# ANNUAL TECHNICAL REPORT 1983

## on

# Earthquake Monitoring of Eastern and Southern Washington

September 1983

Geophysics Program

University of Washington

Seattle, Washington



PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. EY-76-S-06-2225
TASK AGREEMENT NO. 39

and

THE U.S. NUCLEAR REGULATORY AGENCY
UNDER CONTRACT NO. NRC-04-81-177

# TABLE OF CONTENTS



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# INTRODUCTION AND OPERATIONS

## Introduction

This report covers the operations and research performed for D.O.E. and the N.R.C. by the University of Washington Geophysics Program on the seismicity and structure of eastern and southern Washington and northern Oregon during the past year. These contracts help support parts of the Washington state regional seismograph network. There are presently 107 stations in Washington and northern Oregon whose data are telemetered to the University for recording, analysis and interpretation. The Department of Energy supports the stations on the east flank of the Cascades and eastern Washington. The Nuclear Regulatory Commission partly supports stations in southern Washington and northern Oregon. Other major parts of the network are supported by the U.S. Geological Survey.

Section I of this report covers the details of the operation of the network in eastern and southern Washington and northern Oregon. Details of the past year's seismicity is covered in section II. The only seismicity of note during the past year was a M=3.8 felt earthquake in southeastern Washington. Section III covers our recent crustal structure work in eastern Washington. It involves a time term analysis of the shallow crustal structure in and around the Pasco Basin. Section IV summarizes research using the borehole seismometer and gives a brief summary of theories dealing with the effects of cracks and pores on seismic velocities and attenuation and a list of all pertinent publications from 1950 to the present. In the appendices are the earthquake catalog for 1982-1983 and a monthly listing of the station 'up-times' for the eastern Washington network.

**Network Operations**

As of late August, 1983, the University of Washington's seismic telemetry network included 107 stations, 104 of which are operated by the University(see figure I-1). This total includes 32 stations in eastern Washington, 52 stations in Washington west of the Cascade crest, and 20 stations in the northern third of Oregon. Support for stations in eastern Washington is principally derived from the Department of Energy (DOE), while western Washington stations are chiefly funded by the U. S. Geological Survey under two different grants. Operations in northern Oregon are mainly supported by the Nuclear Regulatory Commission (NRC), but both the USGS and DOE contribute. There have been major changes in network configuration, equipment, and mode of telemetry during the past year, particularly insofar as the eastern Washington and northern Oregon stations have been concerned. While most of the changes have been prompted by financial crises of one sort or another, we believe we have made modest improvements in both operational efficiency and data quality. Table I-1 is a list of stations in the eastern and southern Washington and eastern Oregon network.

The most significant change in the network has been the assumption of responsibility for operation of all of the USGS stations in Oregon north of 44.5° north latitude. Due to severe budget cuts in the Volcanic Hazards Program, the USGS could no longer meet the costs of telemetering these stations to Menlo Park. However, capacity remained for ten channels on Seattle-bound data links originating at Augspurger Mountain and Vancouver, Washington, and these mixer sites were within radio range of seven USGS stations. Arrangements for site visits for maintenance and re-orientation of antennas could not be completed before snowfall rendered most of the stations inaccessible in late 1982, so only VGT and VGB were operational at all during the winter. Late snow melt in 1983 delayed field work, but by early August seven of the sites were being received.

Nearly all of these sites have required replacement of defective J402 amp/VCO units.

The UW-installed Oregon stations did somewhat better than the USGS net during the year, but there were some lengthy outages. Only one station (TDH) of the Mt. Hood network remained in reliable operation throughout the winter. Although the overall data loss in northwest Oregon was very high, we are optimistic that the coming winter will show considerable improvement. An improved funding situation would allow more field maintenance and installation of better-quality equipment (no funds for the operation of the additional Oregon stations have been received to date).

In the eastern Washington network, the desire to reduce overall operational costs led us to close three particularly high-cost phone drop stations (GLD, WTP, and DAV) and replace phone drops at several other sites with radio links. The three closed stations will eventually be replaced by radio-linked stations in the same general areas. The radio links have proven to be about as reliable as the phone drops were, and have the advantage of allowing us to exert more control over relative line levels. Overall, telemetry costs have been reduced by about 20-25%.

At the same time that radio links were being installed, a number of new amp/VCO units of the S. T. Morrissey design were deployed. Relatively little trouble has been experienced with the new units (a few failures have now occurred) and the timely installation of these units has given the technical staff and the Stanwick sub-contractors much-needed "breathing space" to concentrate on other problems. An added benefit is the improvement in data quality, as was discussed in last year's annual report. We hope to continue the program of switching to radio links and installing new VCOs in the coming years.

In addition to the replacement of a number of older amp/VCO units, a number of other measures have been taken to improve the quality of the data transmitted from the field stations. Mr. James Ramey of our staff designed a low-power, low-cost filter unit which quiets line noise generated by unsquelched receivers. It can also be used to suppress crosstalk due to excessive VCO center frequency drift. Other applications have included tapping off selected subcarrier frequencies from mixed lines which included unwanted subcarriers, and pre-filtering and conditioning a particular subcarrier for input into a discriminator. The latter application is particularly useful in reducing electronic noise present in the output of several cheap discriminators such as the USGS J101 and J110 units. The filters are of variable center frequency, thus allowing the use of a unit of common design and construction in a variety of situations.

Other contributions by the electronics shop personnel have been directed toward improving the working quality and reliability of the Develco 6202 amp/VCO units which remain in the field. It has become difficult to repair cards from these units since some of the components have been replaced by IC's. A single IC-replacement pre-amp card was designed and is produced in-house whenever additional pre-amp cards are required.

Battery life of 6202 stations has been extended by implementation of a voltage-converter/regulator card which is considerably more efficient than the external units previously in use. It should now be possible to operate a 6202-transmitter site for two years on a single set of 5 air cells -- an improvement of nearly 100%. Phone-drop sites should now average 3 to 4 years on a pair of air cells, as long as no receivers or summing amplifiers are required.

We have been operating a Rex Allen online P-picker since 1981. This monitoring system has the capability to pick earthquake P-wave arrivals from our network stations and obtain a preliminary location within three minutes of the event. We now have the output of the P-picker directed into the PDP-11/70 where its data is analyzed to determine if an earthquake with damage potential has occurred. If the event is large enough the 11/70 will notify any seismologists logged in that a big earthquake has occurred and will call a seismologist at home. This seismic "alarm" system has been triggered 11 times this year by earthquakes of possible interest. None of these events were large enough to cause damage but these triggers are good tests of the system.

Beginning in February, 1983 the P-picker software was changed to perform station operations diagnostics once every six hours as well as locating earthquakes. The P-picker takes 300 second averages of bias and noise level for every station 4 time a day and reports these values to the 11/70. Thresholds for proper station operation have been determined for these reports such that we can tell when a station is not functioning properly. If the bias is too far from zero it can indicate either no subcarrier for that station or a badly drifted VCO. If the noise level is either too small or too large it can indicate a dead seismometer or a dead telemetry link. Of course, some stations will look bad based on these criteria some time since it is possible that it might have a temporary seismic noise which occurs just when the P-picker is sampling each six hours. We feel that, on the average, it gives a fairly representative indication of station operation and has allowed us to spot troubles earlier than was the case without it. It also gives us a good record of operations. In appendix II we show plots of the P-picker determined station operation "up-time". This should be considered a worst case approximation since the thresholds are set to more likely call good stations bad than the other way around.

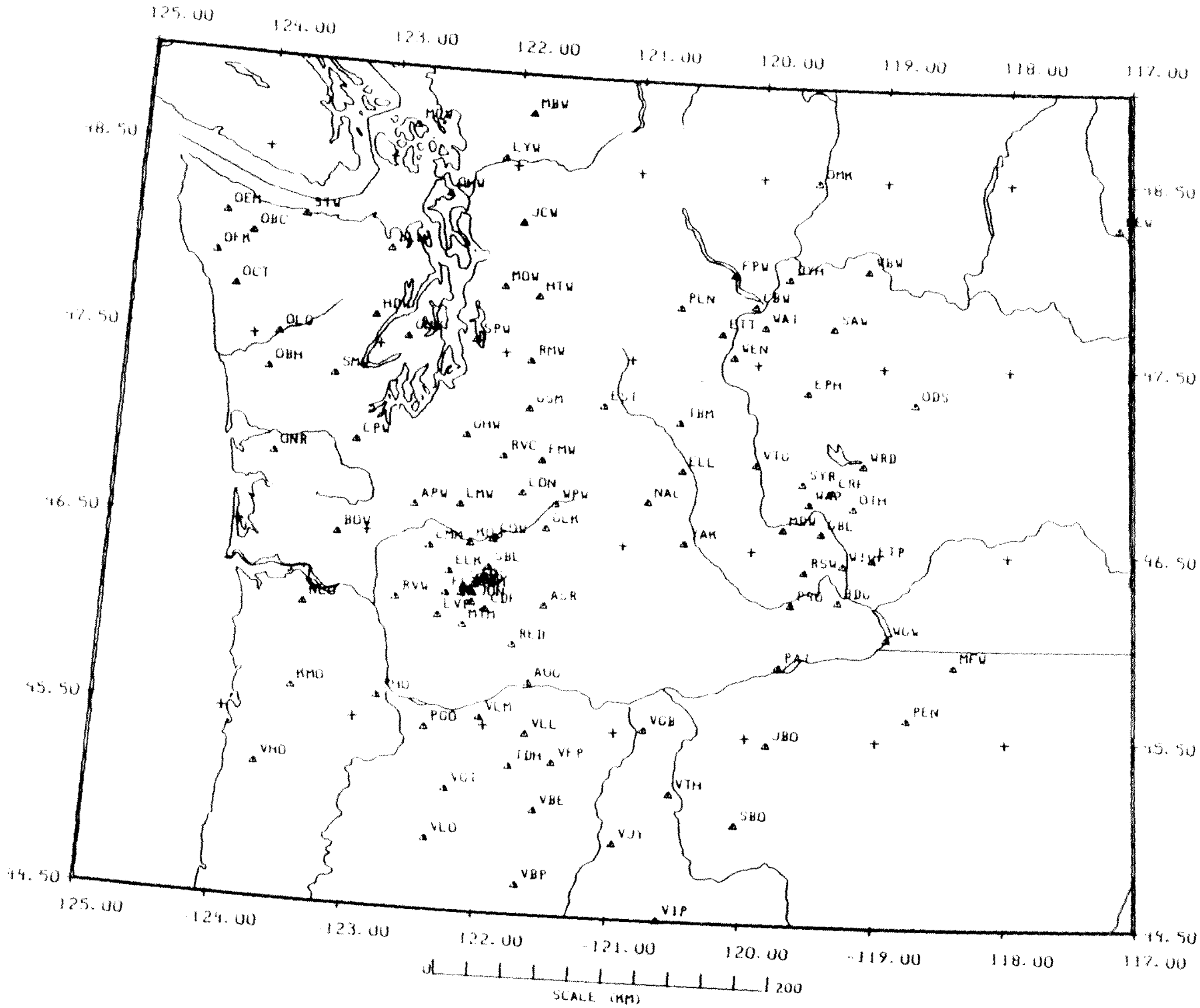


Figure I-1. Currently operating seismograph stations in the Washington regional seismograph network.

