much as 30 km in a north-south direction. The fault plane solution for the 1936 earthquake is not well determined. However, these data are consistent and result in a solution that is roughly similar to the 1979 earthquake solution.

If the epicentral location for the 1936 earthquake is assumed to be correct, then the coincidence of the alignment of the epicenters of the two events with the strike of one of the 1979 earthquake fault planes implies that both earthquakes could have

occurred on the same north-northeast-striking fault. The similarity between the fault plane solutions of these two events tends to support this hypothesis. In addition, the intensity data for the 1936 earthquake and its aftershocks support the possibility that this event occurred near Waitsburg, close to the instrumental location, and that rupture extended to the southwest. The interpretation of activity on a N30°E striking fault is attractive in that it combines all of the 1936 and 1979 data in one consistent explanation. However, the possibility that displacement occurred on the alternate fault plane, or on both fault planes, during the 1979 earthquake cannot be discounted especially because the latter earthquake occurred very close to the intersection of two known fault systems, the trends of which are in apparent agreement with the two planes of the fault plane solution.

The results of this investigation indicate that the probable earthquake source structures in the Walla Walla area are the major fault systems that have been identified by surface geological investigations. From the limited seismological data presently available, it is not possible to positively identify either of these systems as the sole active source in the region, or to further investigate the interaction between them. It is felt, however, that the internal consistency of the data on both

earthquakes favors the north-northeast-trending system as the source of both the July 16, 1936 and April 8, 1979 earthquakes.

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TABLE 1

SEISMOGRAPHIC STATIONS USED IN THE
JULY 16, 1936 EARTHQUAKE INVESTIGATION

Station	State/ Country	Code	Seismogram Received	Estimated Achievable Reading Precision (1) (± seconds)	Record Quality (2)	Remarks
Spokane	WA	SPO	X		E	(S-P) = 24.5 sec.
Seattle	WA	SEA	X	10	G	
Victoria	B.C.	VIC	X	1	G	
Bozeman	MT	BZM	X	1	F	
Ferndale	CA	FER	X	1	P	
Ukiah	CA	UKI				
Berkeley	CA	BRK	X	0.2	G	
San Francisco	CA	SFB	X	0.2	F	
Tinemaha	CA	TIN	X	0.1	G	
Lick	CA	MHC	X	0.1	F	
Palo Alto	CA	PAC	X	0.2	F	
Fresno	CA	FRE	X	0.1	F	
Denver	CO	DEN	X		P	No time correction received
Mt. Wilson	CA	MWC	X	0.1	G	
Pasadena	CA	PAS	X	0.1	G	
Riverside	CA	RVR	X	0.1	F	
La Jolla	CA	LJC	X	0.1	F	
Tucson	AZ	TUO	X	0.1	G	
Sitka	AK	SIT	X	1	P	
Florissant	MO	FLO		1		Time correction from O. Nuttli (personal communication)
St. Louis	MO	SLM		1		" " " " "
College	AK	CMO	X	1	P	
Pulkovo	USSR	PUL				Foreign Station
Sverdlosk	USSR	SVE				" "
Dakar	Senegal	DAK				" "
Tiflis	USSR	TIF				" "

Notes:

1. Includes precision with which times can be measured, and quoted or estimated accuracy of time corrections.
2. Clearness of earthquake record:
   E = Excellent F = Fair
   G = Good P = Poor

Woodward-Clyde Consultants

TABLE 2

HYPOCENTRAL LOCATION SOLUTION FOR THE APRIL 8, 1979 EARTHQUAKE

Origin Time (GMT)	07 29 37.82	
Epicenter	45°59.65'N, 118°26.38'W	
Depth	5.1 km	
RMS Standard error	0.11 seconds	
Spatial errors:	Horizontal	2.5 km
	Vertical	2.3 km

STATION	CODE	DISTANCE (km)	AZIMUTH (degrees)	OBSERVED P TRAVEL TIME (seconds)	RESIDUAL (seconds)
Milton-Freewater	MFW	10.5	165	2.24	0.02
Wallula Gap	WGW	38.6	278	7.59	0.10
Eureka	EUK	45.6	348	8.51	- 0.04
Pendleton	PEN	49.3	211	9.07	- 0.05
Eltopia	ELT	70.9	318	12.59	- 0.23
Badger Mtn.	BDG	73.0	291	13.11	- 0.06
Wooded Island	WIW	81.6	307	14.42	- 0.18
Rattlesnake Hills	RSW	99.1	296	17.29	0.04
Othello	OTH	102.1	324	17.76	0.09
Gable Mtn.	GBL	103.3	310	18.16	0.32
Corfu	CRF	117.5	322	19.90	0.08
Midway	MDW	122.9	304	20.94	0.45
Smyrna	SYR	132.4	317	21.75	0.07

