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Time-Term Analysis of Upper Crustal Structure in the Columbia Basin, Washington

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ABSTRACT

Arrival time data from existing permanent networks and supplementary portable stations were collected during the U.S. Geological Survey (USGS) refraction program in August, 1984. Reduced travel time plots of these data and USGS record sections (Catchings et al. 1984) were used to select data from two branches of the travel time curve. Sixty-six arrival times selected in the distance range 3 to 63 km were fit to a velocity of 5.16 km/s (±0.02 km/s). Time terms determined at 31 stations range from -0.10 to +0.15 s (±0.05 s) and show correlations with elevation and near-surface geology. The four intercept times range from 0.15 to 0.22 s (±0.05 s), implying an average depth of 0.5 km to the 5.16-km/s refracting horizon within the basalt.

Eighty-three arrival times selected in the distance range 50 to 145 km were fit to a velocity of 6.16 km/s (±0.02 km/s). Time terms calculated at 40 stations range from -0.6 to +0.6 s (±0.1 s), with the four intercept times ranging from 1.4 to 2.0 s (±0.1 s). These show a systematic regional pattern consistent with previous studies (Malone and Rohay 1983) but extended by portable-station coverage. Conversion of the time terms to basement depth is dependent upon the lateral extent of an inferred low-velocity layer beneath the basalts, which is suggested by deep-borehole logs and magnetotelluric data.

FIGURE 1

Ongoing studies of the seismic velocity structure of the crust have utilized construction and quarry blasts recorded on seismic networks (Malone and Rohay 1983). These stations are operated by the University of Washington Geophysics Program (UWGP) and the Basalt Waste Isolation Project (BWIP) of Rockwell Hanford Operations (Rockwell). Thirty-eight UWGP stations and 19 BWIP stations were used in this study. Exact origin times for the 18 blast sites used were not available except at the Gable sites.

FIGURE 2

In 1984, the U.S. Geological Survey (USGS) conducted an active seismic refraction project on a northeast-southwest profile through the center of the Columbia Basin (Catchings et al. 1984). Eight accurately timed explosions (two at each of the four locations shown) were recorded by the permanent networks. Additional temporary stations were operated by the UWGP and BWIP to the northwest and southeast of the profile, respectively.

These data sets were analyzed using the time-term method that assumes the arrival times of seismic waves from a refracting horizon have a delay time or time term related to the depth to the refractor, or to the velocity between the refractor and the surface.

FIGURE 3

Data from 11 blasts (112 arrival times at 38 stations) recorded at short distances (up to 60 km) were fit to a velocity of 5.16 ($\pm$0.01) km/s. Intercept times for the USGS blasts were smaller (0.13 to 0.21 s) than for the Gable blasts (0.27 to 0.34 s), resulting in a shallower interpreted depth to the refractor.

There is an apparent dependence on station elevation (0.48 s/km) and surficial geology in the relative time terms. Arrival times at stations on basalt are earlier than stations on sediments by approximately 0.1 s. Most of the time terms for bedrock stations show an elevation dependence.

The two stations (MOW and RC1) are early, and no satisfactory geologic explanation has been found at this point in the study. The station at the highest elevation (RSW) does not appear to be delayed due to elevation. Although in this case, a possible geologic explanation can be made.

FIGURE 4

The time terms for stations in the sediment-filled synclines show delays of approximately 0.1 s. (The less accurate values are shown in parentheses.) The elevation-corrected time term at RSW is -0.34 s; the refracting horizon apparently remains at a shallow depth even beneath the highest station. Other stations on smaller ridges had delay times that, in

contrast, showed a strong correlation with elevation. In these cases, the refracting horizon apparently remains horizontal beneath the smaller ridges, rather than paralleling the topography of the ridges.

FIGURE 5

Borehole velocity measurements show that the surficial sediments have low velocities that can explain a delay time of approximately 0.1 s. The Saddle Mountains basalts have many sedimentary interbeds that may be represented by the 3.6-km/s average. Approximately 100 m into the Wanapum basalt, the velocity increases to about 5 km/s. Using adjustments for surficial sediments and elevation, the USGS origin times indicate a 400-m depth to the 5.16-km/s refractor.

FIGURE 6

Deep-borehole sonic logs show that a sequence of sedimentary rocks produce a low-velocity zone beneath the basalts. Although these boreholes are to the west and northwest of the basin, magnetotelluric data indicate that a sedimentary sequence exists beneath the basalts throughout the study region.

Arrival-time data collected from more distant blasts are interpreted to be refracted arrivals from a basement layer beneath the sedimentary low-velocity zone.

Geographical subsets of the data were analyzed separately. The minimum shot-to-station distances for basement refractions vary geographically (30 km in northern regions up to 70 km in southern regions). The maximum distance for basement refractions ranged from 130 to 150 km. Different blast combinations were used for each subset. Within each subset, approximately 100 arrival times from 10 to 15 blasts were available. The velocity of the basement refractor ranged from 6.06 to 6.22 km/s; the latter found predominately in the southern, deeper portions of the basin. The standard error in the velocity determinations was generally 0.04 km/s.

FIGURE 7

The relative time terms calculated for the dense network in the Pasco Basin show two apparently perpendicular gradients north and east of the Columbia River, where progressively earlier arrival times are observed. No corrections for elevation or surface sediments have been made, because the scatter in these data was on the order of 0.1 s.

FIGURE 8

Relative time terms were calculated over a larger region for a somewhat different combination of shots and stations. The time terms are generally consistent with the previous pattern, and extend the coverage to the north, south, and east.

FIGURE 9

Data from the portable stations operated by the BWIP show a continued decrease in the time terms to the east and southeast. The portable station data also shows a southeastward extension of the region of maximum travel-time delay.

FIGURE 10

Data from the northern Columbia Plateau show contours that parallel the Columbia River in the northeast, which is the approximate northernmost extent of the basalts. The time terms are observed to increase by approximately 0.8 s towards the southwest.

FIGURE 11

Time-term analysis of the UWGP temporary station data was not as successful as in other regions. Stations to the north of this diagram show reasonable station-to-station consistency, but southern stations could not fit accurately. Additional data may be required to resolve the structure in this area (dashed contours).

FIGURE 12

A simplified velocity model is used to convert the time terms and intercept times to relative and average depths-to-basement, respectively (the inset velocity model does not show the near-surface low velocities described earlier, and is not to scale). The basalt and (subbasalt) sediment thicknesses are assumed to be equal for the regional interpretation. Alternative models, ranging from no sediment (to the north) to twice as much sediment as basalt (to the west), could also be used. However, the velocities of the sediments may vary in an unknown manner. More complex models may be incorporated as more data become available.

The accuracy to which the time terms were calculated suggests that implied depth variations are accurate to better than 1 km.

FIGURE 13

The intercept times for the USGS blasts, calculated as a part of the time-term solutions, were used to obtain absolute time terms by adjusting the average time term so that intercept times and nearby time terms agreed internally. The subsets of stations overlapped (each had several common stations) so that all subsets of time terms could be adjusted to a common baseline.

The depth to basement increases from approximately 1 to 2 km at the northern edge of the basalts to a maximum value of approximately 10 km in the central basin. Towards the west, the values shown may be too great, because the basalts are much thinner than the sediments there. Depths of approximately 6 km are found at the southeastern edge of the basin where the basalt thins rapidly over the metamorphic rocks of the Blue Mountains.

In summary, time-term analyses of the seismic network data have provided a nearly complete set of station corrections and a geologic interpretation that can be used to improve earthquake locations in the Pasco Basin. Regional variations in basement depth (related to the aggregate thickness of basalts and sediment) are well defined and are similar to the present-day shape of the basin. This structural information may be used in refining earthquake locations throughout eastern Washington, in interpreting magnetotelluric data, and in constraining tectonic models of the region.