TABLE I-1 D.O.E. - N.R.C - U.S.G.S. SUPPORTED SEISMIC STATIONS

| STA | LAT | LONG | TIME | NAME |
|---|---|---|---|---|
| AUG | 45 44.17 | 121 40.83 | 10/81 | Augsburger Mt. |
| BDG | 46 14.08 | 119 19.05 | 7/75- | Badger |
| CBW | 47 48.42 | 120 01.960 | 7/75- | Chelan B |
| CRF | 46 49.51 | 119 23.09 | 7/75- | Corfu |
| DYH | 47 57.63 | 119 46.16 | 7/75- | Dyer Hill |
| ELL | 46 54.58 | 120 34.10 | 7/79- | Ellensburg |
| EPH | 47 21.13 | 119 35.77 | 7/75- | Ephrata |
| EST | 47 14.28 | 121 12.53 | 7/79- | Easton |
| ETP | 46 27.89 | 119 03.54 | 7/75- | Eltopia |
| ETT | 47 39.30 | 120 17.60 | 6/77- | Entiat |
| FPW | 47 58.00 | 120 12.77 | 7/75- | Fields Pt. |
| GBL | 46 35.86 | 119 27.59 | 7/75- | Gable |
| JBO | 45 27.00 | 119 51.00 | 9/82- | Jordan Butte |
| KMO | 45 39.00 | 123 27.00 | 9/82- | Kings Mt. |
| MDW | 46 36.80 | 119 45.65 | 7/75- | Midway |
| MFW | 45 54.18 | 118 24.35 | 7/75- | Milton-Free. |
| NAC | 46 43.98 | 120 49.47 | 8/79- | Naches |
| NEW | 48 15.83 | 117 07.22 | /77- | (USGS) |
| NLO | 46 05.30 | 123 27.00 | 10/81 | Nicolei Mt. |
| ODS | 47 18.40 | 118 44.70 | 7/75- | Odessa |
| OMK | 48 28.82 | 119 33.65 | 7/75- | Omak |
| OTH | 46 44.34 | 119 12.99 | 7/75- | Othelo |
| PAT | 45 52.85 | 119 45.68 | 6/81- | Paterson |
| PEN | 45 36.72 | 118 45.78 | 7/75- | Pendleton |
| PGO | 45 28.00 | 122 27.17 | 6/82- | Gresham, Or. |
| PHO | 45 37.14 | 122 49.80 | 4/82- | Portland Hills |
| PLN | 47 47.08 | 120 37.97 | 6/77- | Plain |
| PRO | 46 12.76 | 119 41.15 | 7/75- | Prosser |
| RSW | 46 23.47 | 119 35.32 | 7/75- | Rattlesnake |
| SAW | 47 42.10 | 119 24.06 | 7/75- | St. Andrews |
| SBO | 45 02.00 | 120 06.00 | 9/82- | Squaw Butte |
| SYR | 46 51.78 | 119 37.07 | 7/75- | Smyrna |
| TBM | 47 10.17 | 120 31.00 | 7/79- | Table Mt. |
| TDH | 45 17.39 | 121 47.26 | 9/82- | Tom,Dick,Harry |
| VBE | 45 3.62 | 121 35.21 | 10/79- | Beaver Butte |
| VBP | 44 39.63 | 121 41.34 | 10/79- | Bald Peter |
| VFP | 45 19.08 | 121 27.91 | 10/80- | Flag Point |
| VGB | 45 30.94 | 120 46.65 | 4/80- | Gordon Butte |
| VGT | 45 8.09 | 122 15.92 | 4/80- | Goat Mt. |
| VIP | 45 13.15 | 120 37.13 | 12/79- | Ingram Pt. |
| VJY | 44 54.13 | 120 58.45 | 3/80- | Jersey |
| VLL | 45 27.80 | 121 40.75 | 10/80- | Laurance Lk. |
| VLM | 45 32.31 | 122 2.35 | 6/80- | Little Larch |
| VLO | 44 52.77 | 122 23.58 | 6/80- | Lookout Mt. |
| VTG | 46 57.48 | 119 59.24 | 7/75- | Vantage |
| VTH | 45 10.87 | 120 33.68 | 3/80- | The Trough |
| WA2 | 46 45.40 | 119 33.76 | 5/78- | Wahluke2 |
| WAT | 47 41.92 | 119 57.25 | 11/76- | Waterville |
| WBW | 48 1.07 | 119 08.23 | 7/75- | Wilson B |
| WEN | 47 31.77 | 120 11.65 | 7/75- | Wenachee |
| WGW | 46 2.68 | 118 55.96 | 7/75- | Wallula Gap |
| WIW | 46 25.93 | 119 17.29 | 7/75- | Wooded Is. |
| WRD | 46 58.19 | 119 08.60 | 7/75- | Warden |
| YAK | 46 31.73 | 120 31.22 | 7/79- | Yakama |

# SEISMICITY 1982 - 1983

## Introduction

During the period 1 July 1982 through 30 June 1983, the level of seismicity in Washington state and northern Oregon has remained at similar level compared to the previous year. No significant earthquakes occurred in Washington state or Northern Oregon. The largest magnitude earthquake was a magnitude 3.8 earthquake which occurred in southeastern Washington and was felt in the Walla Walla area.

## Data

1554 events located in the state of Washington and northern Oregon have been processed for the time period discussed in this report. The digital method of recording and processing the seismic data on- and off- line has kept up with activity levels during this period. Activity levels in the state of Washington this period have remained at levels comparable to last year. During the past year, only 8 earthquakes of magnitude 3.0 or greater have been recorded in the state. The largest earthquake was a M=3.8 which occurred in southeastern Washington and will be discussed in detail later in this report. Twelve felt events occurred in the state of Washington and northern Oregon.

## Eastern Washington and Northern Oregon

During the period 1 July 1982 through 30 June 1983, 451 events which occurred in Eastern Washington and Northern Oregon were processed. Of these 157 were known or probable blasts. Figure II-1 and II-2 show the known and probable blasts in Eastern Washington and Northern Oregon, respectively. The remaining 294 events were earthquakes, of which 30 were hand-picked because the on-line computer system did not record them. Figure II-3 and II-4 show the epicenters of earthquakes in Eastern Washington and Northern Oregon, respectively. Appendix I is the event catalog for this period. It may show changes from the preliminary catalogs published in the quarterly technical reports because errors have been found and corrected in the interim.

The earthquake of most interest in eastern Washington during the report period was a M=3.8 earthquake which occurred near Walla Walla on 22 March at 12:47 GMT. The event was felt in Walla Walla, Milton-Freewater and Helix,Oregon(NEIS). No damage was reported to have resulted from this earthquake. No aftershocks were detected in the hours or days following the earthquake, however a magnitude 2.6 occurred in the same area on 13 April, 1983 at 1638 GMT. These earthquakes occurred in the same area as the M=5.8 1936 Milton Freewater earthquake. The last felt event in this area was a M=4.2 in 1979. The 1979 and 1983 earthquakes are similar in their lack of associated seismicity. Neither earthquake had any detected foreshock or aftershock activity associated with it.

A focal mechanism solution for this event is shown in figure II-5. First motions were used from stations in Idaho(CPI, WPI, and PID) in addition to data from the Washington state net to calculate the focal mechanism. Takeoff angles were calculated assuming a constant velocity gradient with a starting velocity of 5.1 km/sec and a gradient of 0.09 km/sec/km. The first motion data is plotted on an equal area upper hemisphere stereographic projection. The solution shows a strike slip solution with fault planes striking N26$^{o}$W and N65$^{o}$E and a maximum compressive stress direction of N63$^{o}$W. A focal mechanism solution was also calculated using the eastern Washington layered velocity model. The focal mechanism solution determined using these take-off angles is not as well-constrained as that using a velocity gradient. The solution shows a strike slip mechanism with fault planes oriented approximately the same as the previous one but with a small component of normal dip-slip.

There are three striking clusters of seismic activity in eastern Washington(see figure II-3). In the region south of Lake Chelan , 48 earthquakes were located; the maximum magnitude earthquake was a magnitude 2.7. West of this group of earthquakes is a cluster of 8 earthquakes occurring south of Leavenworth. The maximum magnitude earthquake in this group was a magnitude 2.1. Neither of these sequences show any temporal or spatial pattern. The second notable cluster is centered around Corfu. The majority of this cluster occurred in two distinct swarms. The first, between 23 October 1982 and 12 December 1982, contained 9 earthquakes with depths between 8 and 14 kilometers. The second consisted of 7 events with depths shallower than 5 kilometers and occurred between 5 May, 1983 and 26 May, 1983. Figure II-6 shows a time versus depth plot of the Corfu swarms. The third noticeable group of earthquakes in south-central Washington are aftershocks of the 1981 Goat Rocks earthquake. Twenty-six earthquakes occurred in the aftershock zone of the Goat Rocks earthquake. The maximum magnitude earthquake was a M=2.9.

In northern Oregon, three felt events occurred. Two were located near Mount Hood. The first was a M=3.4 which occurred on 18 August 1982. A M=2.7 earthquake occurred on 23 February 1983 at 0539 GMT. Earthquakes greater than M=3.0 have occurred at Mt. Hood in 1972, 1974 and 1978. In none of these cases was the earthquake associated with volcanic activity. Lack of seismic stations in the area have made detection of smaller events difficult. Station TDH is recorded continuously on a helicorder , and magnitude 0 to 1.5 events in the immediate Mt. Hood area are observed routinely. The third felt event northern Oregon on 11 May 1983 at 20:20 GMT was located near Portland and was strongly felt in Portland but no damage was reported. This event has been identified as a blast based on the characteristic of the time series and the predominance of compressive first motions. Attempts to track down the source of this blast have been unsuccessful.

Appendix I is a catalog of the located events between July 1, 1982 and June 30, 1983. The locations reported in this catalog have been determined using a location routine obtained from Dr. Bob Herrmann at St. Louis University and extensively modified and tested here at the University of Washington. Azimuthal weighting is used and obviously bad readings are automatically thrown out. There is a special depth adjustment algorithm for events with poorly controlled shallow depths.

Most of the columns in the catalog are self explanatory. Times are in coordinated universal time(PST + 8hr). The * sometimes following the depth means that the depth has been fixed. **$** and # mean that the maximum number of iterations has been exceeded without meeting convergence tests and both this and the depth have been fixed. Events flagged with these symbols may be very poorly located even if the quality factors are good. NS/NP is the number of stations and the number of phases used in the location determination. The *types* listed in the catalog are as follows:

**X**-Known explosion

P-Probable explosion(based on seismogram character)