TABLE 3

UNIVERSITY OF WASHINGTON "SOUTH" VELOCITY MODEL

P-WAVE VELOCITY (km/sec)	DEPTH TO TOP OF LAYER (km)	LAYER THICKNESS (km)
3.70	0.0	0.8
4.70	0.8	0.4
5.15	1.2	6.3
6.05	7.5	11.5
7.20	19.0	9.0
8.00	28.0	

TABLE 4

STATION DATA FOR THE APRIL 8, 1979
EARTHQUAKE FAULT PLANE SOLUTION

Station	Code	Distance (km)	Azimuth (Degrees)	First Motion[1]
Milton-Freewater	MFW	10.5	165	C
Wallula Gap	WGW	38.6	278	D
Eureka	EUK	45.6	348	-
Pendleton	PEN	49.3	211	C
Eltopia	ETP	70.9	318	D
Badger Mountain	BDG	73.0	291	-
Wooded Island	WIW	81.6	307	D
Rattlesnake Hills	RSW	99.1	298	D
Othello	OTH	102.1	324	D
Gable Mountain	GBL	103.3	310	D
Corfu	CRF	117.5	322	D
Wahluke 2	WA2	121.0	314	+
Warden	WRD	121.2	334	D
Midway	MDW	122.9	304	D
Alder Ridge	ALD	127.7	261	D
Smyrna	SYR	132.4	317	D
Roosevelt	RPK	141.4	259	D
Odessa	ODS	147.8	351	D
Vantage	VTG	160.0	312	-
Davenport	DAV	183.5	5	+
St. Andrews	SAW	203.5	339	+
Wilson Butte	WBW	231.1	347	+
Burke (ID)	BUI	260.9	51	+
Newport	NEW	271.5	22	C
Missoula (MO)	MSO	357.1	73	C
Rexford (MO)	RXF	405.6	38	+
Hungry Hourse (MO)	HHM	424.7	52	+
Suffield (Alberta)	SES	736.2	48	+

Notes:

1. See Figure 2 for explanation of first motion codes.

TABLE 5

APRIL 8, 1979
EARTHQUAKE FAULT PLANE SOLUTION
INTERPRETATION

Type of Faulting: Thrust with strike-slip component

Fault Plane A*:

Strike	N30°E
Dip	68°NW
Sense of motion	Oblique, right lateral, reverse
Motion vector	Hanging wall (west side) moved N50°E, 40° up

Fault Plane B*:

Strike	N40°W
Dip	48°NE
Sense of motion	Left lateral, reverse
Motion vector	Hanging wall (northeast side) moved N60°W, 20° up

Compressional Axis:

Orientation	East-west (N91°W)
Incliniation	11°

Tension Axis:

Orientation	North-south (N166°E)
Inclination	48°

*NOTE: See Figure 2

TABLE 6

RESULTS OF THE RELOCATION OF THE JULY 16, 1936 EARTHQUAKE

Origin time (GMT)	07 07 49		
Original Epicenter (ISC)	46°12'N, 118°12'W		
Relocated Epicenter	46°12.5'N, 118°14.0'W		
Depth	Shallow		
Residual Standard Error	1.75 seconds		
90% Confidence ellipse:	Semi-major axis	N89°E,	16 km
	Semi-minor axis	N179°E,	11 km

STATION CODE	DISTANCE (Degrees)	AZIMUTH (Degrees)	OBSERVED P TRAVEL TIME (min)	(sec)	RESIDUAL (seconds)
SEA	3.1	299	0	42	- 8.5
VIC	4.1	304	1	3	- 0.6
BZM	5.1	94		17	0.3
FER	7.1	220		55	9.9
UKI	8.0	209		59	2.6
BRK	8.9	201	2	7.2	- 1.4
SFB	9.0	202		8.3	- 2.2
TIN	9.2	180		10.9	- 1.7
MHC	9.2	197		13.6	0.0
PAC	9.3	200		14.3	0.1
FRE	9.5	188		20.3	2.4
DEN	11.6	119		22	- 23.9
MWC	12.0	179		51.2	0.3
PAS	12.1	180		51.7	- 0.2
RVR	12.2	177		53.5	- 0.8
LJC	13.4	176	3	10.5	1.0
TUO	15.1	155		33.0	0.6
SIT	15.1	322		32	- 0.9
FLO	21.8	100	4	53	0.6
SLM	21.9	100		54	- 0.2
CMO	24.7	330	5	24	2.5
PUL	71.3	16	11	23	2.9
SVE	77.4	1	11	54	- 1.4
DAK	86.9	72	12	42	- 3.9
TIF	91.2	13	14	12	66.2

