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Crustal structure within southwestern Montana and adjacent northeastern Idaho : a seismic refraction study

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CRUSTAL STRUCTURE WITHIN SOUTHWESTERN MONTANA AND ADJACENT NORTHEASTERN IDAHO: A SEISMIC REFRACTION STUDY

By

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Crustal Structure within Southwestern Montana and Northeastern Idaho: A Seismic Refraction Study

Director: Steve S. Sheriff

Previous crustal refraction studies have shown a wide range of values for crustal thickness and upper-mantle velocity within western Montana and adjacent northeastern Idaho. The previous estimates of crustal thickness ranged from 33 km to 50 km and upper-mantle velocity range from 8.0 km/sec to 8.4 km/sec thus indicating the need for a consistent crustal model for this region.

I employed seismographs along three refraction profiles recording both mine explosions and earthquake aftershocks within western Montana and adjacent Idaho. An apparent velocity of 7.57 km/sec was recorded along one of my lines extending from Butte, Montana to Wallace, Idaho. Taking a true velocity of 7.95 km/sec and a strike line from Challis to Butte as indicated from a reversed refraction profile from Stickney and Sheriff (1983), the 7.57 km/sec apparent velocity can be explained by a 3 degree regional dip to the Moho in the northwest direction. The other two refraction lines in my study, north from Challis to Missoula and south from Clinton to Darby strongly support the dip to the Moho. A thin crust (30 km) lies between Challis and Missoula coincident with an area of high seismicity, high heat flow (63-104 mW/m^2) and low Bouguer gravity values. These regional geophysical characteristics are indicative of extension within the Basin and Range province. The crust thickens to the northwest to 47 km at Wallace near the northwestern part of the Idaho batholith and the thickest package of Precambrian Belt Supergroup rocks.

The crust and upper-mantle within my study area can be explained by a relatively simple three layer model with a dip to the Moho. Apparent velocities of 3.40 km/sec to 5.03 km/sec reflect the near surface geology with apparent velocities of 5.86 km/sec to 6.05 km/sec from the intermediate layer and an upper-mantle velocity of 7.95 km/sec. Apparent upper-mantle velocities recorded along unreversed refraction lines will most likely differ from the true velocity because of the dip.

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Chapter 1

INTRODUCTION

Three seismic refraction profiles were employed to study crustal structure and upper mantle velocity for the northern Rocky Mountain region. The study area, shown in Figure 1, includes southwest Montana and part of adjacent Idaho. Preliminary results from one of the lines (Figure 1, line A-B), were given earlier in Carlson and Sheriff (1983), Sheriff and Carlson (1984), and Carlson (1984). The other two lines cross this one near Missoula, Montana, providing extensive seismic refraction coverage for the area and allowing comparison and re-evaluation of our preliminary results (Figure 1, lines C-D and E-F). The primary objective here is to achieve a coherent crustal and upper mantle velocity model for the northern Rocky Mountain region of the contiguous United States.

This region exhibits a diverse and complex regional geology (Figure 1). The Lewis and Clark lineament (Weidman, 1965) defines the northern limit of the study area and may denote a boundary between the craton and a tectonically transported continental margin (Sears, 1983). South of the area are Tertiary and Quaternary volcanic cover of the Snake River Plain-Yellowstone Park region. The eastern end of the study area is a diffuse transition to the plains of central and eastern Montana. Key tectonic features in the east are complexly folded and faulted Paleozoic and Mesozoic age sedimentary rocks, the Cretaceous age Boulder batholith at Butte, Montana and several Tertiary age sedimentary basins