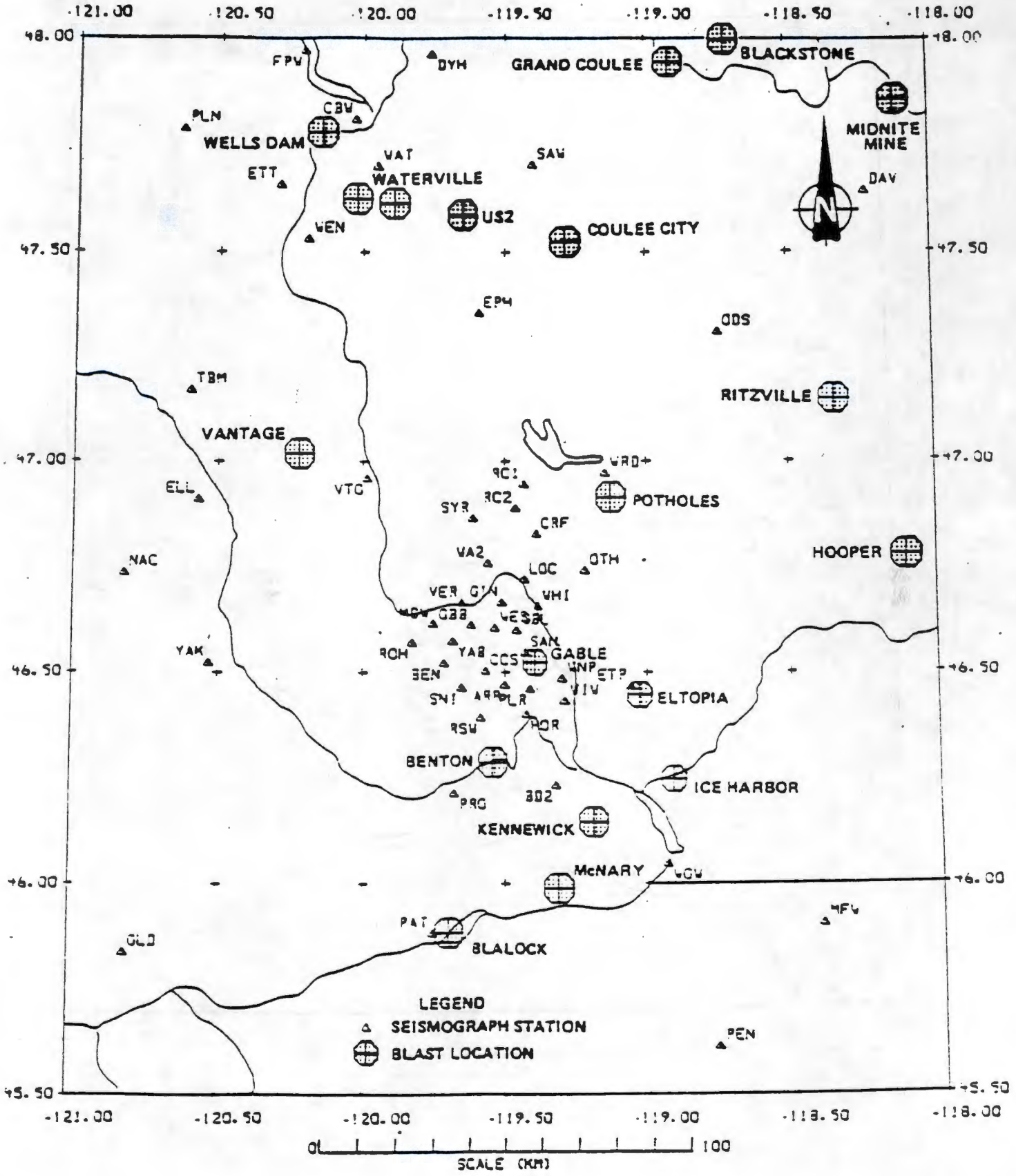

Figure 1. Blast and Station Locations through 1983.

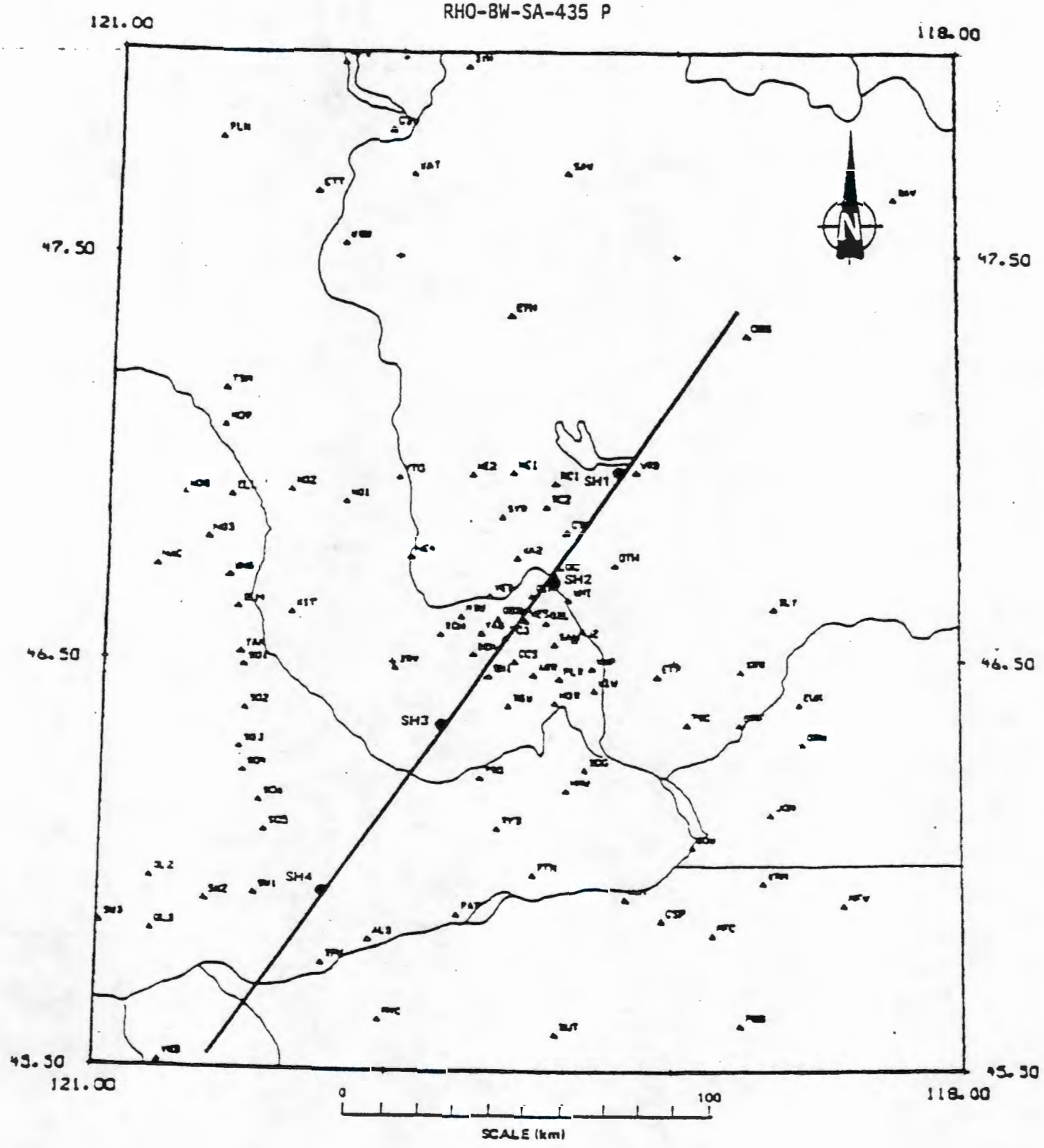

Figure 2. Blast and Station Locations, August 1984.