TABLE 7

STATION DATA FOR THE JULY 16, 1936
EARTHQUAKE FAULT PLANE SOLUTION

Code	Distance (Degrees)	Azimuth (Degrees)	First Motion	S/P Amplitude Ratio (Horizontal Components)
SPO	2.2	25	P:C	large
SEA	3.1	299	S:N40°W	"
VIC	4.1	304	P:C	"
BZM	5.1	94		"
FER	7.1	220		"
BRK	8.9	201		"
TIN	9.2	180	P:C	"
DEN	11.6	119		"
MWC	12.0	179	P:C	unity
PAS	12.1	180	P:C	"
RVR	12.2	177	P:C	"
TUO	15.1	155	P:C	"
SIT	15.1	322		large
CMO	24.7	330		"

Explanation:

P: P (compressional) wave

S: S (shear) wave

C: Compressional first arrival

TABLE 8

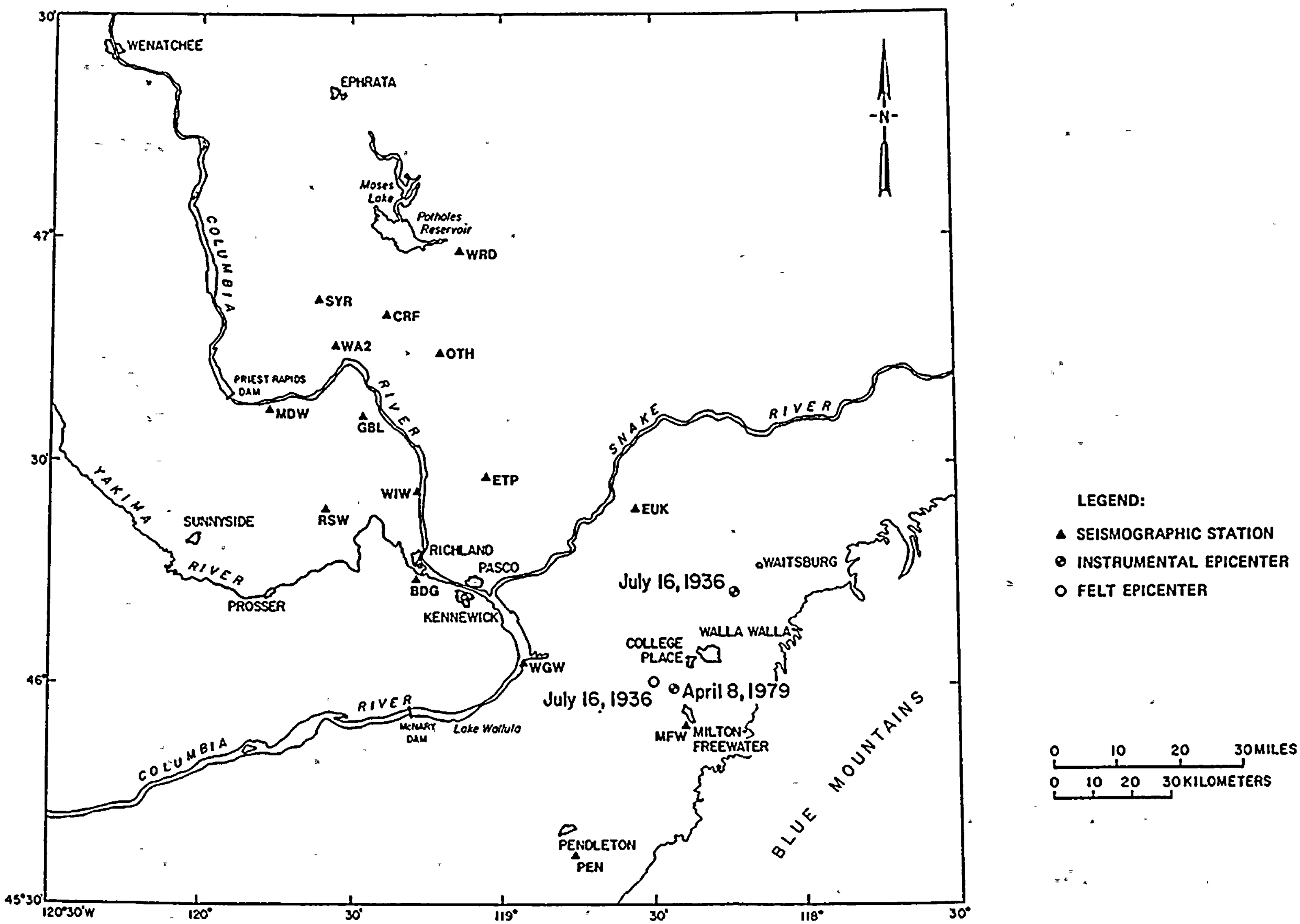
MAGNITUDE DATA - JULY 16, 1936 EARTHQUAKE