F-Earthquake reported to have been felt

L-Low frequency earthquake

H-Hand picked event from film records

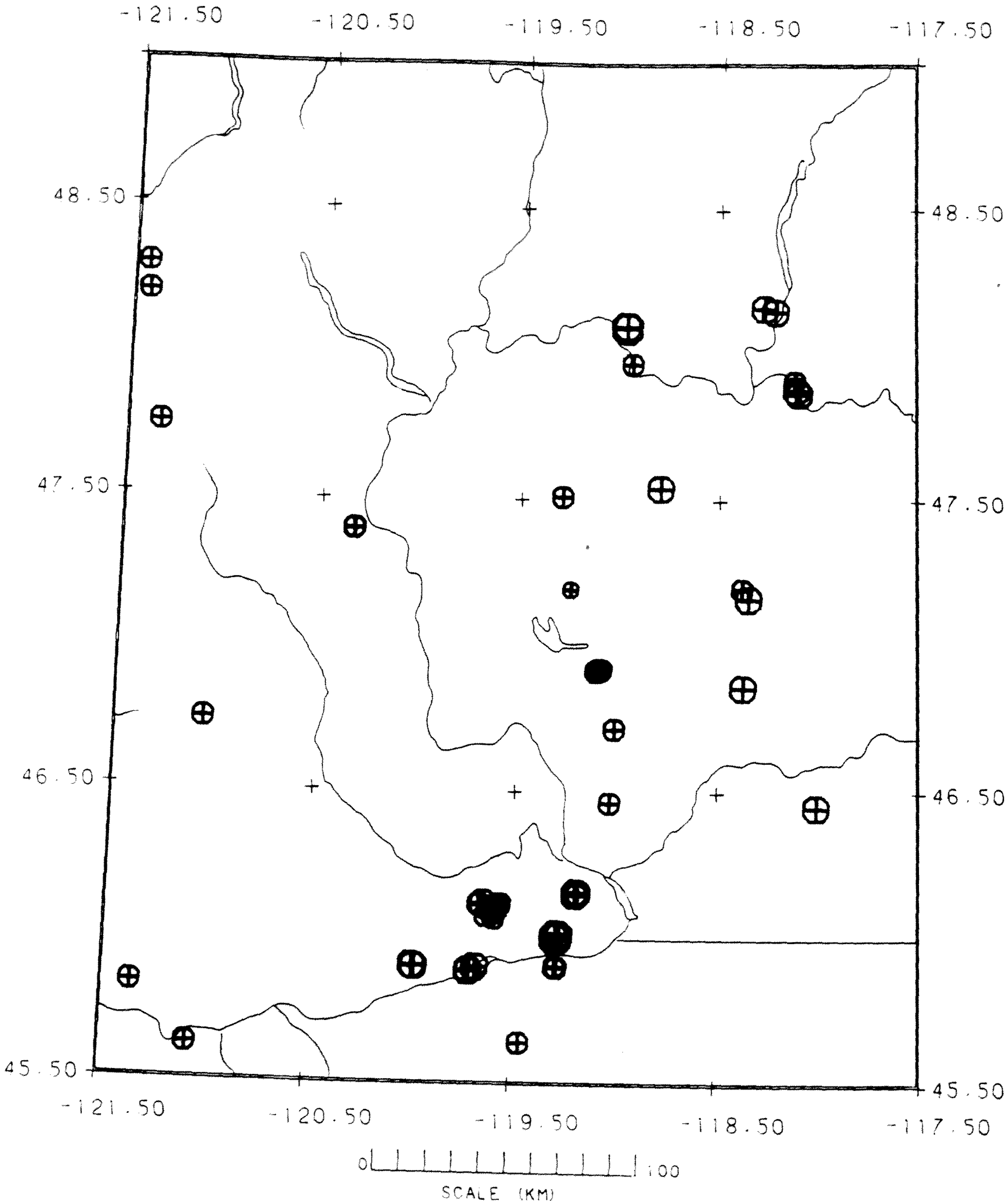


Figure II-1. Eastern Washington known or probable explosions
July 1,1982 - June 30,1983

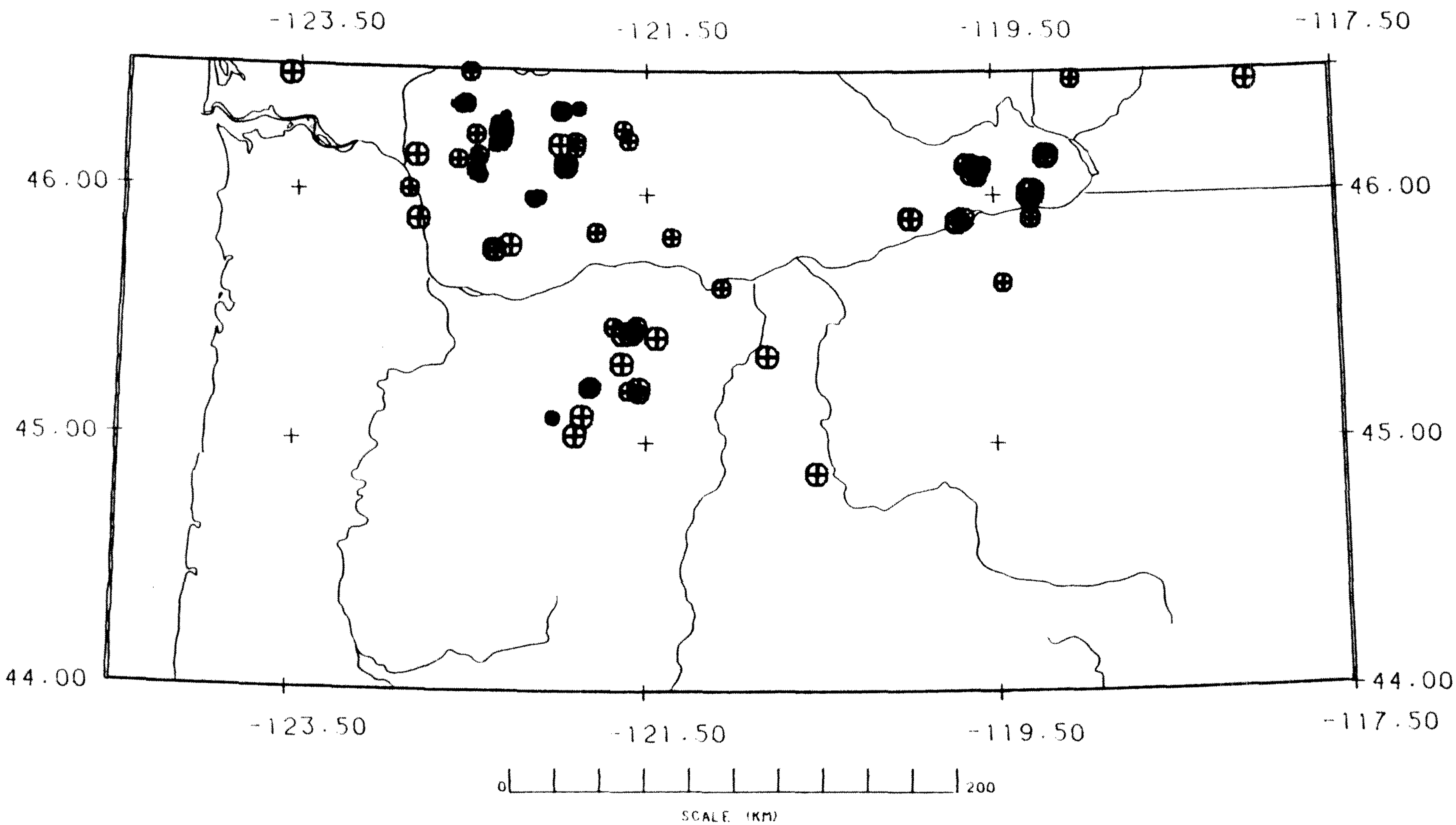


Figure II-2. Southern Washington-Northern Oregon known or probable blasts
July 1,1982 - June 30,1983