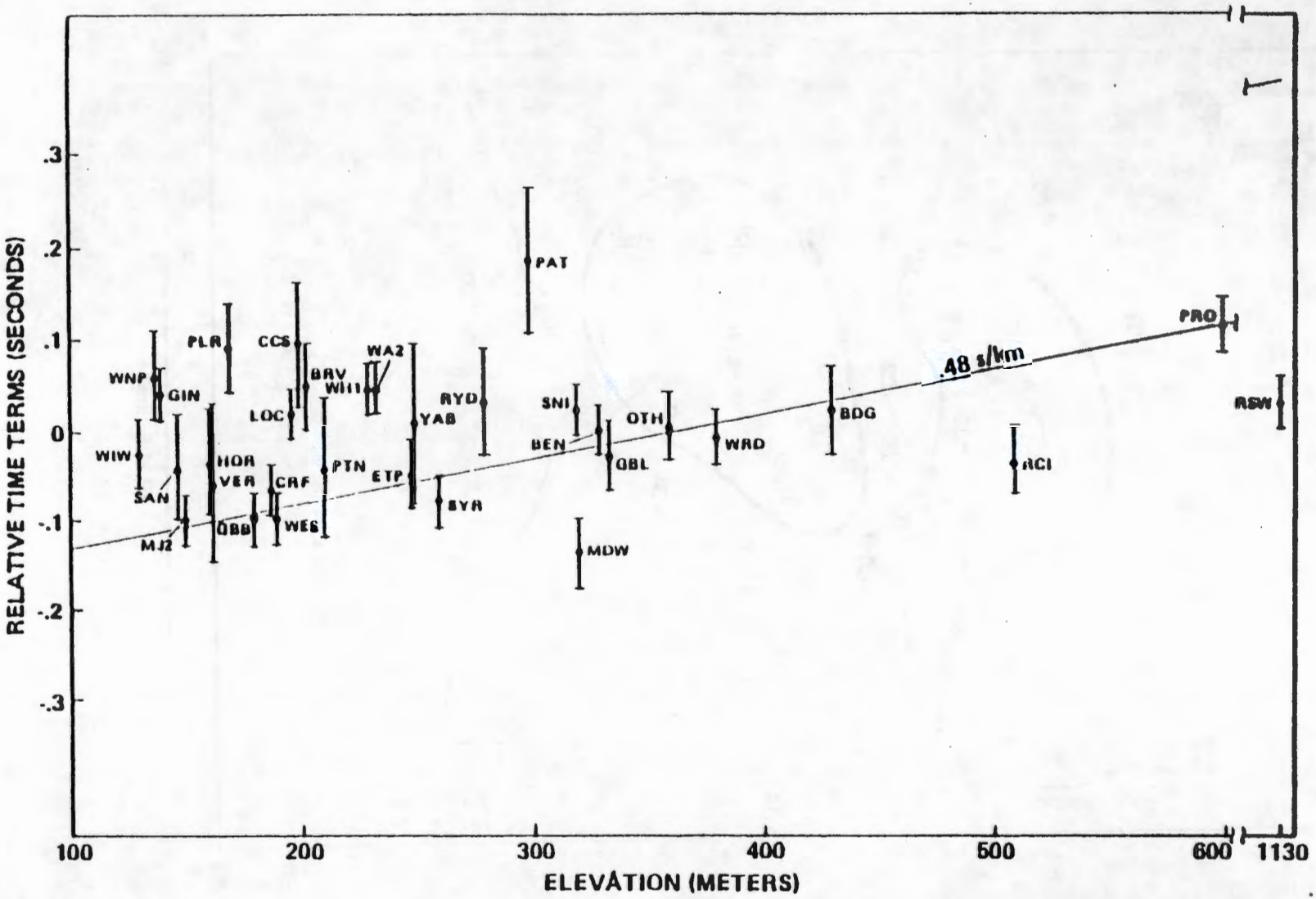

Figure 3. Time Terms from the 5.16-km/s Refractor.

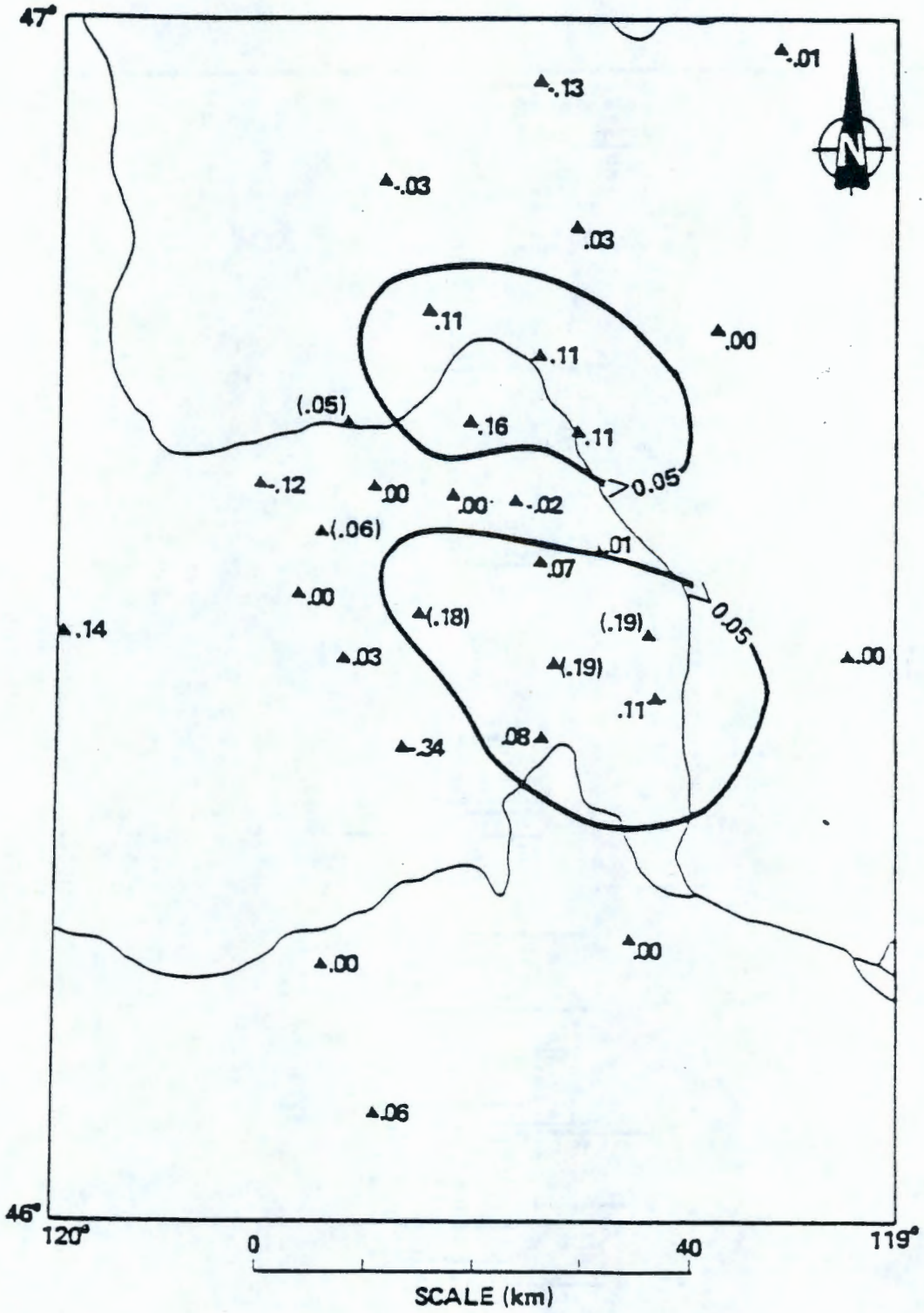

Figure 4. Map of Elevation-corrected Time Terms.