Station Code	Distance (Degrees)	Seismometer	Component	Record Amplitude (mm)	Period (sec)	Magni-fication	Free Period (sec)	Damping (ε)	Equivalent Wood-Anderson Amplitude (mm)	Magnitude
SEA	3.1	Bosch-Onori	E	19.0	10.0		15			5.1*
			N	32.5	6.8		15			
BZM	5.1	McComb-Romberg	E	9.5	5.3	81	12	3-10	7.7	(5.8)
			N	17.0	7.5	84	12	3-10	6.5	
FER	7.1	Bosch-Osori	E	10.2	10.0	37	(12)	(4)	5.3	(6.0)
			N	3.0	7.6	37	(12)	(4)	2.7	
BRK	9.0	Wood Anderson	E	1.25	7.0					6.0
			N	1.25	4.3					
		Bosch-Onori	E	0.75	8.8	(53)	12		0.33	(5.5)
			N	1.05	8.0	(52)	12		0.57	
SFB	9.0	Wood Anderson	N	1.2	8.0					6.1
MHC	9.0	Wood Anderson	E	2.0	4.0					6.1
			N	2.5	3.6					
PAC	9.1	Wood Anderson	E	3.0	6.0					6.1
			N	3.45	6.8					
TIN	9.2	Wood Anderson	E	3.5	2.1					6.4
			N	6.0	3.0					
FRE	9.5	Wood Anderson		4.0	2.5					6.3
MWC	12.0	Wood Anderson	E	1.8	7.5					6.1
			N	0.7	3.0					
PAS	12.1	Wood Anderson	E	1.5	6.0					6.2
			N	1.0	6.0					
SBC	12.2	Wood Anderson	E	1.3	3.0					6.1
			N	0.95	2.8					
RVR	12.2	Wood Anderson	E	1.15	6.5					6.2
			N	2.0	6.6					
LJC	13.4	Wood Anderson	E	1.75	3.3					6.4
			N	1.6	3.0					
SIT	15.1	Wenner	E	19.0	10.0	780	7.0		0.43	5.8
			N	12.5	10.0	780	7.0		0.28	
TUO	15.1	Wood Anderson	E	10.75	14.0	200	10.0	30	0.49	6.1
			N	7.5	8.0	370	10.5	30	0.57	
CHO	24.2	McComb-Romberg	E	3.0	12.0		12.0	10	0.33	6.2
			N	3.15	12.0		12.0	10	0.35	

$\overline{M} = \overline{6.1 \pm 0.2}$

Note: (   ) indicates a degree of uncertainty due to conflicting information from separate sources, or due to a range rather than a specific value having been given. In the latter case, a mid-range value was used.

*Based on standard instrument constants. Magnitude value not used in average.



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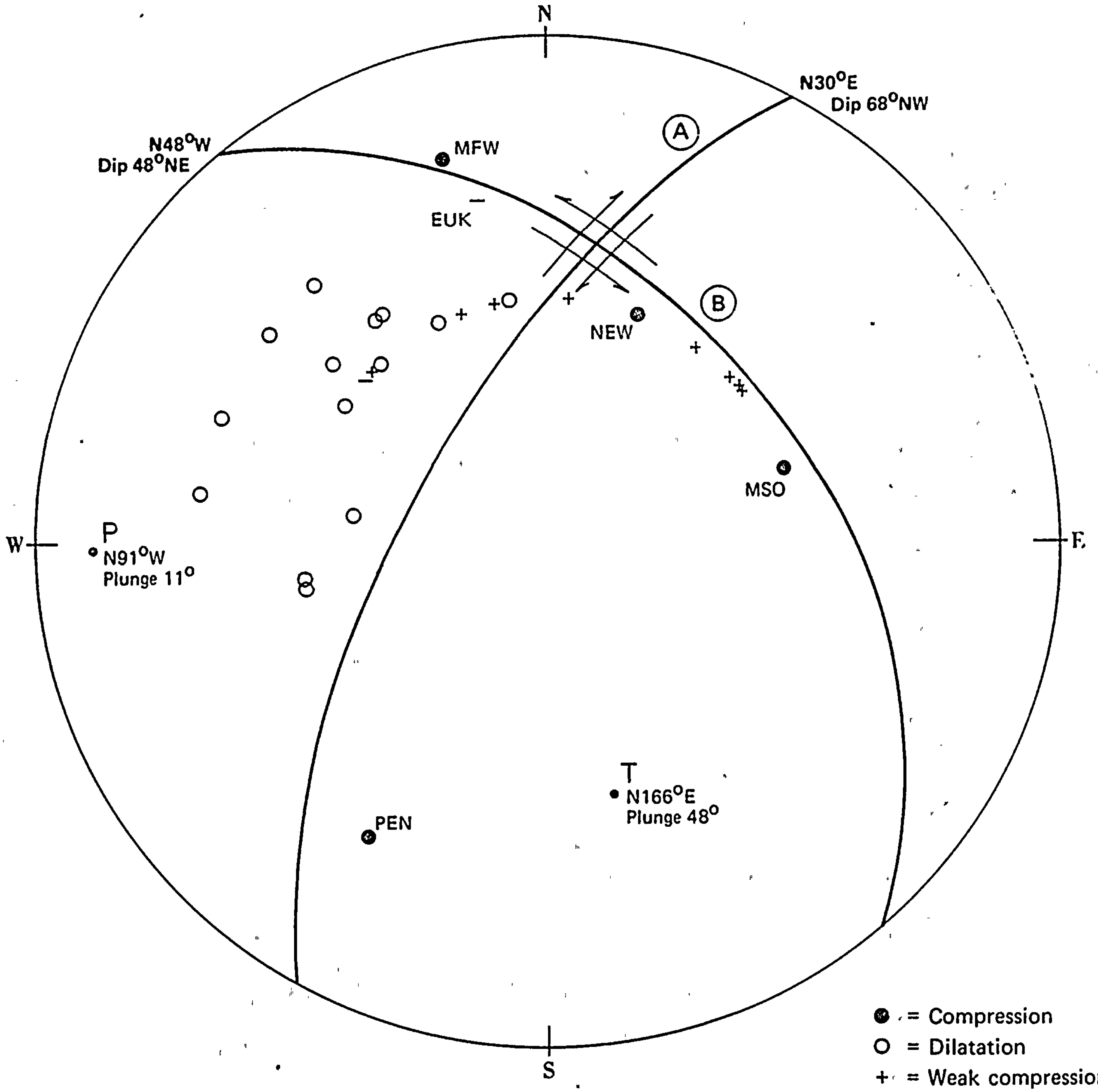
Project No. 13891C