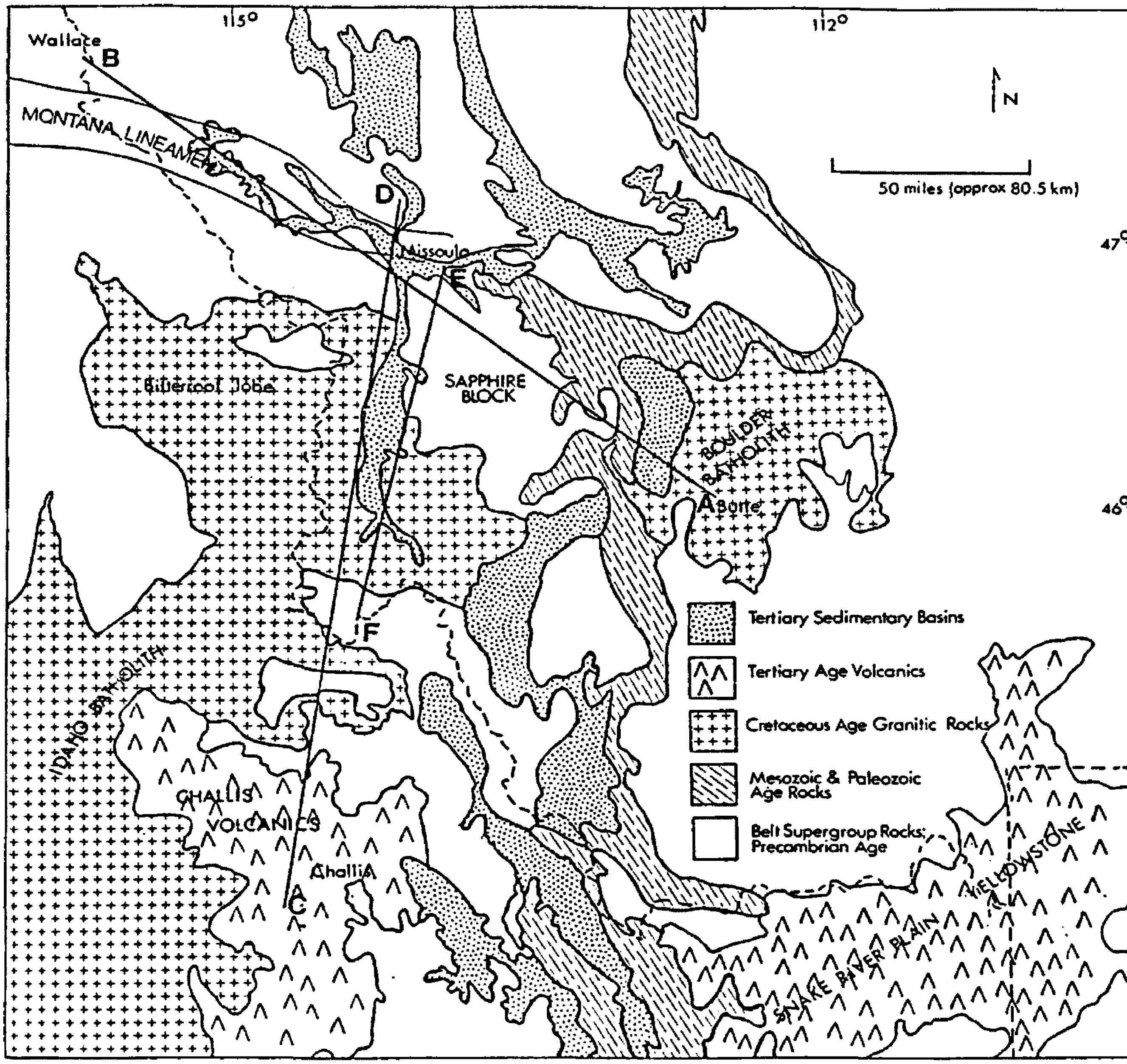

Figure 1. Generalized tectonic and geologic map of study area. Three lines from the study are depicted: line A-B, Butte to Wallace profile, line C-D, Challis to Missoula profile and line E-F, Missoula South profile.

(Thompson, et al., 1982). Most of the folded and faulted Mesozoic and Paleozoic rocks reflect Late Cretaceous-Early Tertiary orogeny and outline the overthrust belt. Superimposed on these structures are structures related to Tertiary extension. This extension is evidenced by normal faulting and seimentary fill and volcanics within the basins. The western boundary is delineated from north to south by: a relatively thick package of Belt Supergroup sedimentary rocks of Precambrian age, the Late Cretaceous Idaho Batholith and Tertiary Challis volcanics and sedimentary rocks.