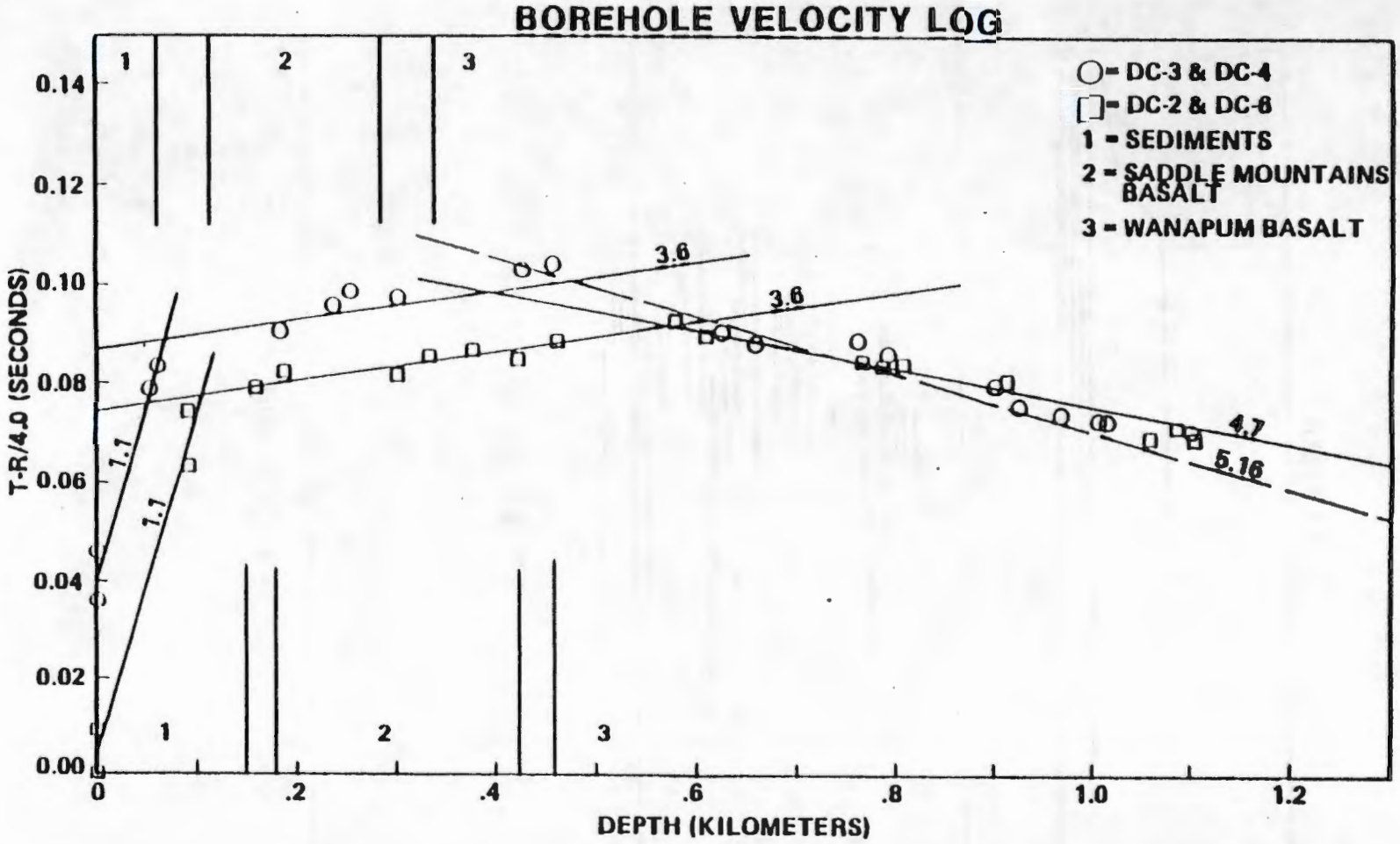

Figure 5. Reduced Borehole-velocity Logs.

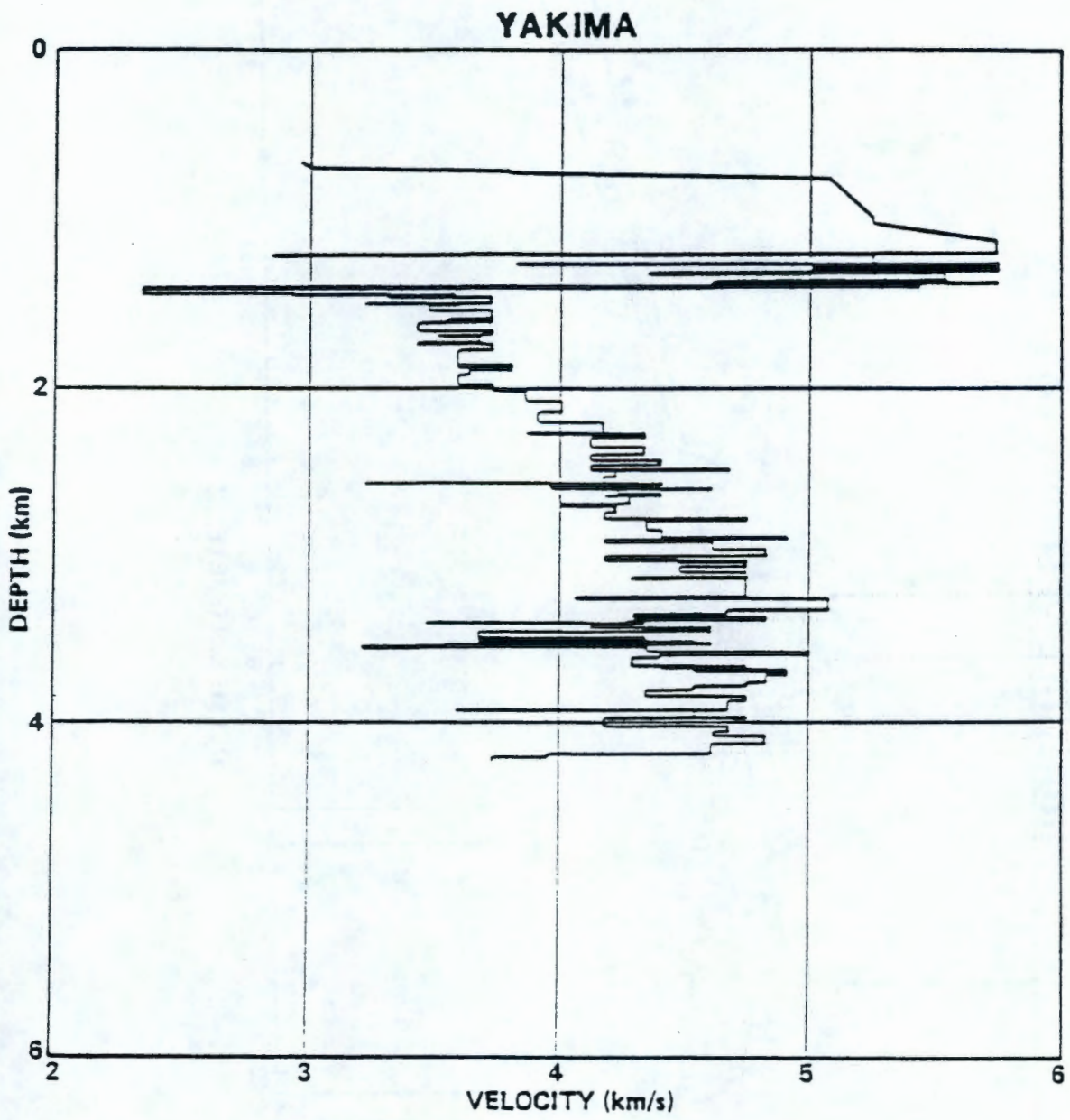

Figure 6a. Deep-borehole Velocity Log, Yakima.