WASHINGTON PUBLIC POWER SUPPLY SYSTEM

MAP OF THE SOUTHERN COLUMBIA PLATEAU SHOWING SEISMOGRAPHIC STATIONS AND EARTHQUAKE EPICENTERS

Figure 1



● = Compression
○ = Dilatation
+ = Weak compression
− = Weak dilatation
P = Compression axis
T = Tension axis
A = Fault Plane

VELOCITY MODEL:
University of Washington "South" model

LOWER HEMISPHERE EQUAL AREA PROJECTION

Project No. 13891C	WASHINGTON PUBLIC POWER SUPPLY SYSTEM	FAULT PLANE SOLUTION FOR THE APRIL 8, 1979 EARTHQUAKE	Figure 2
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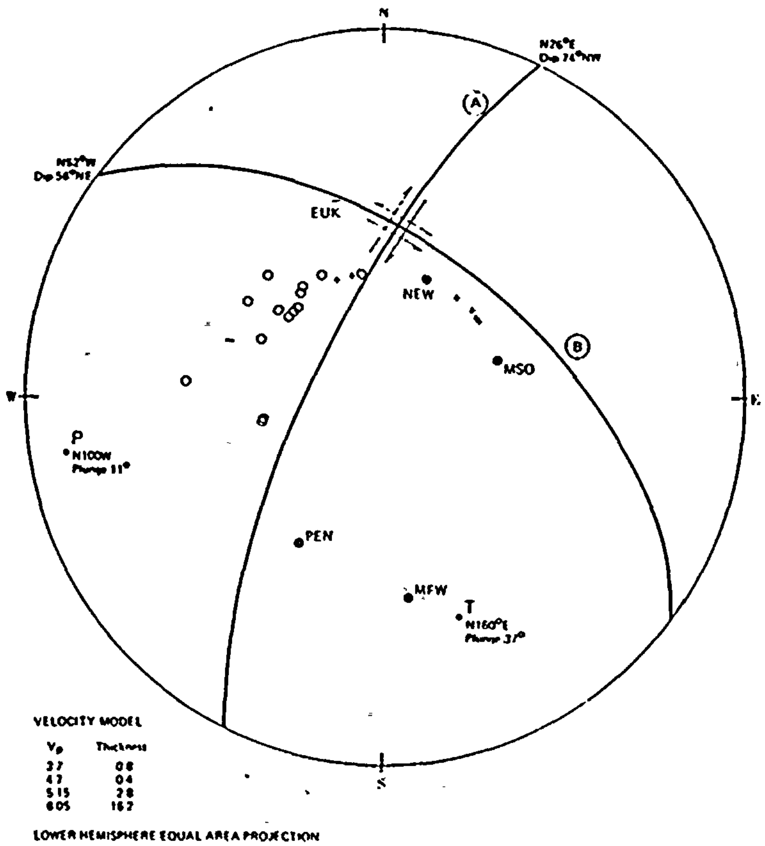