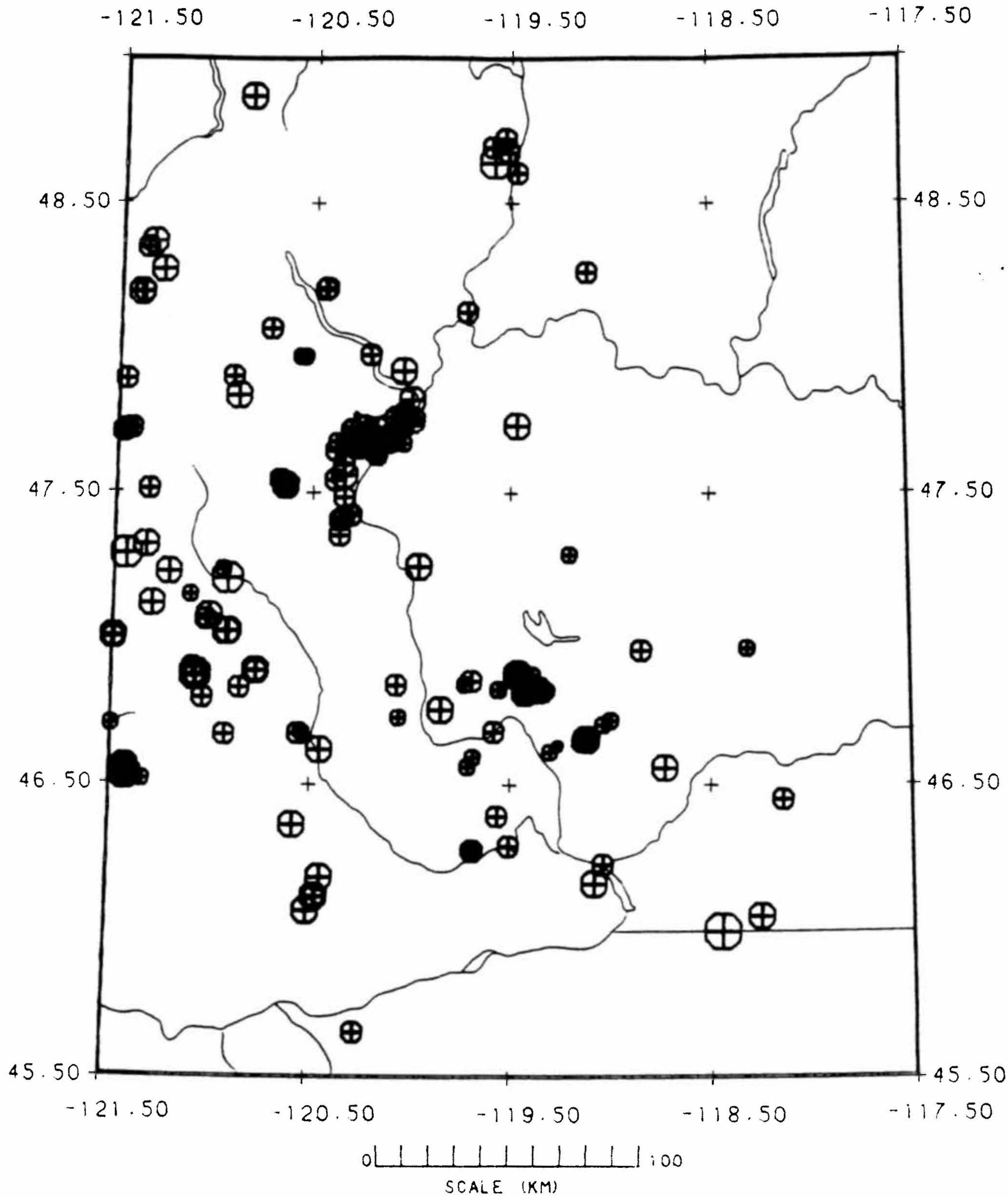


Figure II-3. Eastern Washington earthquakes, July 1,1982 - June 30,1983

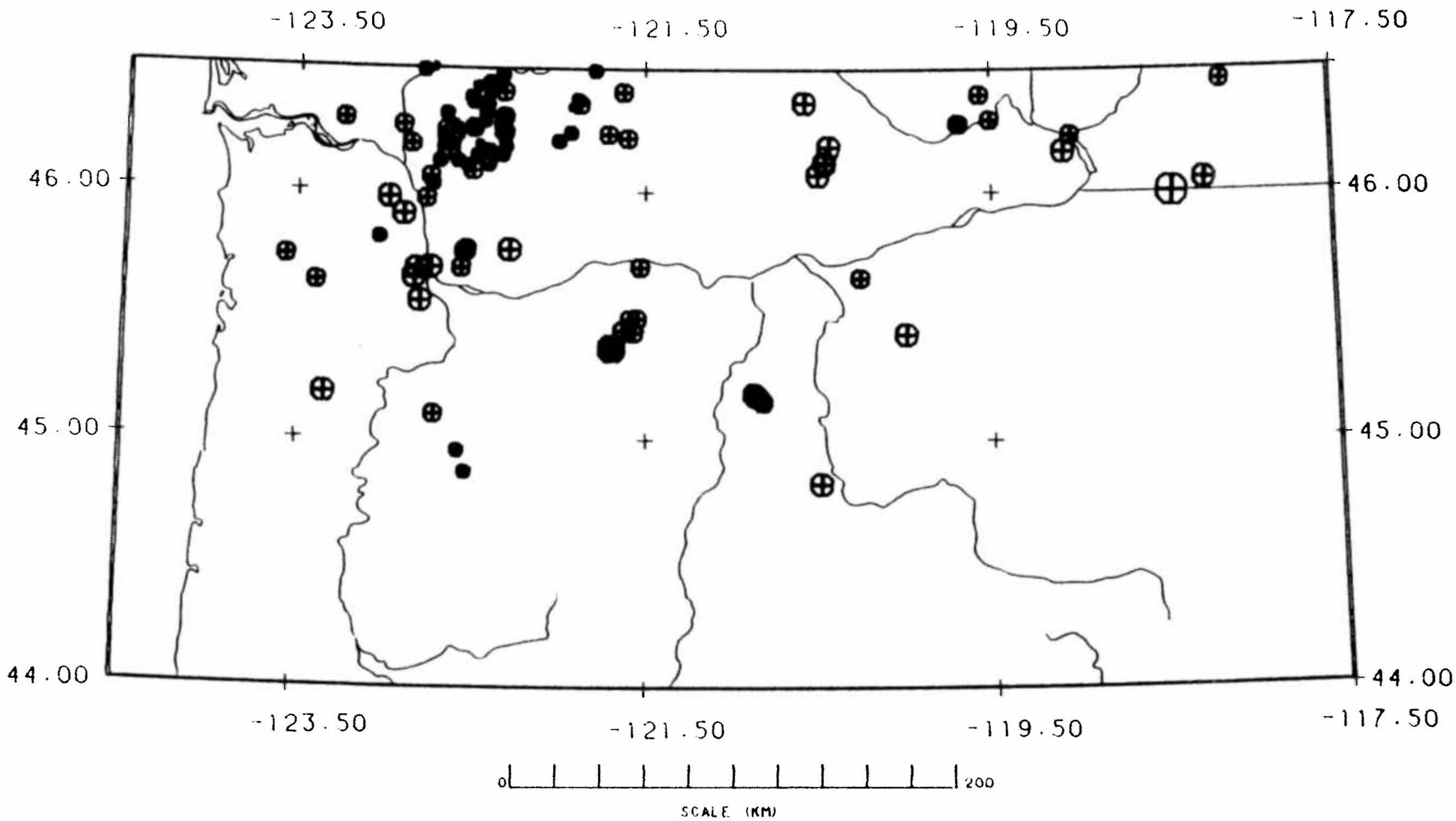


Figure II-4. Southern Washington-Northern Oregon earthquakes
July 1,1982 - June 30,1983.

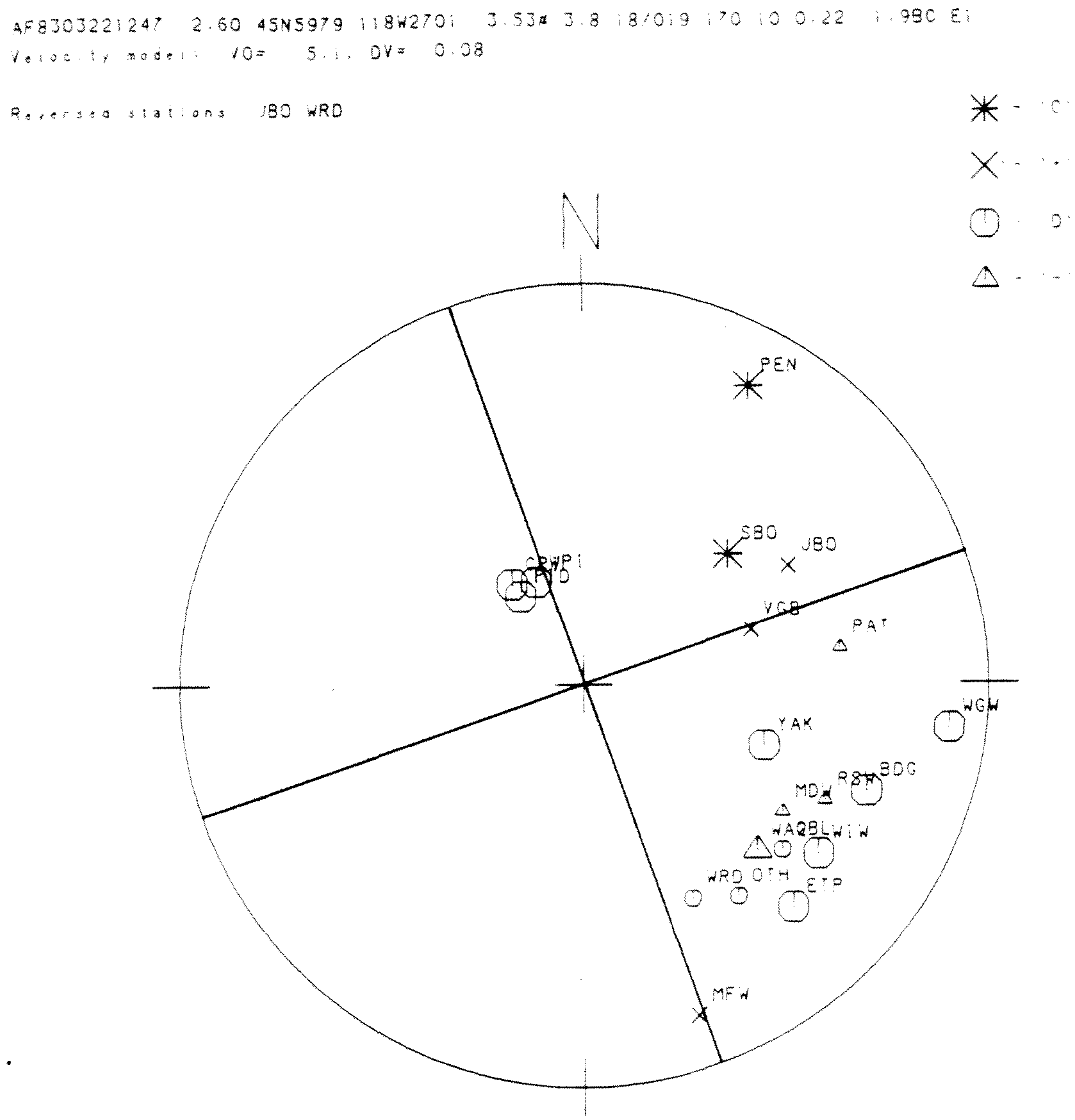


Figure II-5. Focal mechanism solution for Walla Walla Earthquake.

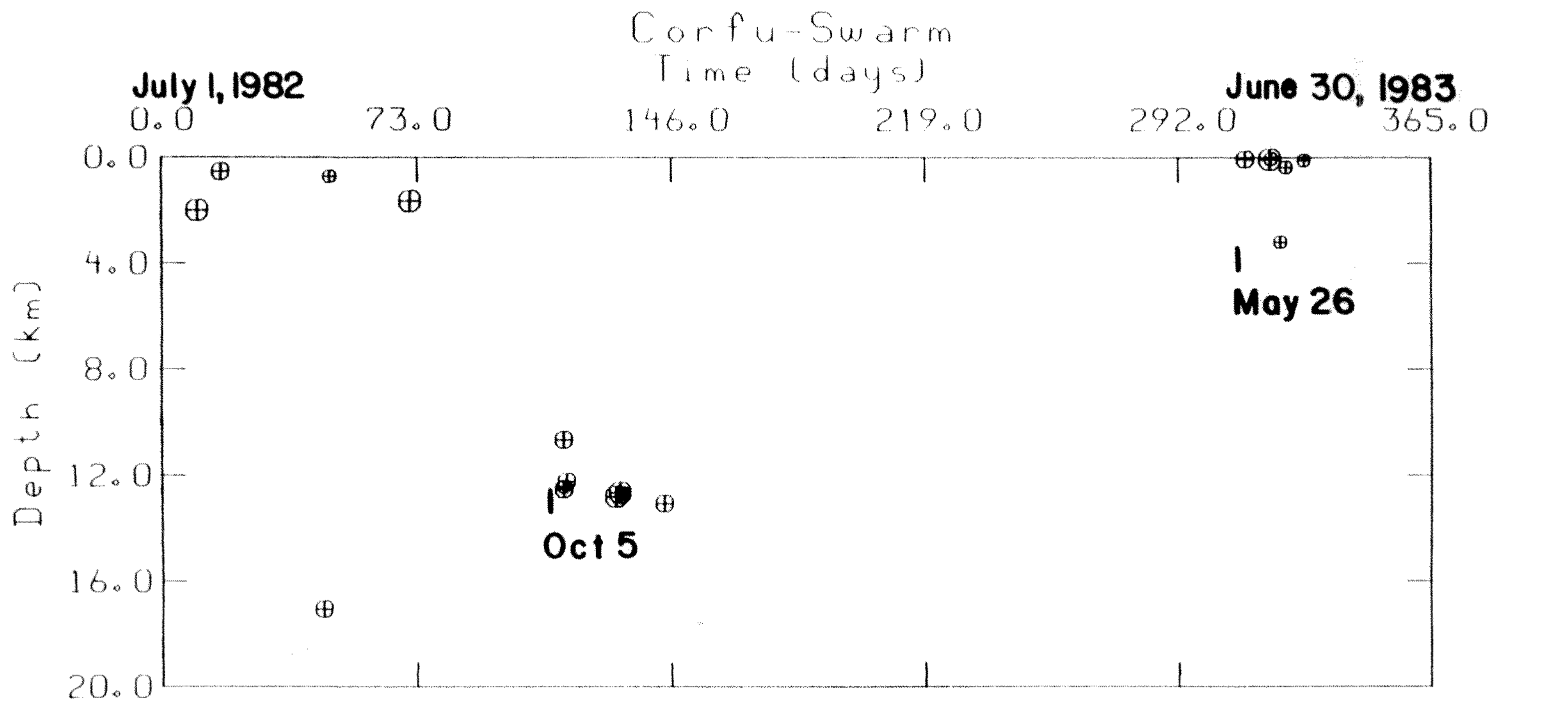


Figure II-6. Time versus depth plot of the Corfu swarms. The first began on October 23,1982; the second began on May 5,1983.

# III. STRUCTURAL STUDIES

During the past year we have concentrated our seismic velocity structure studies to the major refractors in, and surrounding the Pasco basin. We used quarry blasts recorded on the University of Washington regional seismic network as well as additional data from a dense network in the central Pasco Basin operated by the Basalt Waste Isolation Project of Rockwell Hanford Operations. The major crustal refractors are a 5.1 km/s shallow layer with first arrivals observed at distances of 15 to 50 km and a 6.05 km/sec deeper layer observed from about 30 to 130 km. The cross-over distance between these major refractors varies considerably for different parts of eastern Washington because of the widely differing thickness of the first layer.

The results of this study were presented at the annual meeting of the Seismological Society of America in Salt Lake City last spring[1] (The abstract is given at the end of this section.) and are summarized in Rohay and Malone.[2] In the current report we cover in more detail the data aquisition, data processing, some of the analysis, and implications of the results.

## Data Aquisition

The existence of a number of operating quarries in eastern Washington has facilitated the relatively easy aquisition of data useful for a study of the regional velocity structure. Because the seismograph stations are distributed over a large area rather than along lines radial to blast sites, traditional "refraction line" techniques of data reduction and interpretation are not appropriate. Instead, we use the widely spaced blasts recorded on the permanent stations to form a data base for a "time term" technique which simultaneously derives an

1. Malone, Stephen D. and and A. Rohay, "Crustal structure of the Columbia Plateau Region, Washington," *Earthquake Notes, 54*, p.39 (abs) (1983).

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

average refractor velocity and station delays interpretable as the depth to this refractor under each station.

Digitally recorded data have been available since mid 1980 on the University of Washington regional network and since late 1982 on the Basalt Waste Isolation Project Pasco basin network. The digital recording systems in Seattle and Richland are similar enough such that tapes from both systems can be analysed with the same software. We have developed the capability to merge data from both systems such that they appear to have been recorded together. In doing this we discovered that there is a 0.03 seconds delay between the data recorded on the Richland computer and that recorded in Seattle. We do not know the exact cause for this delay but suspect it is due to the way time is recorded on each system. WWVB is used in Seattle without any correction for propagation delay, while NBS satellite time is used in Richland. This time correction is constant and was removed before merging the data.