The northern Rocky Mountain region is the northernmost extent of the regional Bouguer gravity low and high regional heat flow (62.7-104.5 mW/m^2) which typify the Basin and Range province (Eaton et al., 1978; Blackwell, 1978). The region also lies within the Intermountain seismic belt (ISB) (Smith, 1978); 1119 earthquakes of magnitude 1.5 or greater were recorded in 1984 within the Montana area (Stickney, 1986). Figure 2 shows the epicenters of these earthquakes clustering within the study area and marking a zone of intense seismic activity. The October 30, 1983 Borah Peak earthquake of magnitude 7.3, certainly signifies the prevalant seismicity within the area. Studies of focal mechanisms indicate normal movement with occasional strike slip motion for most of the earthquakes in the region (Stickney, 1986; Smith, 1978).

There are several reasons why a cohesive crustal structure and velocity model are needed for the study area. It would aid in more accurately determining locations of earthquakes and provide the groundwork for possible deep reflection profiling. In addition, an accurate model is a critical first step in evaluating the

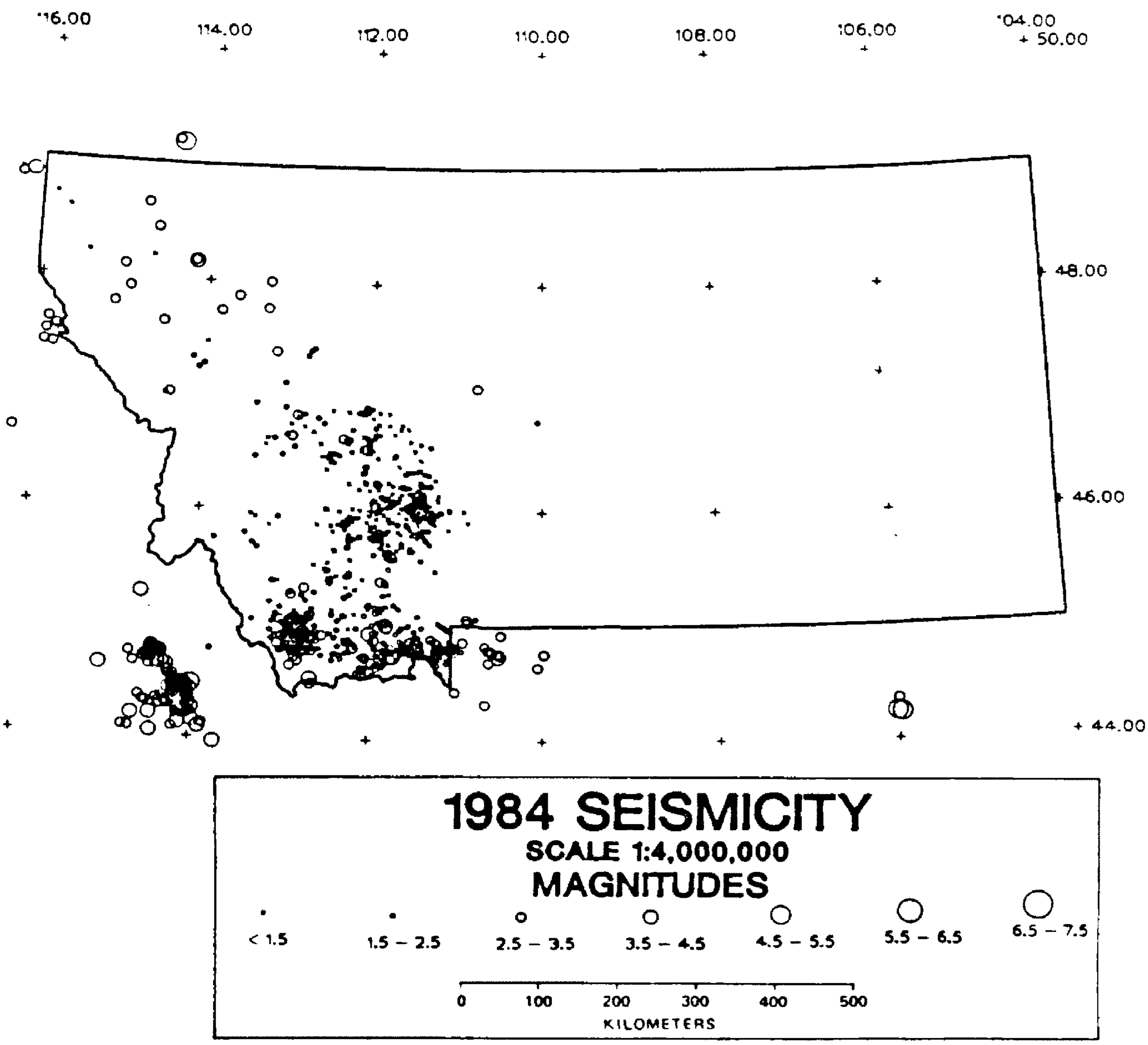

Figure 2. Epicenters for 1984 earthquakes recorded in the Montana region (Yellowstone Park included) from Stickney, 1986

tectonic framework for geologic and geophysical investigations within the area.

For example, on the basis of crustal thickness, Coney and Harms (1984) invoke a unified model to explain metamorphic core complexes within the western Cordillera. Figure 1 shows two refraction lines (A-B, C-D) crossing near the Bitterroot lobe of the Idaho Batholith, a metamorphic core complex described by Hyndman (1983). Also, Hyndman (1983) infers that eastward unloading of the 17 km thick Sapphire tectonic block formed the mylonitic zone which outlines the eastward dipping fault at the base of the block. One of the lines in the study (Figure 1, line E-F) transects the western edge of the Sapphire tectonic block and provides an interesting test for seismic refraction.