Figure 3a

FAULT PLANE SOLUTION FOR THE APRIL 8, 1979
EARTHQUAKE USING ALTERNATIVE VELOCITY MODEL

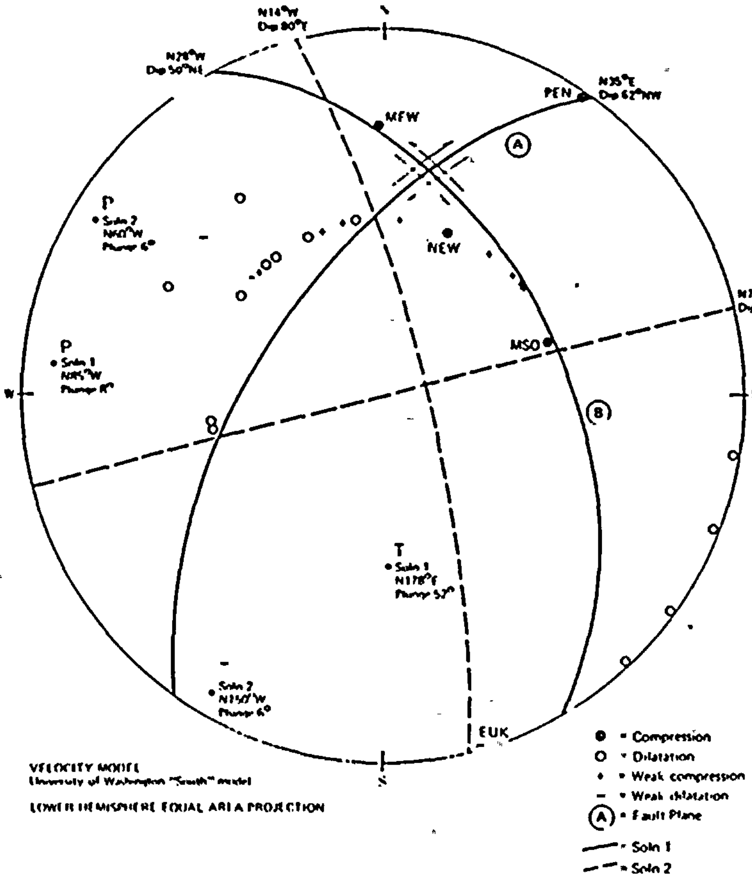

Figure 3b

FAULT PLANE SOLUTION FOR THE APRIL 8, 1979 EARTHQUAKE
WITH FOCAL DEPTH CONSTRAINED AT 8 KILOMETERS

Project No. 13891C

WASHINGTON PUBLIC POWER SUPPLY SYSTEM

FAULT PLANE SOLUTIONS FOR THE APRIL 18, 1979 EARTHQUAKE (3a) USING ALTERNATIVE VELOCITY MODEL AND (3b) WITH FOCAL DEPTH CONSTRAINED AT 8 KILOMETERS