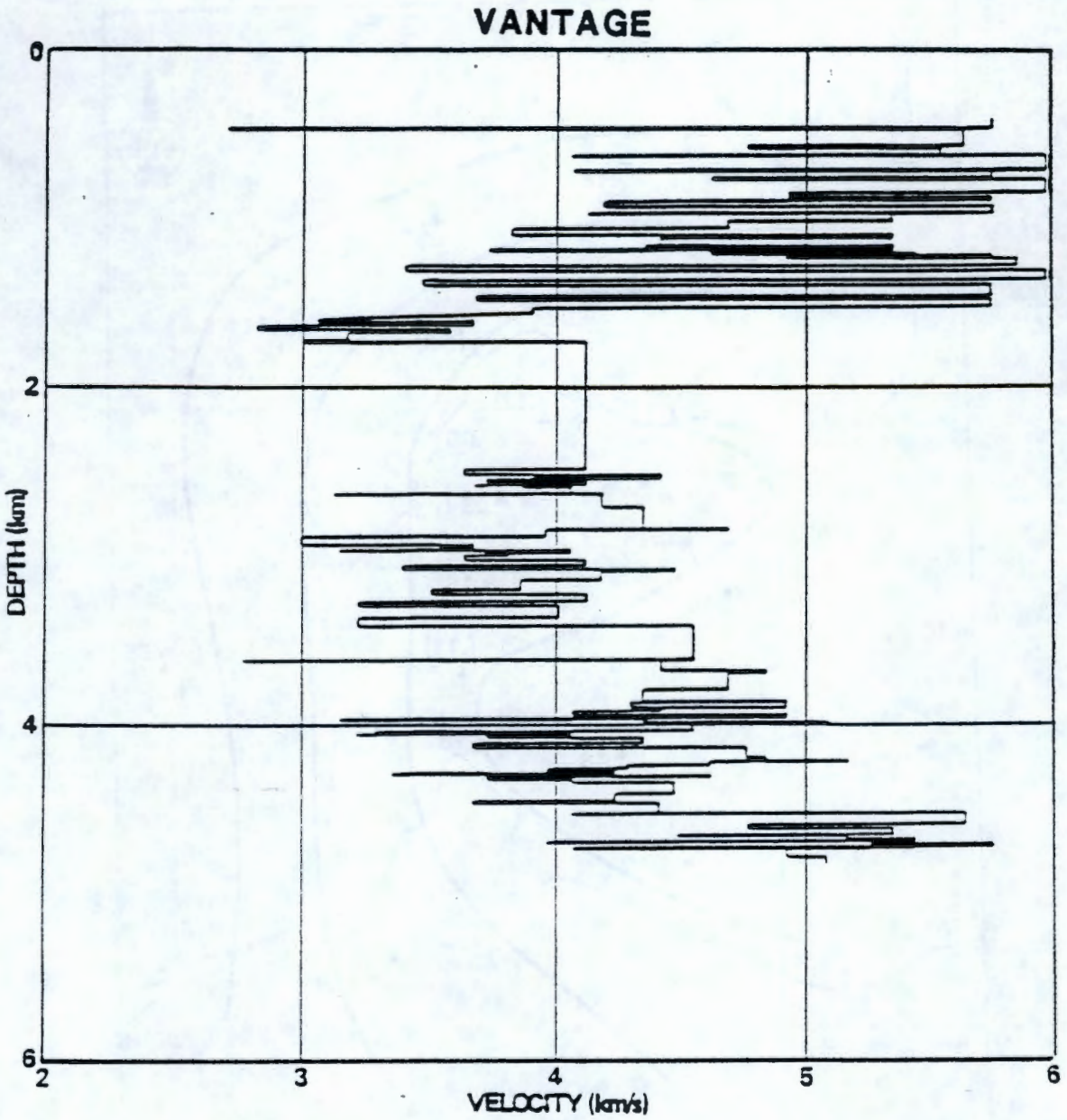

Figure 6b. Deep-borehole Velocity Log, Vantage.

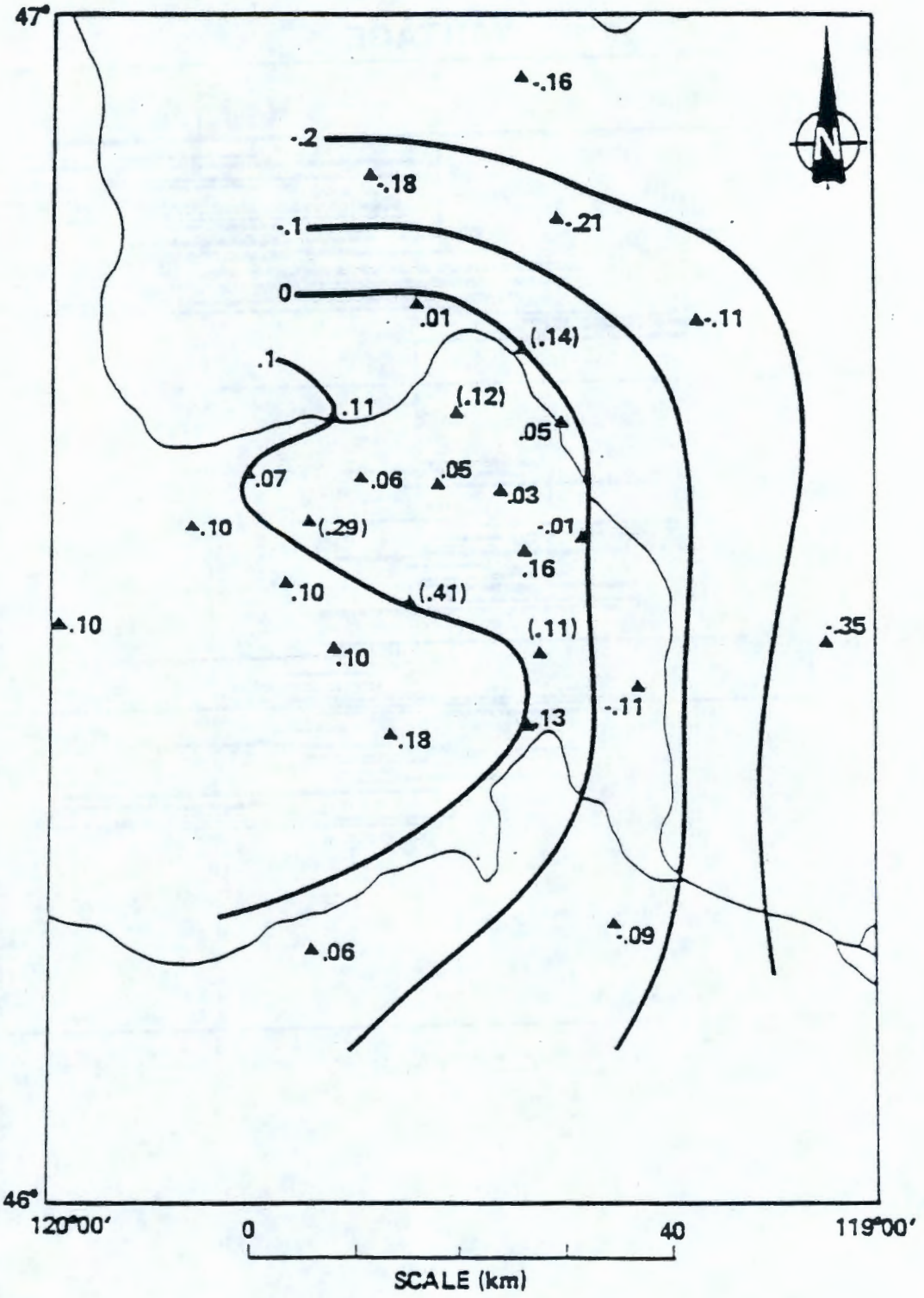

Figure 7. Relative Time Terms, BWIP Network.