We have selected 17 blast sites which have up to 33 well recorded arrivals from known locations, but unknown origin times. Not all of these blasts nor arrivals have been used in the preliminary analysis reported here. The blasts, their locations, number of stations recorded, and number of stacked sections are listed in table III-1. The blast and station locations are shown in figure III-1.

Many of the blast sites have repeated shots in the same or nearly the same location. We have developed the software to stack seismograms from more than one shot such that an improved signal to noise ratio is obtained. We first determine the relative difference in time between the beginning of the recorded data for each individual shot. This is done by cross-correlating pairs of records from the same station but different shots and noting the time offset of the maximum peak, and taking the average of these offsets for a number of station pairs distributed both azimuthally and over a reasonable distance range from the shots.

Eastern Washington Blast Sites

| Name | Latitude | Longitude | # stacked | # records |
|---|---|---|---|---|
| Benton City | 46° 17.2' | 119° 32.6' | 1 | 13 |
| Eltopia | 46° 26.8' | 119° 01.7' | 1 | 28 |
| Gable Mt* | 46° 31.4' | 119° 23.5' | 1 | 9* |
| Hooper | 46° 46.0' | 118° 0.4' | 1 | 23 |
| Ice Harbor | 46° 14.9 | 118° 53.5' | 6 | 21 |
| Kennewick | 46° 08.8' | 119° 11.3' | 4 | 27 |
| Midnight Mine | 47° 52.5' | 118° 07.9' | 4 | 17 |
| McNary Dam | 45° 59.3' | 119° 18.5' | 3 | 33 |
| Blalock Is. | 45° 53.0' | 119° 42.1' | 1 | 26 |
| Potholes Res. | 46° 54.9' | 119° 07.4' | 4 | 30 |
| Coleville | 48° 05.6' | 118° 58.3' | 2 | 24 |
| Ritzville | 47° 08.8' | 118° 20.4' | 2 | 30 |
| Sunyside | 46° 18.6' | 119° 49.5' | 1 | 10 |
| Vantage | 47° 01.1' | 120° 13.3' | 2 | 25 |
| Waterville-1 | 47° 36.8' | 119° 53.7' | 3 | 21 |
| Waterville-2 | 47° 37.1' | 120° 00.2' | 2 | 18 |
| Prosser | 46° 04.7' | 119° 36.1' | 2 | 14 |

* There were 8 Gable blasts separated by about 8 km from each other which were recorded on an average of only 9 stations within ~30km.

Those blast sites for which most of the normalized cross correlation coefficients were less than 0.75 or blasts whose maximum cross correlation offsets verried by more than 0.02 seconds, were not stacked. There were several blast sites for which we could not stack individual shots because of these criteria.

The blast site at Coolee City had relatively small blasts, each of which was not strong enough to be well recorded within the central Pasco basin. Since the wave forms of individual shots varried considerably, (cross correlation coefficients usually much less than 0.75) we could not stack these data and thus have had to throw this site out entirely.

Blasts at Ice Harbor dam, on the other hand, while not strong enough to be individually well recorded in the Saddle Mountains, could be stacked in a number of cases to produce significantly improved record sections. An example of the individual records and the stacked record for one station (WIW) from four Ice Harbor Dam blasts is shown in figure III-2. Since there have been over 80 of these blasts with precisely known locations we have been able to determine what the limit of spacial separation is for stackable blasts. Individual shots within 300 meters of one another, in general, satisfy the above criteria for stacking. Those shots more than 500 meters apart do not satisfy the same criteria. The blast signals have a peak frequency around 3-4 Hz and the first major refractor velocity is about 5 km/sec. This give a wave length of about 1.4 km. Shots within 1/4 wave length of each other ( ~360 m) should have fairly similar wave forms and thus meet our stacking criteria.

**Data Analysis**

After selecting the blasts, stacking those records for which it is possible, and picking the first arrivals for all traces with a good signal to noise ratio, record sections are plotted. (See an example in figure III-3.) These record sections are then used to try to separate the arrivals for the major crustal refractors. Since there is considerable variability in the depth of the 6 km/sec refractor it is not appropriate to use a single distance cut off for separating the 5 km/sec from the 6 km/sec arrivals. Instead the record sections are examined for each shot to see where an obvious break in slope occurs and then individual traces around this break are examined to determine if there are any obvious wave form characteristics that would identify which layer the arrivals were coming from. If there is any doubt about which layer an arrival is coming from, that arrival is not used in subsequent analysis. The break between the 5 and 6 km/sec layers spanned the distance range from 10 to 60 kilometers depending on the depth to the 6 km/sec layer under the shot point.

Arrivals from the two major crustal refractors were analysed separately, but using the same time-term technique. This technique uses a computer program developed at the University of Washington by Al Rohay [3] and adapted to a Prime computer in the Richland offices of the Basalt Waste Isolation project. It calculates the station time terms and the average refractor velocity for a suite of data from an areal distribution of shots recorded on a network of stations. Statistical weighting is employed to account for the uncertainties in the data, and a parameter separation technique is used to insure that biasing of certain shot-station combinations does not occur due to sparse data for some combinations. The average time term for a data set is mathematically constrained to allow for a conventional least squares inversion process.

There were 76 arrivals from the 5 km/sec layer in the distance range 9 to 44km. The average refractor velocity is 5.16 km/sec ± 0.04. There is no obvious spacial pattern to the station time terms as would be expected if there was a uniform or systematic change in the depth to this refractor. Instead there is a slight dependence of time term on station elevation (figure III-4). The stations are used in this analysis are on a variety of geologic structures from directly on bed rock to being on several hundred meters of sediments. The combination of

3. Rohay, Alan C., "Crust and Mantle Structure of the North Cascades Range, Washington," *University of Washington PhD Dissertation* (1982).

the elevation and sediment thickness could account for most of the time terms for this layer. Stations such as WA2 and MDW have time terms which are larger than can be easily accounted for and are of unknown origin. The velocity of this layer and its time terms are important in converting time terms for the deeper layers into actual depths.

The data for the 6 km/sec layer were divided into two overlapping subsets because of the difference in station density in the Pasco basin relative to the rest of eastern Washington. First, 10 blasts recorded at 28 stations in the Pasco basin area for a total of 91 arrivals were used to study the details of this area. Then, 8 blasts recorded at 23 stations distributed over most of eastern Washington with a total of 90 arrivals were used to study the larger area. The degree to which these two results agree within the central basin is a measure of the consistency of the results. First arrivals for this layer began as early as about 10 km for shots in the north and as late as 60 km for shots in the south. An average refractor velocity of 5.99 ±0.04 km/sec and 6.02 ±0.06 km/sec was found for the central basin and larger region respectively.

The time terms for the subset from the central Pasco basin are listed in table III-2 and after applying an elevation correction are plotted in figure III-5.

Time Terms For Basement Layer

| Station | Time term | # readings | Station | Time term | # readings |
|---|---|---|---|---|---|
| GBL | 0.14zz0.05 | 6 | PRO | 0.11zz0.11 | 2 |
| MDW | 0.03zz0.05 | 5 | ETP | -0.42zz0.05 | 3 |
| BEN | 0.09zz0.05 | 4 | GBB | 0.01zz0.06 | 4 |
| ROH | 0.09zz0.08 | 3 | WES | 0.06zz0.05 | 3 |
| WIW | -0.22zz0.07 | 3 | VER | 0.13zz0.15 | 3 |
| RSW | 0.08zz0.05 | 5 | RC1 | -0.16zz0.17 | 4 |
| SNI | 0.04zz0.05 | 4 | BDG | -0.19zz0.12 | 2 |
| WA2 | -0.05zz0.05 | 7 | MJ2 | -0.18zz0.06 | 3 |
| CRF | -0.25zz0.06 | 6 | SAN | 0.09zz0.09 | 3 |
| SYR | -0.22zz0.05 | 6 | WHI | -0.05zz0.07 | 2 |
| OTH | 0.04zz0.07 | 4 | WNP | -0.29zz0.34 | 2 |
| HOR | 0.05zz0.13 | 2 | | | |

Most of the station time terms can be contoured with fairly smooth simple contours showing positive terms in the central and western parts of the area and then a rather sharp transition to negative time terms to the east and north. Two stations show significant trends from this pattern. Station OTH shows a slightly positive time term surrounded by stations with negative ones, and RSW is very negative compared with the positive time terms around it. First arrivals at RSW have a peculiar character, often very sharp but with reverse first motion even though the station polarity is known to be correct. It is the highest station in the network and is directly on a basalt outcrop with no sediment cover. Because of these observations we do not consider the data from this station to be the most reliable and thus are not overly concerned with its anomalous time term. The cause for the anomalous time term at OTH is unknown.

We convert the time terms to depths to the 6.0 km/sec basement refrator using the relation illustrated in figure III-6. This assumes that the velocity of the layer above the basement is constant and that its thickness alone is the cause for the areal distribution of time terms. Intercept times for a number of the blasts are used to get an average depth to the basement layer of 9.2 km. The time terms are then used to calculate the deviation from this depth under each station. The resulting depths and depth contours are shown in figure III-7. As with the time terms themselves, the basement topography is deep in the central basin and to the west but sharply shallows to the east and north. This is consistent with the data for the larger area which were analysed in the same way and whose time terms convert to a depth to basement plot shown in figure III-8. The deep basement in the central basin shallowing to the east and north is similar to the results of Eaton[4] and agrees with our previous work[5] in the north

4. Eaton, J. P., "Crustal Structure from Explosions and Notes on Earthquake Distribution," *Preliminary report to D.O.E (not published)* (1976).

5. —–, *Annual Technical Report on Earthquake Monitoring of the Hanford Region, Eastern Washington,* Geophysics Program, University of Washington (1977).

which defined the depth to the basement north of 47°N. The area where the basement topography can thus far not be defined is to the west of the central basin, in the Yakama valley area and the foot hills of the Cascade Range. Our station density in this area is not high enough to resolve how the deep basement in the central basin shallows to the west.

**Discussion**

The 6.0 km/sec layer ranges from 3 to 11 km deep in our area of study. Its continuity with rocks of a similar velocity in adjacent areas suggests that it is made up of igneous and metamorphic rocks which typify the major shallow crustal refrator of the Cascade mountains and Okanogan Highlands to the west and north. This layer is overlain in eastern Washington by massive miocene basalt flows which have thicknesses of a few kilometers in the north and perhaps are as much as 10 kilometers in the central Pasco Basin. Alternatively, there may be low velocity, low density sediments between the basalts and the basment in the central Pasco Basin which are not directly detectable seismically but contribute to the apparent depth of the basement in this area. Geophysical techniques other than seismic may be most appropriate for detecting and defining this layer if it exists.

The work reported on here is preliminary for several reasons. In the past several months additional blasts have taken place at new blasts sites. Data from these have not been included in the analysis thus far, and while we do not think they will change the main conclusions reached, they will probably contribute to the spacial resolution of the basement layer, particularly in the north. Also a planed multi-station refraction program is to take place this fall in the central Pasco Basin organized by Rockwell Hanford Operations. This experiment has the potential to define the edges of the depression of the basement with much greater accuracy than what we have done so far.

As examples of what some of the data from these profiles might look like, we have run several two dimensional raytrace profiles across our model for the structure we have determined for the central basin. Figure III-9 shows a map with two of the shot points for the time term analysis shown (Kennewick and Potholes), and the direction of pseudo-refraction lines from them. These lines go through existing stations though these stations do not fall directly on a line. Figure III-10 shows the two record sections; from Kennewick to the north-west and from Potholes to the south-west with synthetic seismograms superimposed. These record sections illustrate some of the differences in wave characteristics and cross-over distances to be expected from the planned multi-station refraction program.