Regional studies of mineral occurrences and oil and gas potential within the study area attest to the importance of knowing crustal thickness and structure (Lopez, 1984; Warne, 1984; Lange and Sherry, 1983; Winston, 1983; Kansanewich, 1968). Kansanewich (1968) suggests that a major Precambrian rift underlies the northerly trend of productive sediment hosted mineral deposits from the Kimberely Field, Canada to the Cour de' Alene district of eastern Idaho and western Montana. Apparently, faults related to this rifting event are periodically reactivated during orogenic events and act as conduits for mineral rich fluids (Kansanewich, 1968). Lange and Sherry (1983), and Winston (1983) also invoke a similar crustal model to explain the extensive sediment hosted mineral occurrences within western Montana.

Lopez (1984), and Warne (1984) report on favorable oil and gas potential north of the Snake River Plain in the southeast part of the study area. They also discuss the critical need to develop the tectonic and orogenic framework here as related to this potential. Thus, the results of this study may also provide a foundation to understand the regional tectonics for these and other geologic and geophysical investigations.

Chapter 2

PREVIOUS RESULTS

In discussing the results and interpretations, the following notations will be used for identifying phases: P stands for compressional wave and S stands for shear wave; P1 is the direct wave from near surface geology, Pg (Sg) is the critically refracted wave from the upper crustal layer, Pn (Sn) is the critically refracted wave from the top of the mantle (M-discontinuity), and PmP is the reflected wave from the M-discontinuity. Figure 3 shows the locations of several previous seismic refraction studies in the northern Rocky Mountains. These studies present a wide range of estimates for crustal thickness and upper mantle velocities for the region. The discrepancies result because these studies are beset with some of the problems in seismic refraction analysis. For example, with the exception of the results from Hales and Nation (1973), all the previous refraction data for the region are presented as points on a time-distance graph. None of the previous studies have identified or utilized wide angle reflections from the M-discontinuity. These reflections, if recorded and properly recognized, would strongly supplement determination of crustal thickness. Also, all the studies within the northern Rocky Mountain region entail relatively widely spaced stations. Furthermore, only three out of the eleven profiles for the area are reversed. These three reversed profiles are from the crustal studies of McCamy and Myer (1964), Ballard (1980) and Sheriff and Stickney (1984).