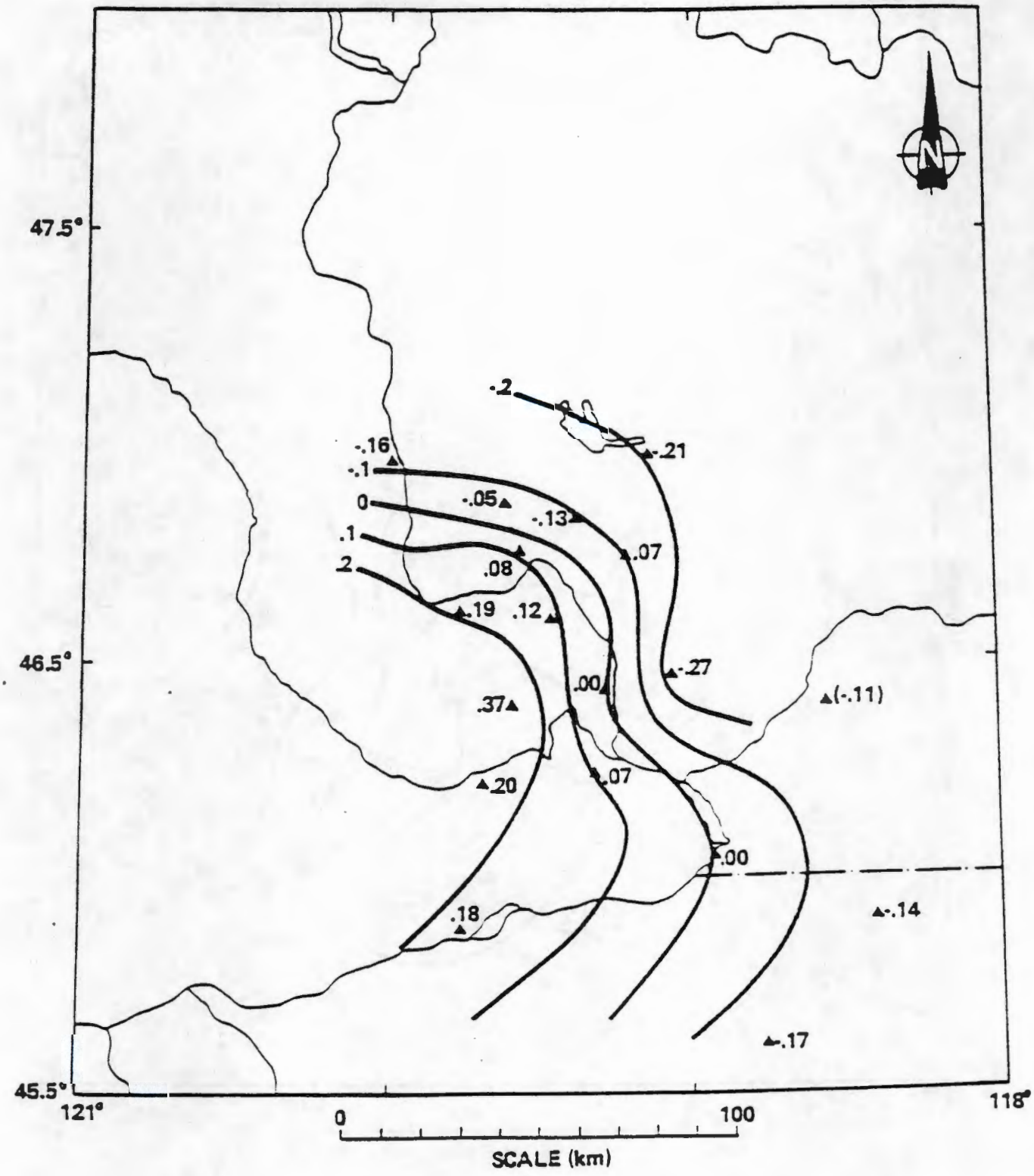

Figure 8. Relative Time Terms, UWGP Network.

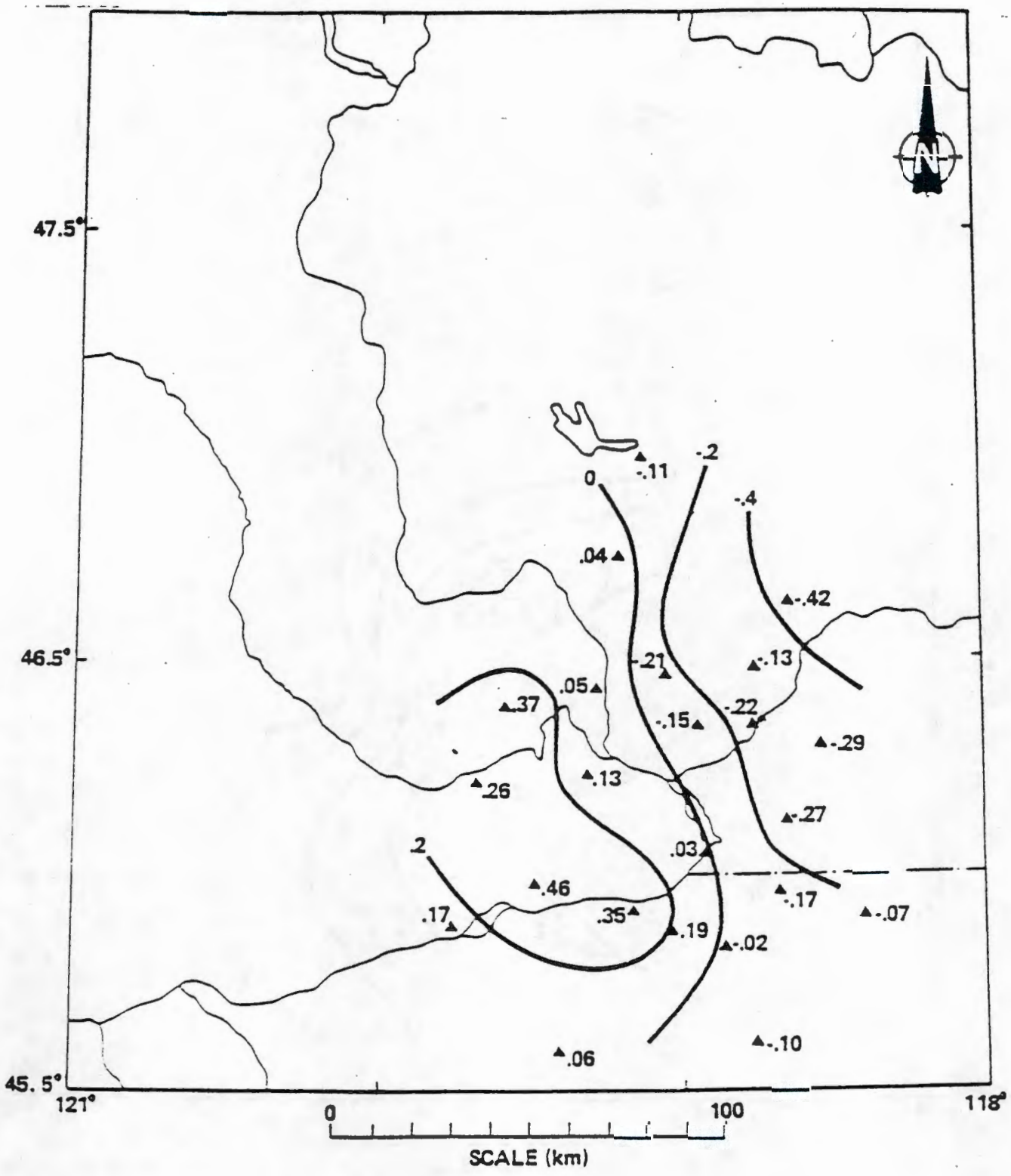

Figure 9. Relative Time Terms, BWIP Temporary Network.