Figure III-9 also shows the predicted cross-over distance for different potential shot points for a reversed refraction line; one end near Kennewick and the other near Vantage. These values were determined by running the two dimensional ray trace program over our model with different shot points as illustrated in figure III-11. Note that the position of the cross-over point in the central basin is very sensitive to shot point placement and the detail in our model. It will be very interesting to check the accuracy of these predictions with the data from the planned refraction experiment.

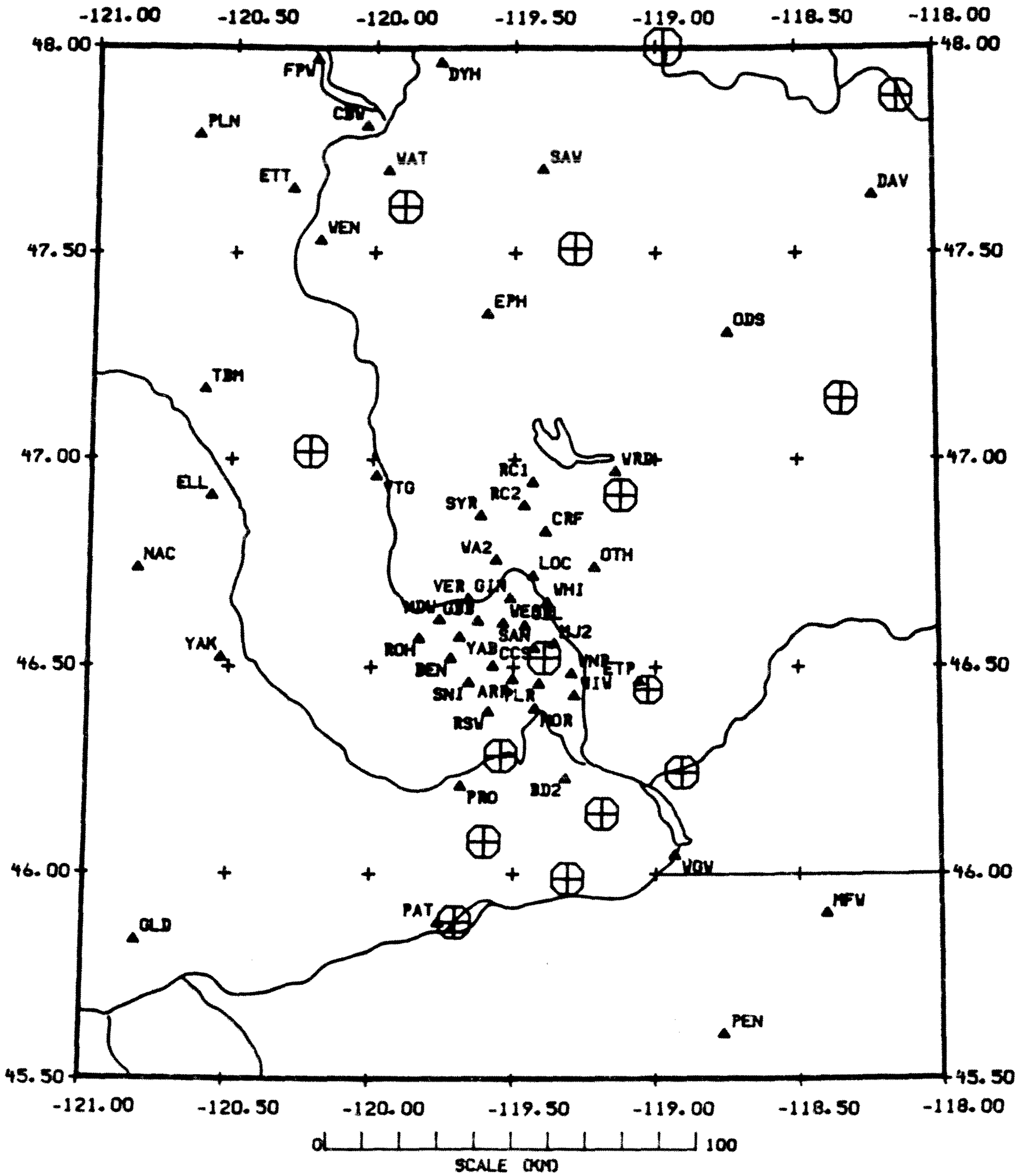


Figure III-1. Map of Eastern Washington showing blast sites (open circles) and seismic stations (triangles) used in time term study.

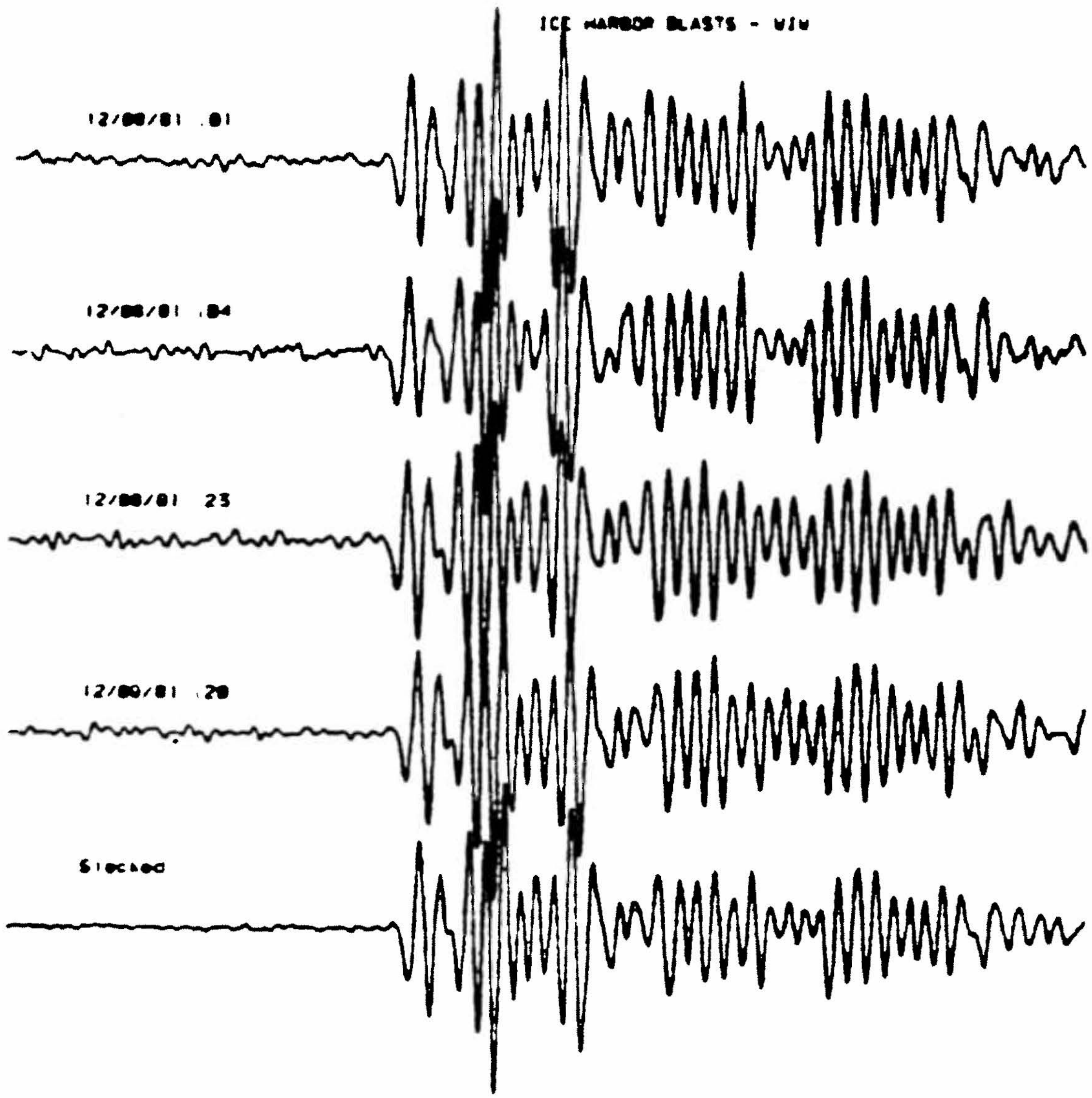


**Figure III-2.** Example of seismograms from four Ice Harbor Dam blasts recorded at station WIW and the stacked trace using these four (bottom trace).

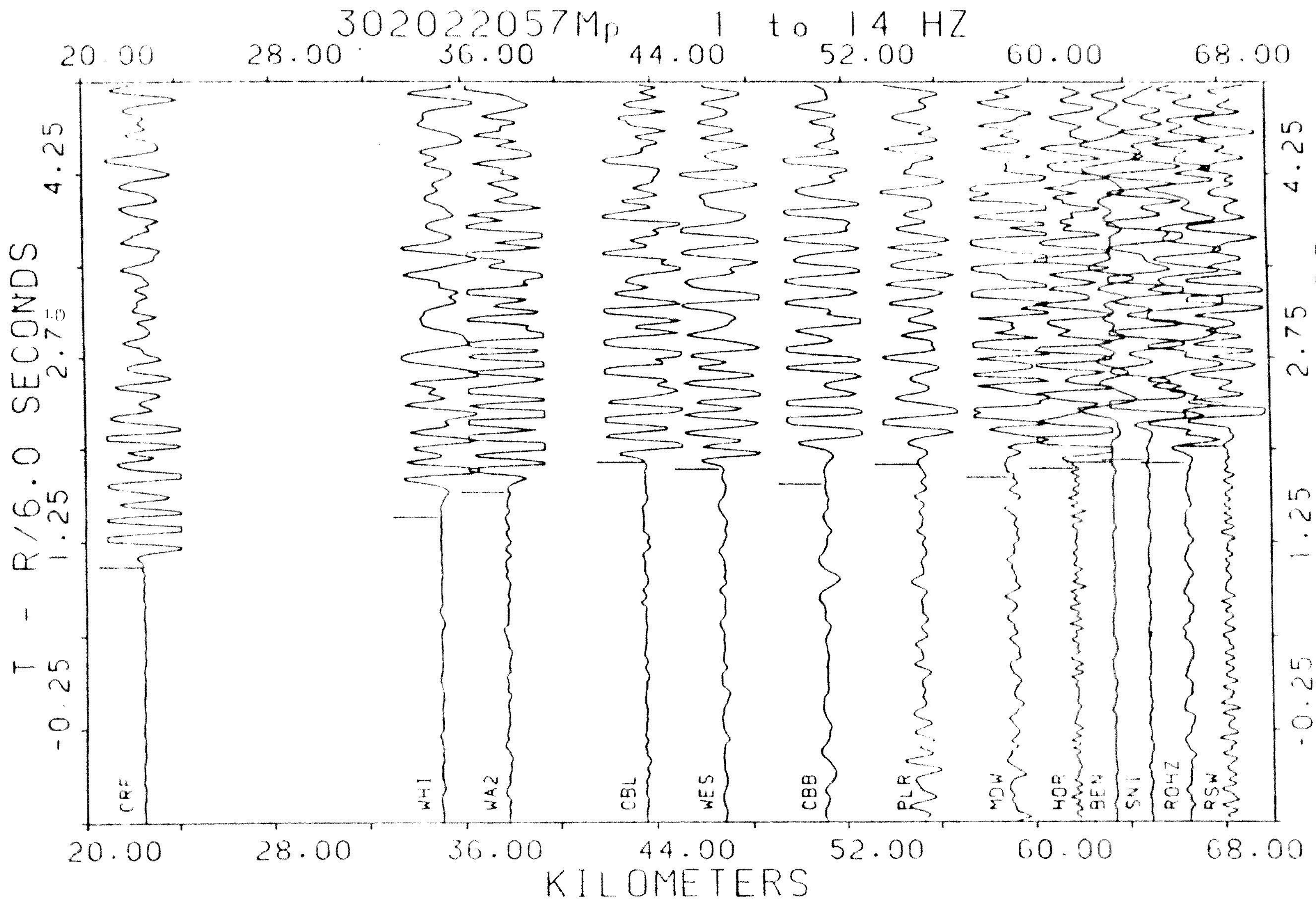


**Figure III-3.** Example of a typical record section used for determining on which branch of the travel time curve an arrival falls. This section is from a blast near McNary dam recorded to the north through the central Pasco basin.