Figures 3a and 3b

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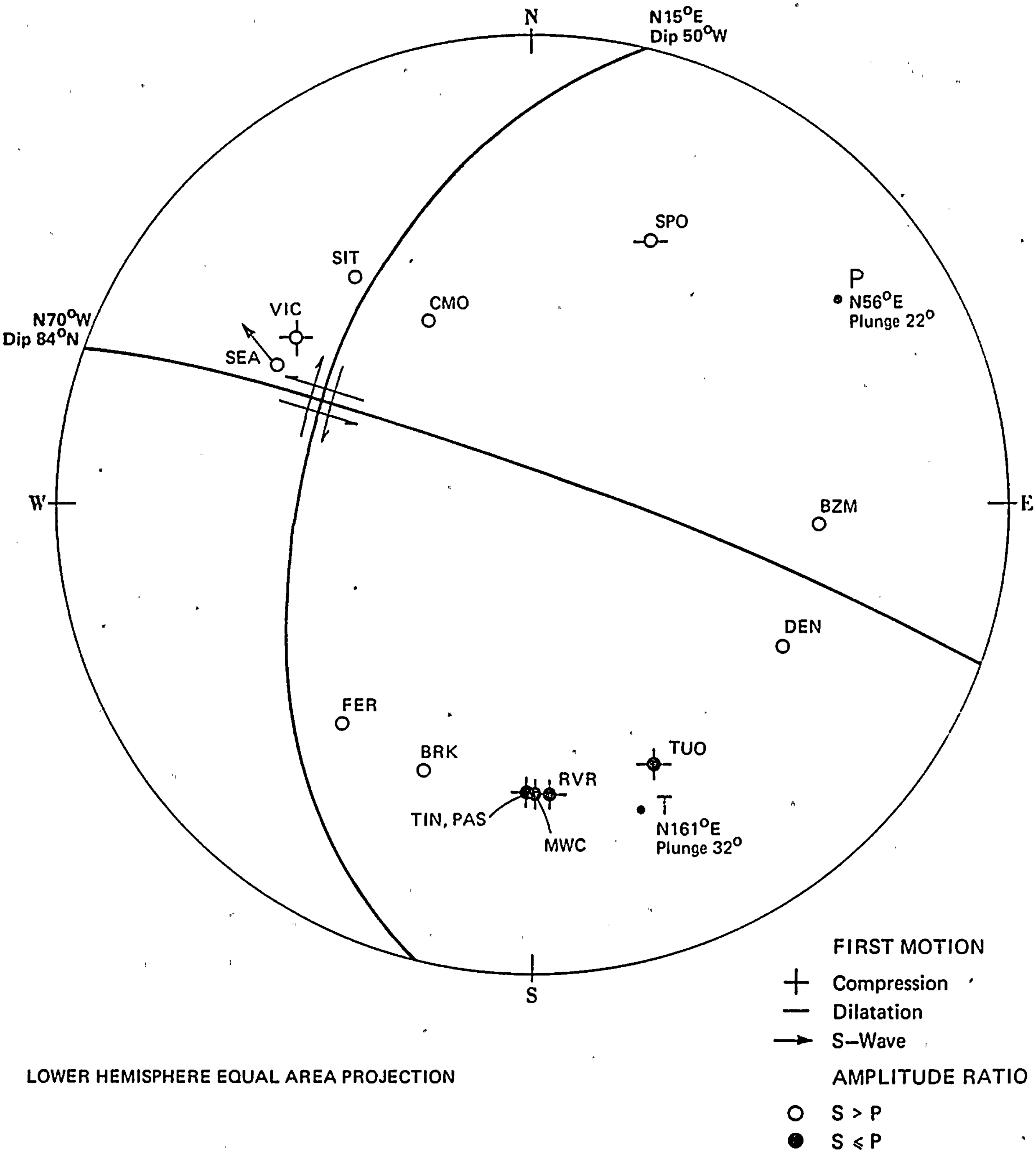

LOWER HEMISPHERE EQUAL AREA PROJECTION

Project No. 13891C	WASHINGTON PUBLIC POWER SUPPLY SYSTEM	FAULT PLANE SOLUTION FOR THE JULY 16, 1936 EARTHQUAKE	Figure 4
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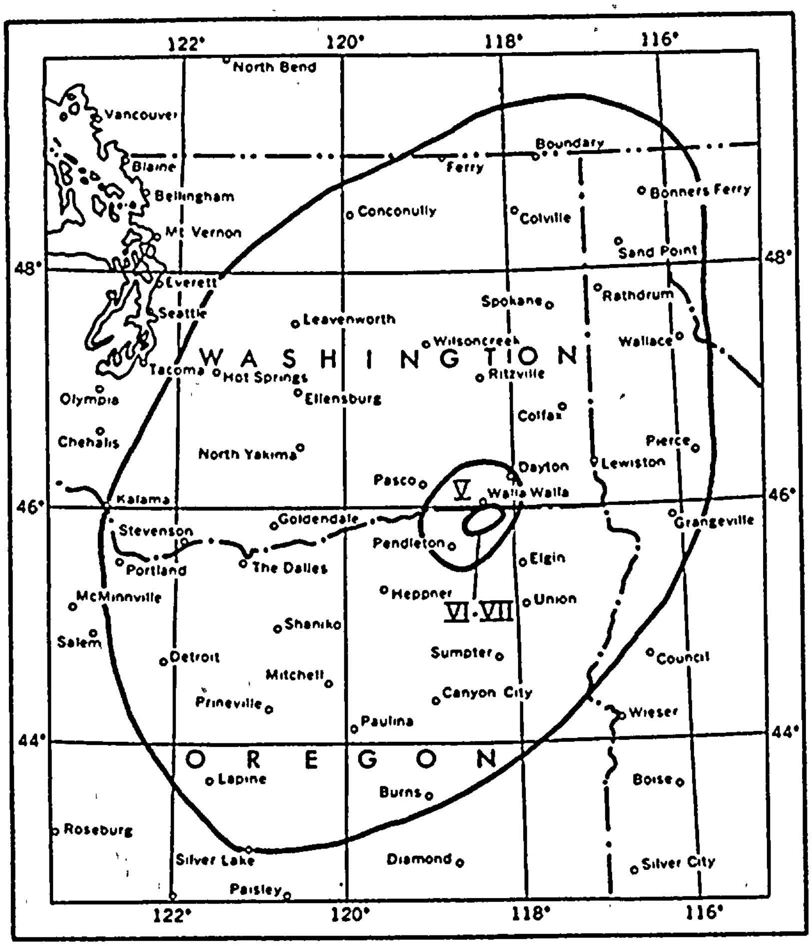

From Neumann (1938), Figure 6.