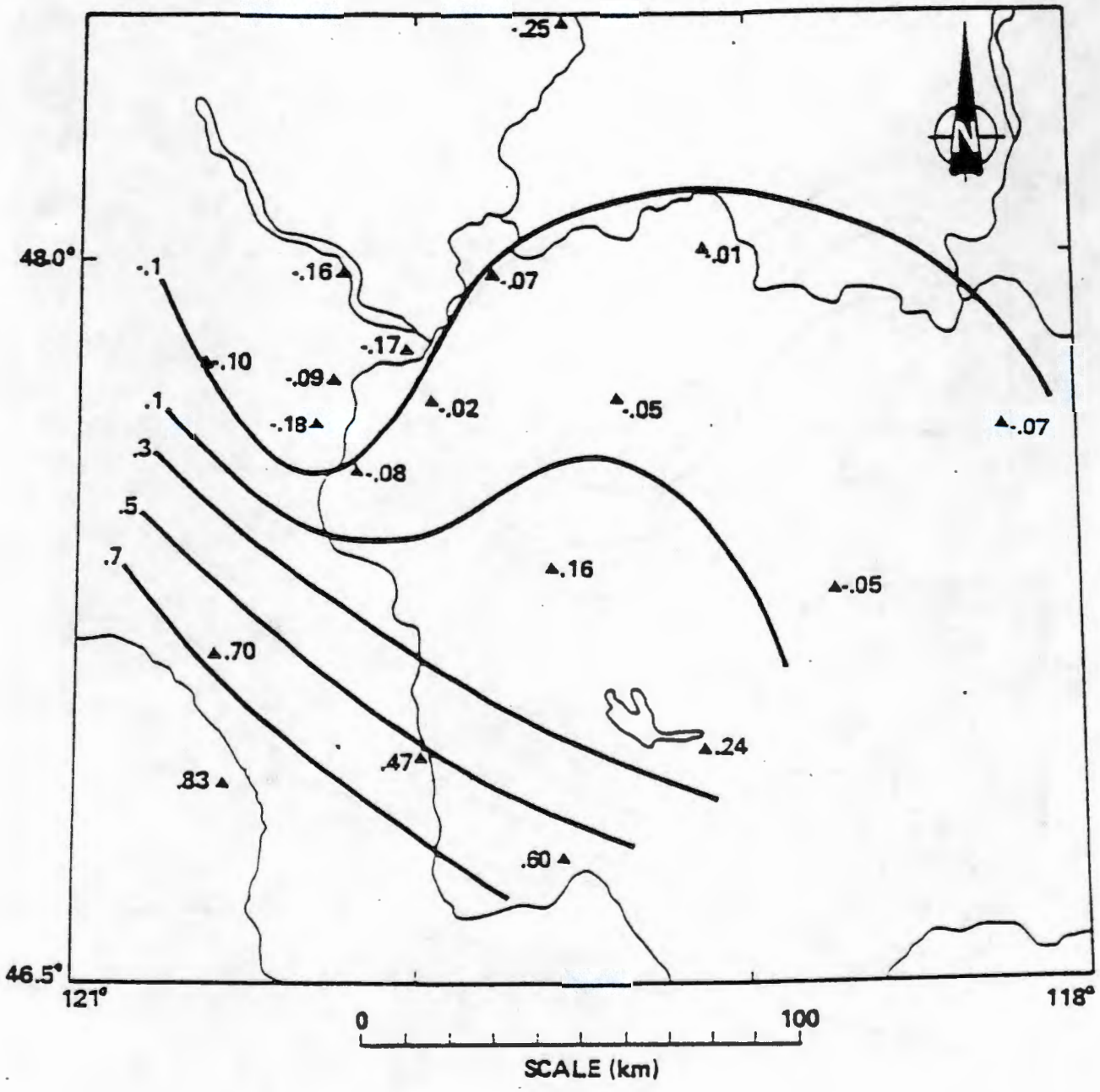

Figure 10. Relative Time Terms, Northeastern Washington.

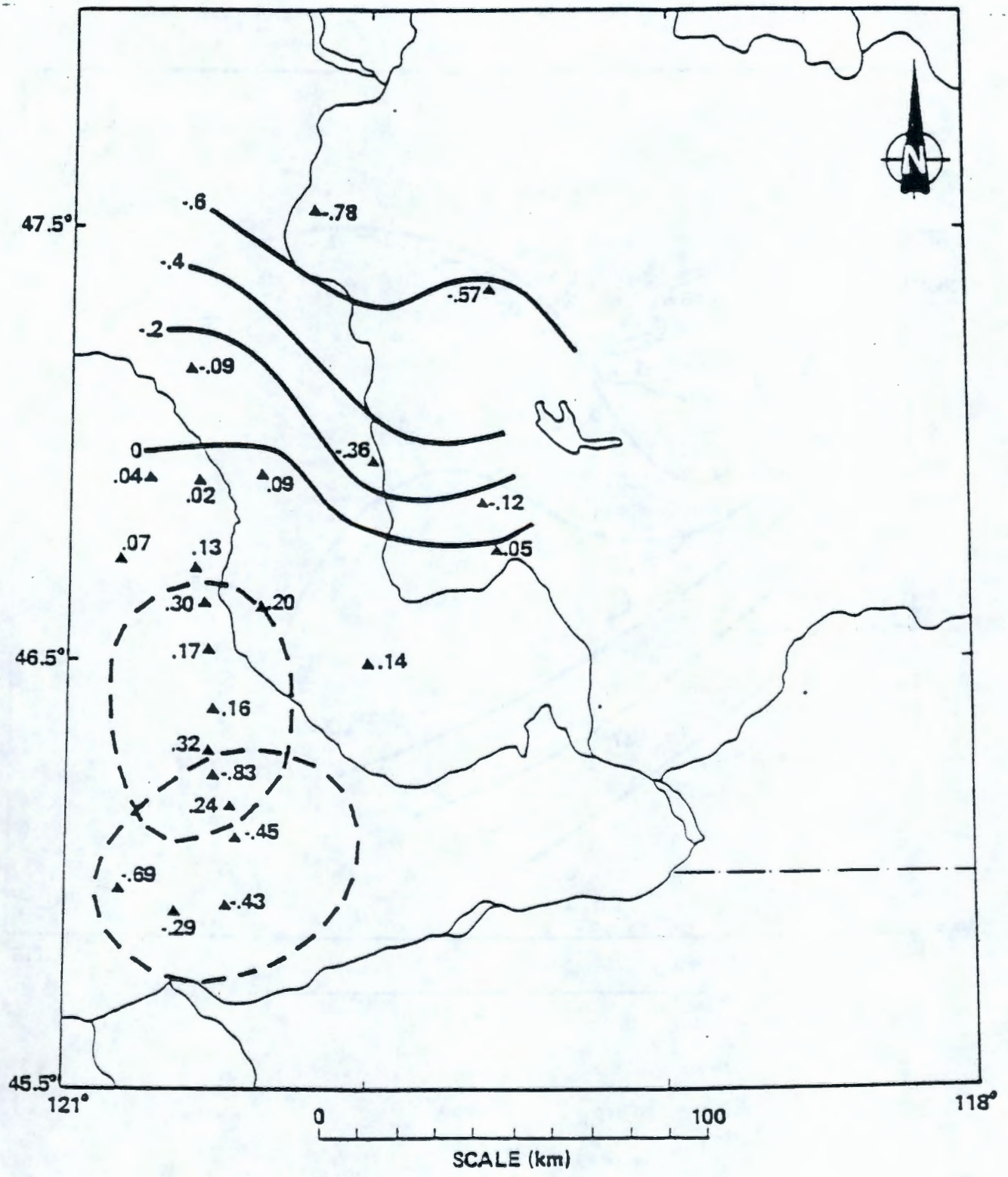

Figure 11. Relative Time Terms, UWGP Temporary Network.