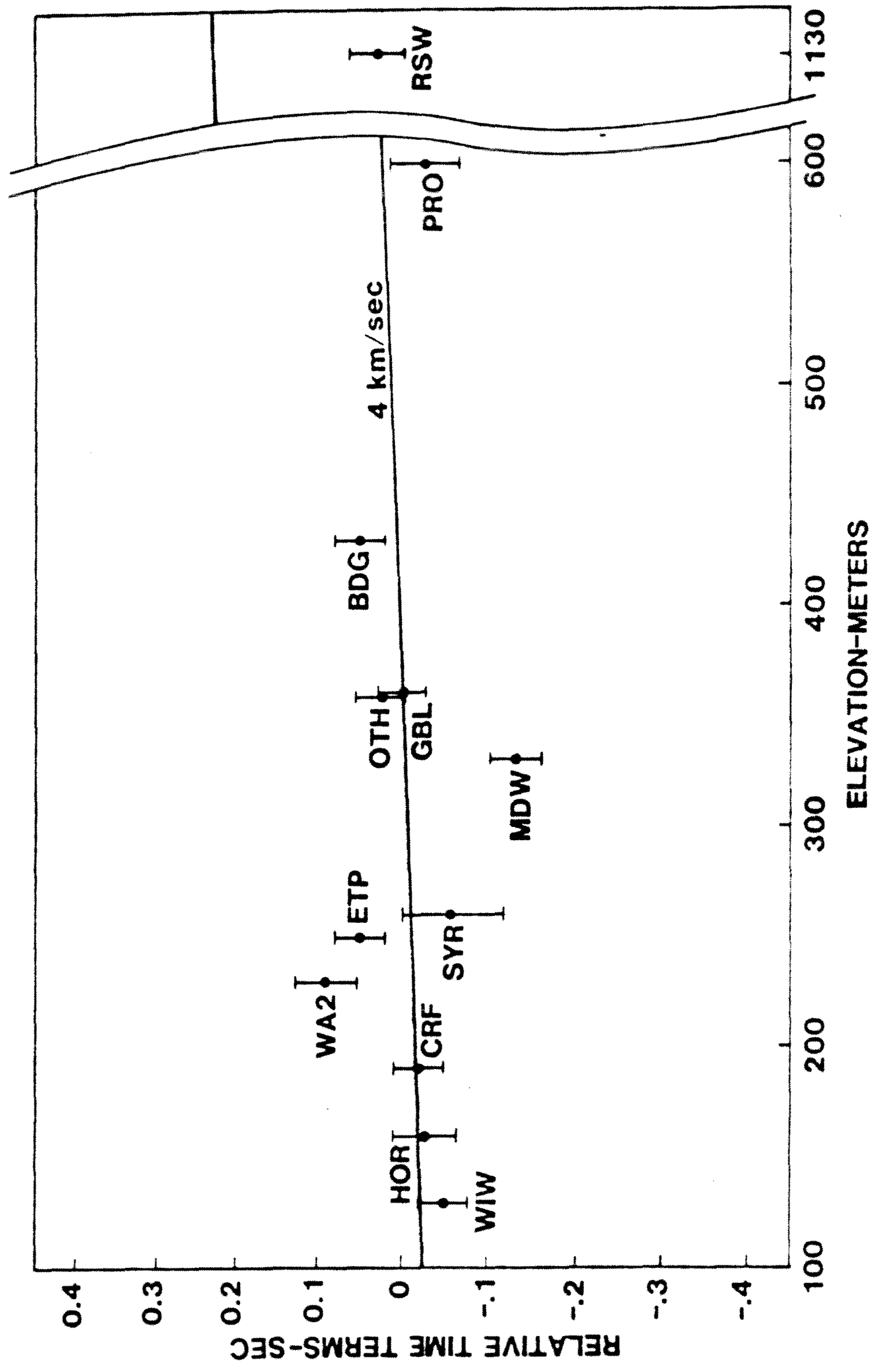


**Figure III-4.** Plot of station time terms for the 5 km/sec layer verses station elevation.

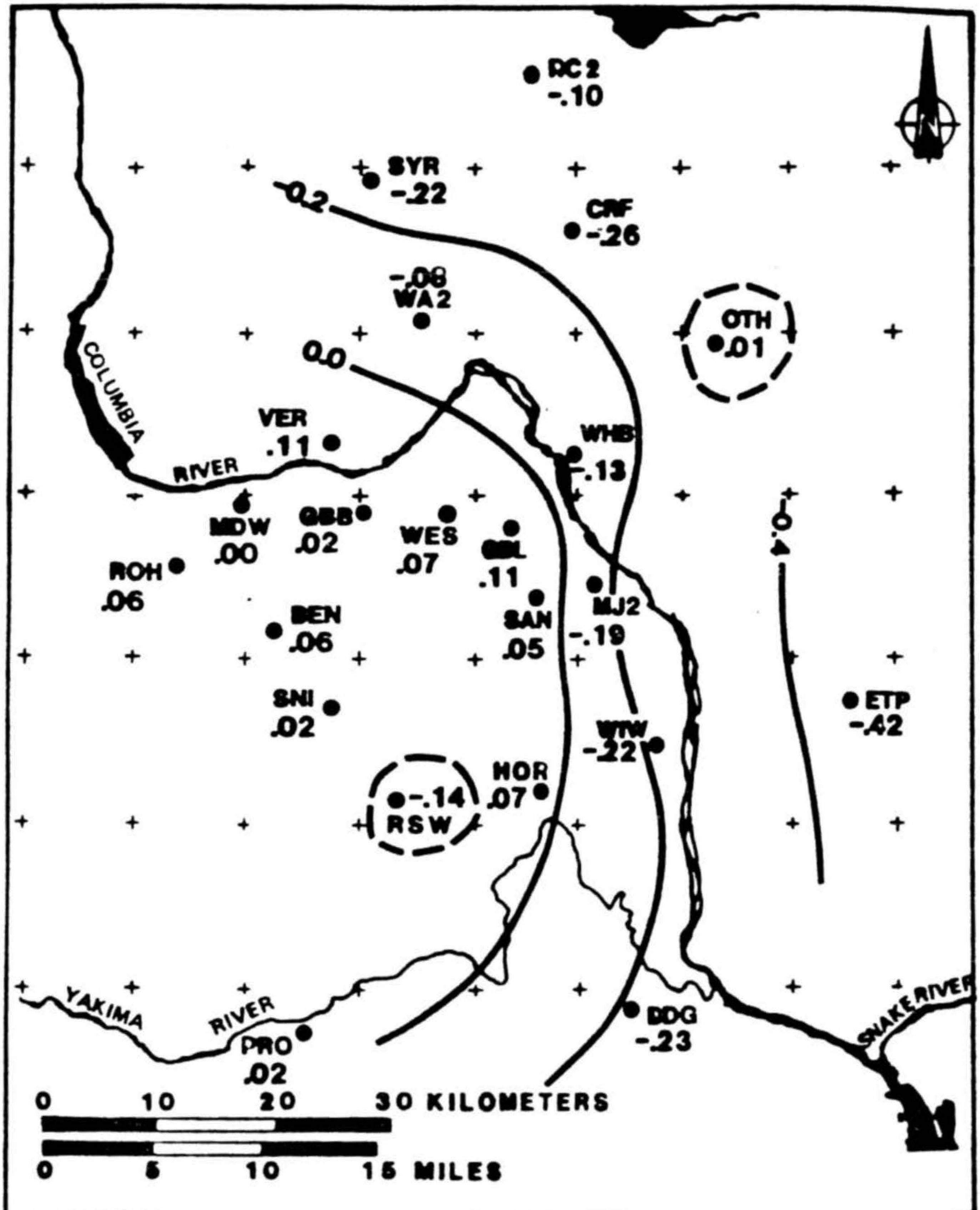


Figure III-5. Map of station time terms for the 6km/sec layer in the central basin and contours.

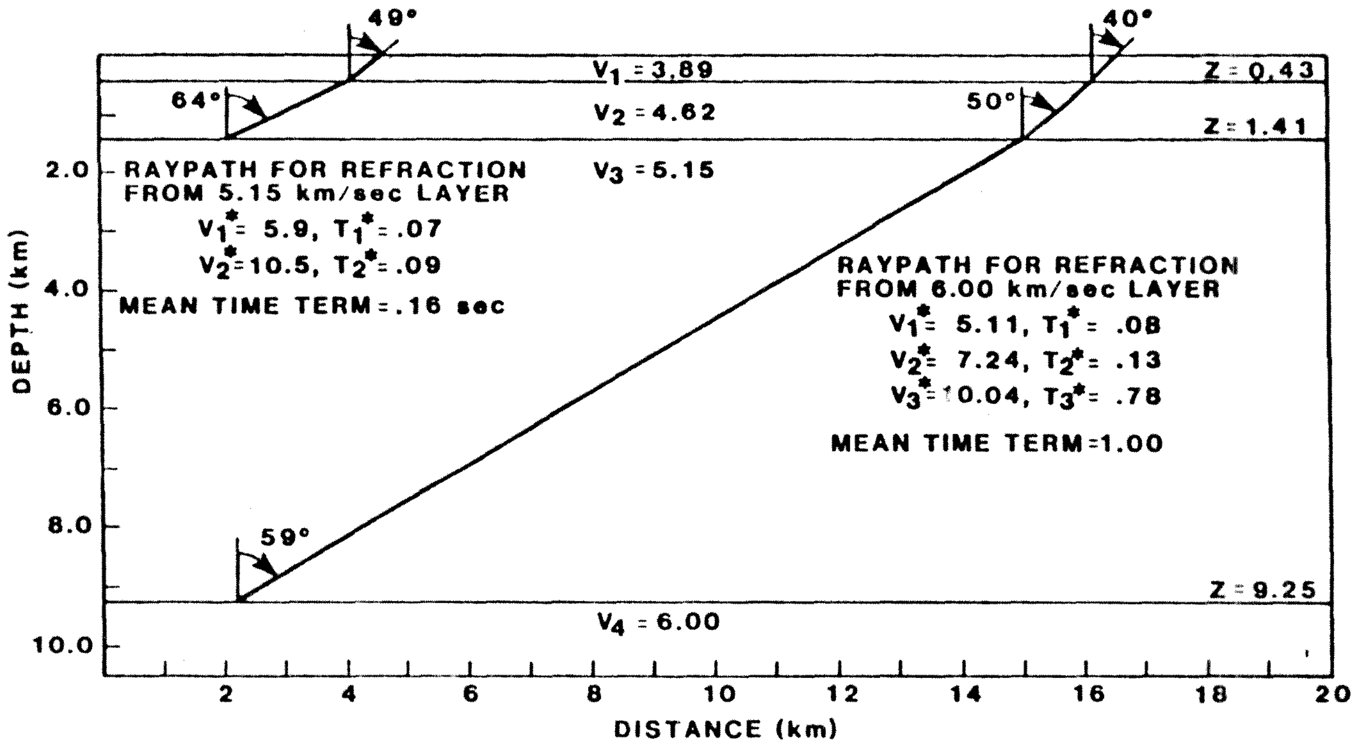


**Figure III-6.** Cross section of the shallow velocity structure showing sample critically refracted waves from the 5 and 6 km/sec layer and the relationships used in determining depth to these layers from time terms.