Project No. 13891C	WASHINGTON PUBLIC POWER SUPPLY SYSTEM	ORIGINAL ISOSEISMAL MAP FOR THE JULY 16, 1936 EARTHQUAKE	Figure 5
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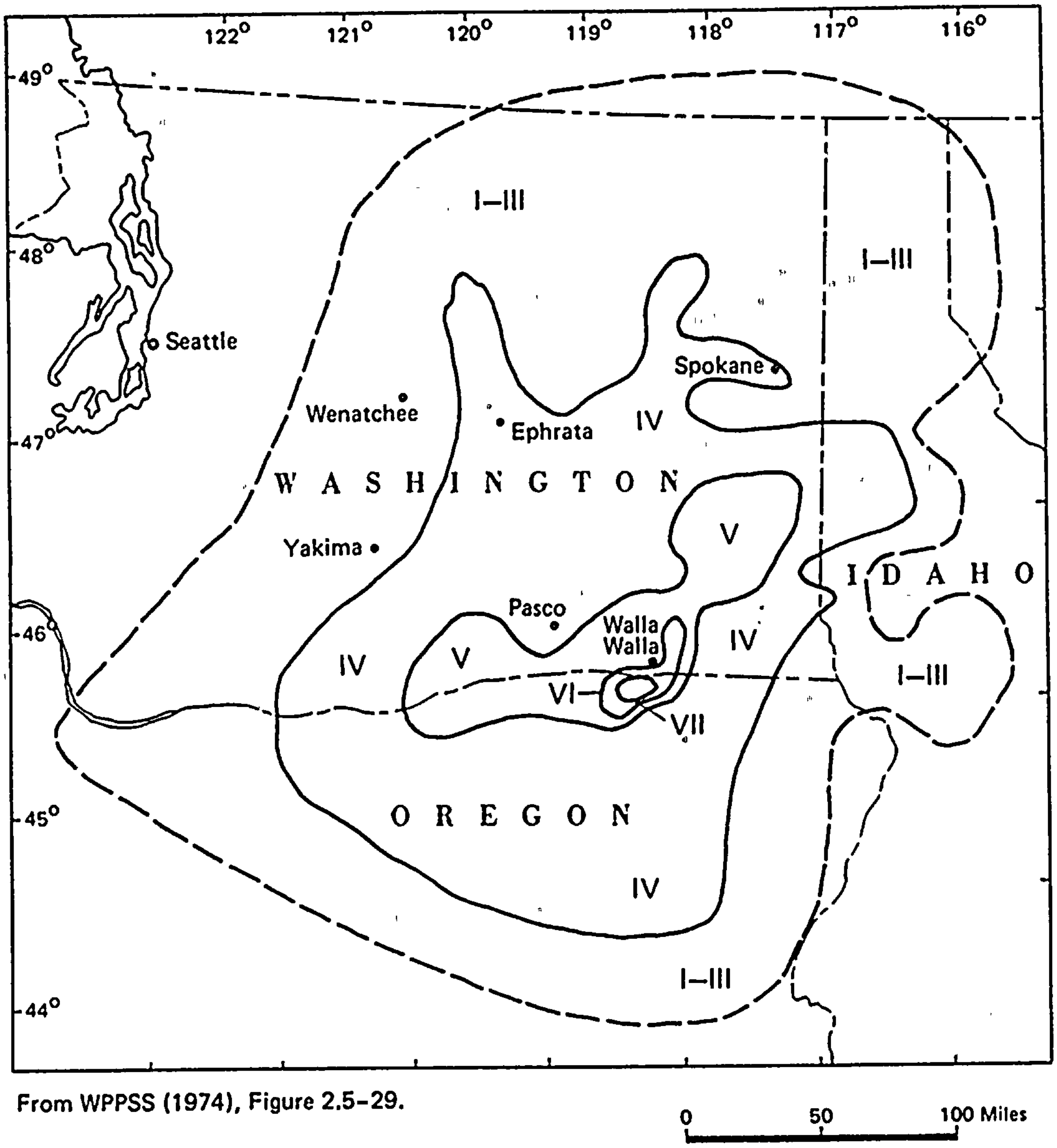

From WPPSS (1974), Figure 2.5-29.

Project No. 13891C	WASHINGTON PUBLIC POWER SUPPLY SYSTEM	ISOSEISMAL MAP FOR THE JULY 16, 1936 EARTHQUAKE, BASED ON REANALYSIS OF INTENSITY DATA	Figure 6
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