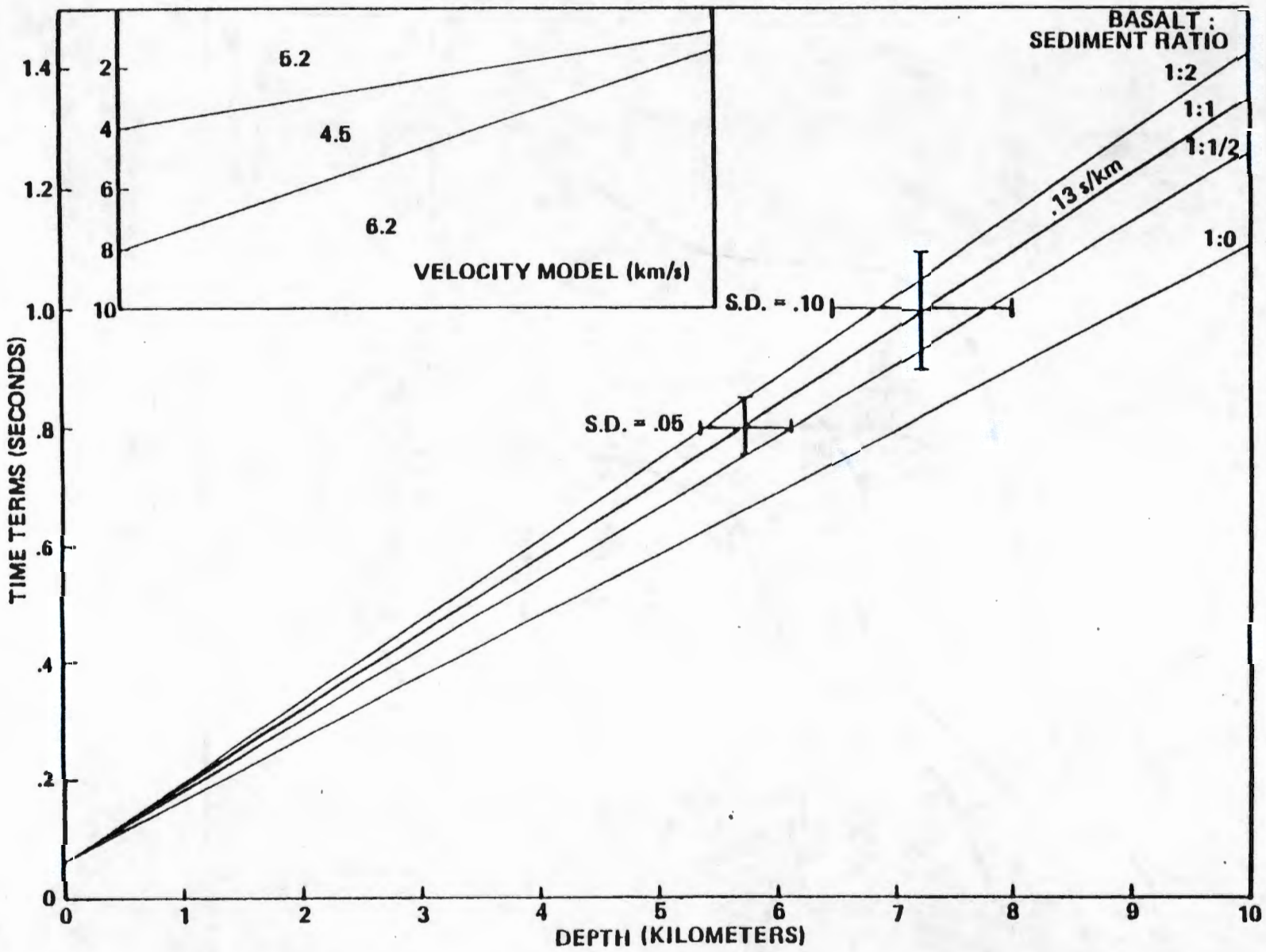

Figure 12. Conversion of Time Terms to Depth.

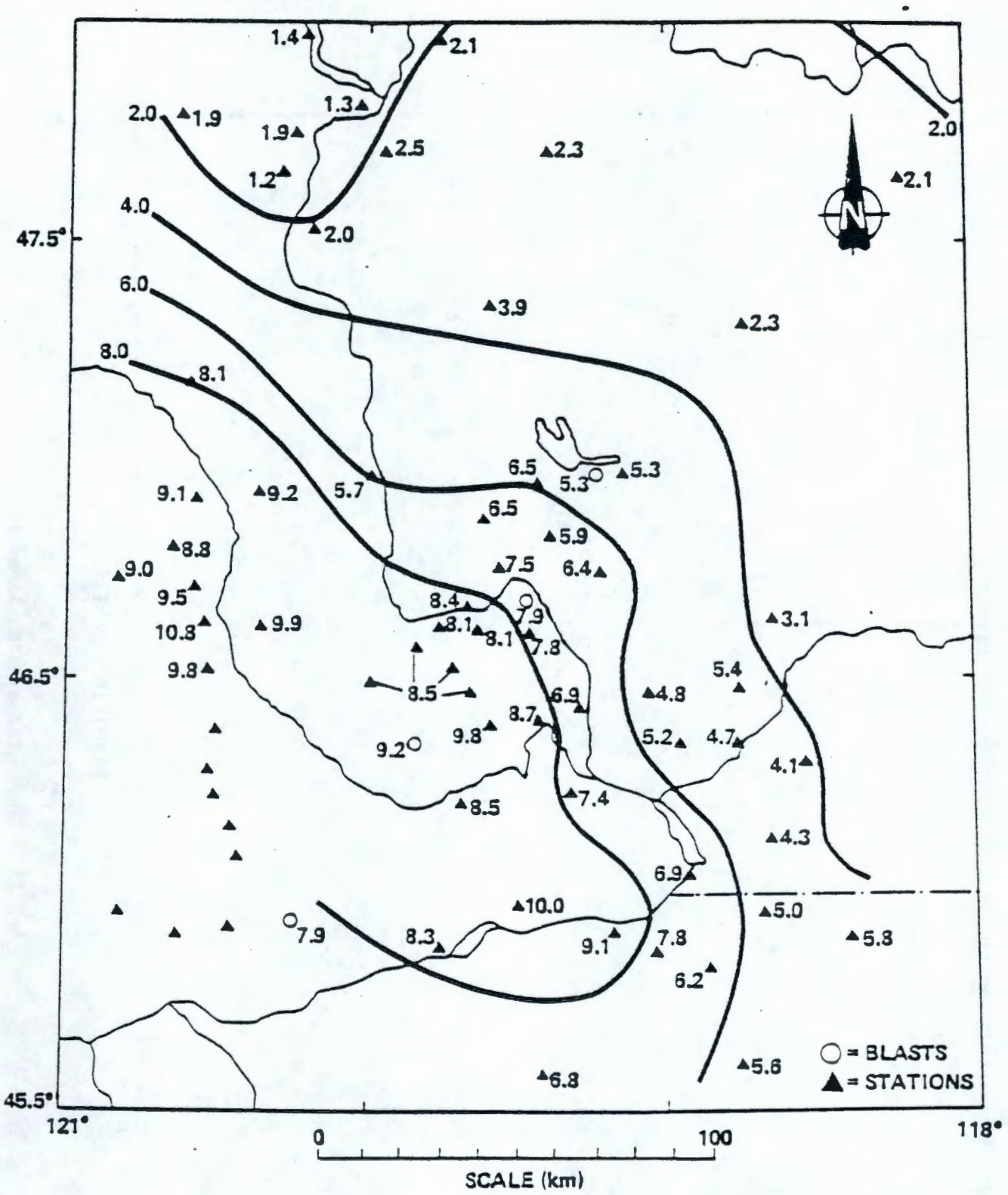

Figure 13. Depth to Basement Derived from Time Terms.

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Catchings, R. D., W. D. Mooney, and W. S. Hollbrook, 1984, Crustal Structure of Southeastern Washington from Seismic Refraction, EOS, vol. 65, no. 45, p. 988.

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

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