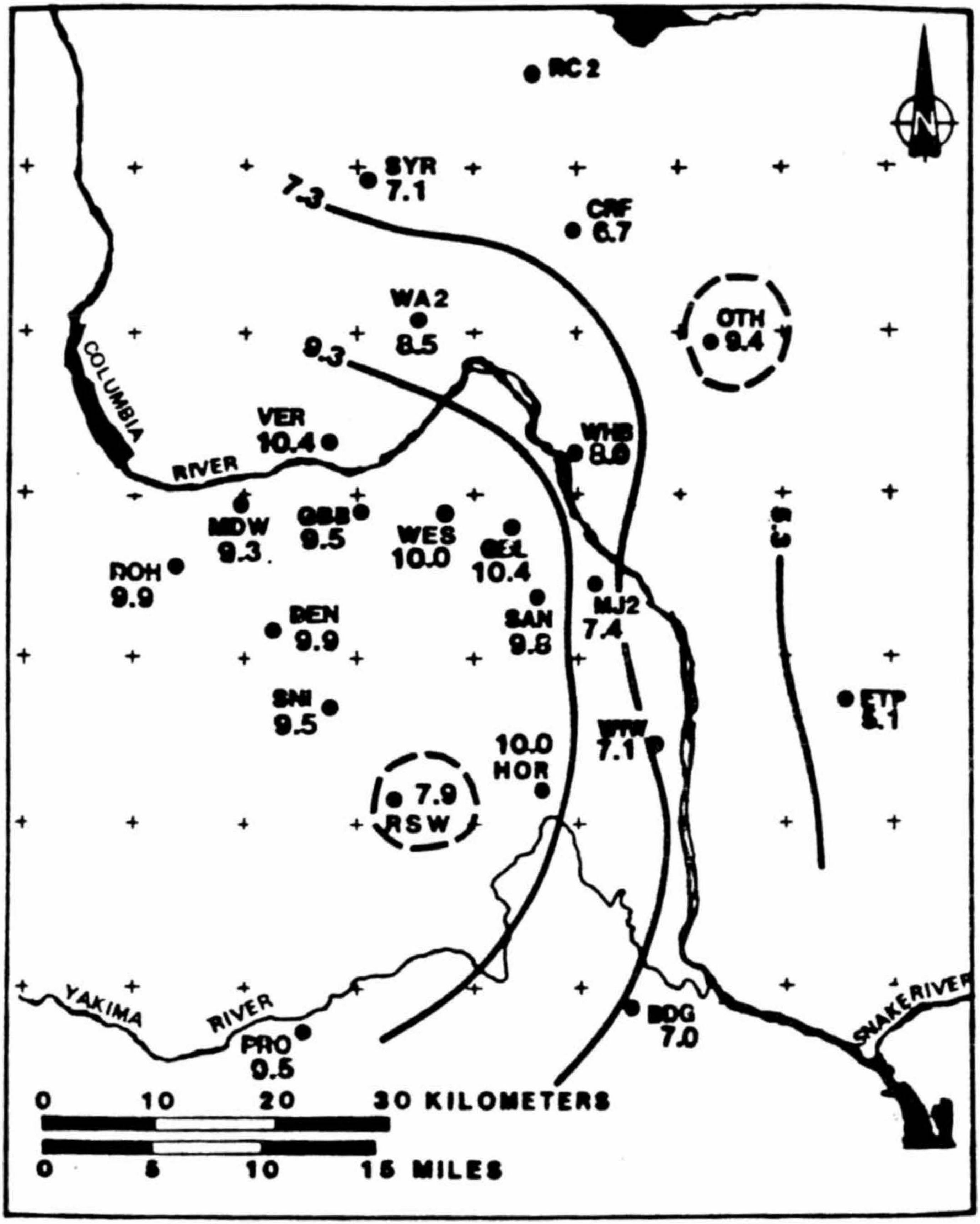


**Figure** III-7. Depth to the basement 6 km/sec layer for the central Pasco basin contoured from the station time terms shown in figure III-5 and corrected for the near surface time terms from the 5 km/sec layer.

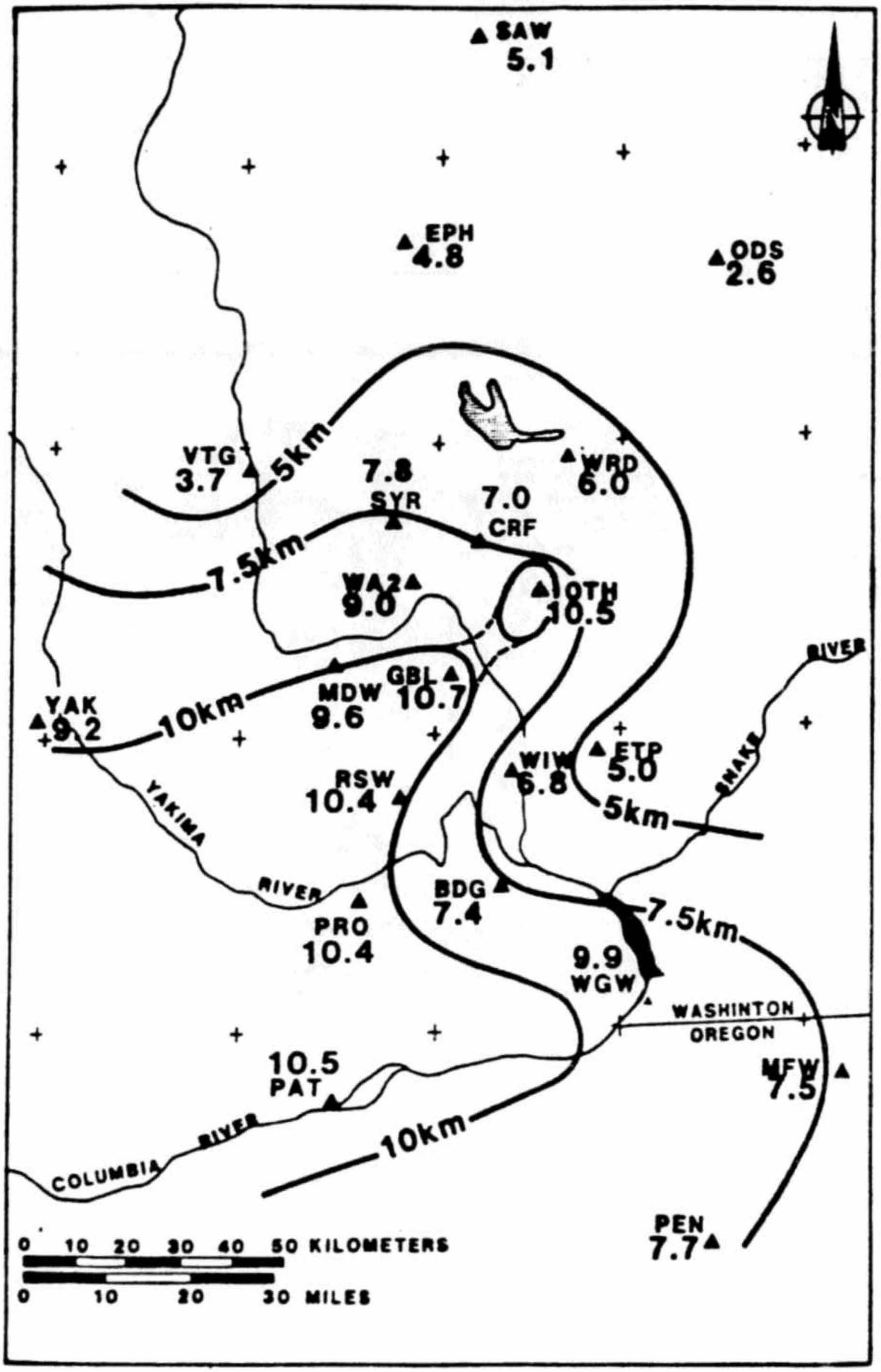


**Figure III-8.** Depth to basement for the larger eastern Washington subset of data contoured from time terms and corrected for the near surface.

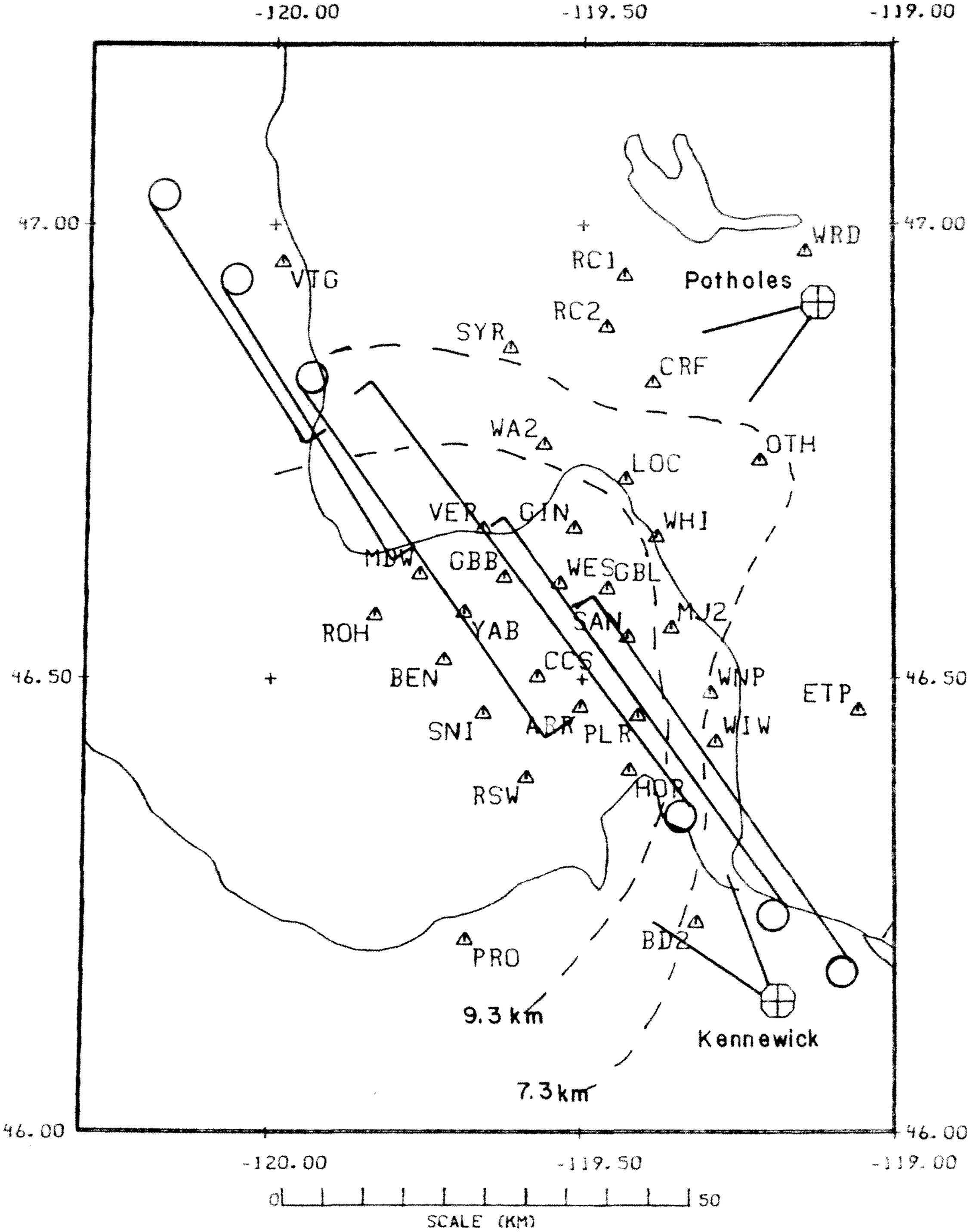


**Figure III-9.** Map showing the location of two of the more important blast sites and the direction of pseudo refraction lines illustrated in figure III-10. Potential blasts sites are shown as open circles; the line extending away from each shows where the predicted cross over from 5 km/sec to 6 km/sec would be based on our model.