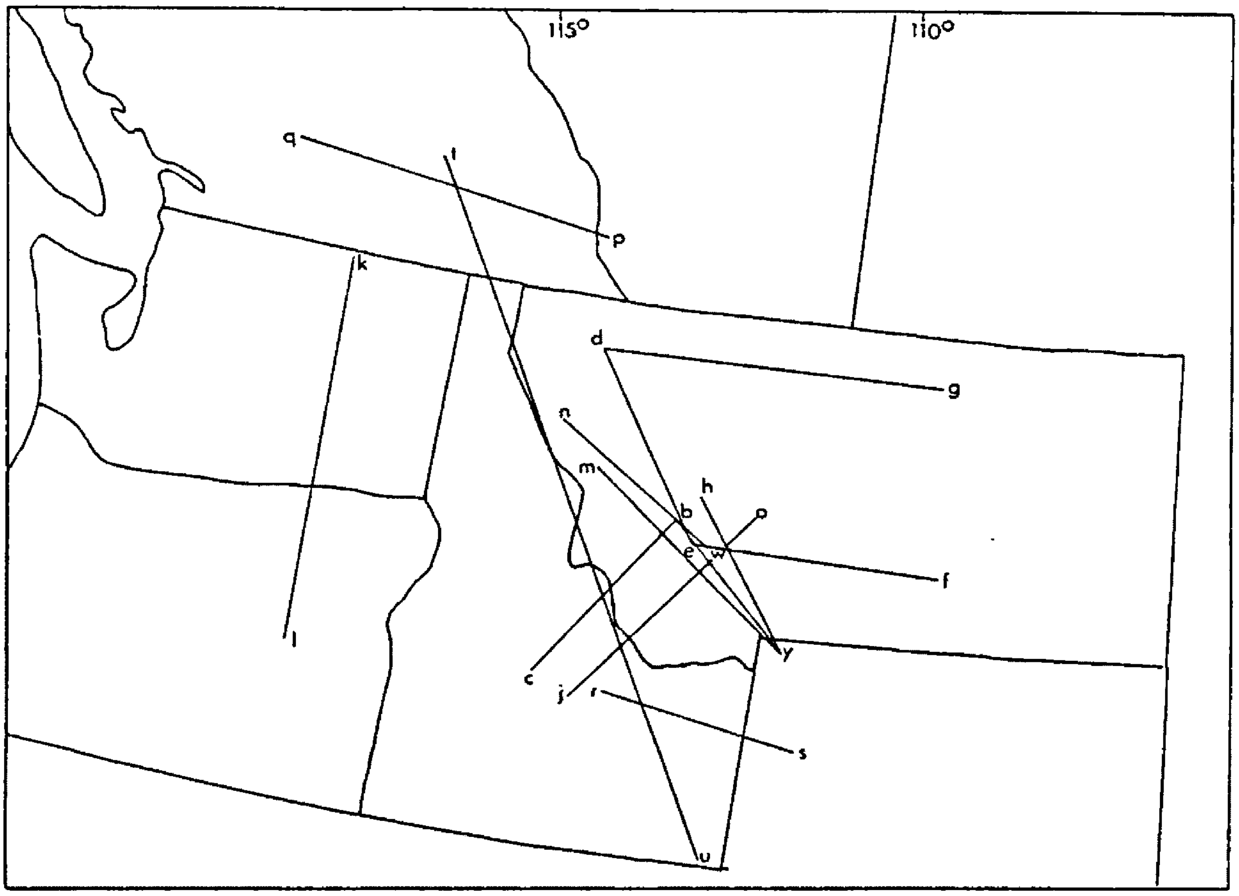

Figure 3. Location map showing previous refraction lines pertinent to the northern Rocky Mountain region, r stands for reversed line. Line e-d (r), McCamy and Myer (1964); lines d-g, e-f, Asada and Tuve (1959) and McCamy and Myer (1964); line c-b (r), Stickney and Sheriff (1983); lines y-h (r), y-b, y-m, Ballard (1980); line t-u, Hales and Nation (1966); line w-m, DeBoer (1983); line j-o, Stickney (1985); line r-s, Sparlin et. al., (1982); line p-q (r), Cumming et. al., (1978), line k-j, Hill (1972).

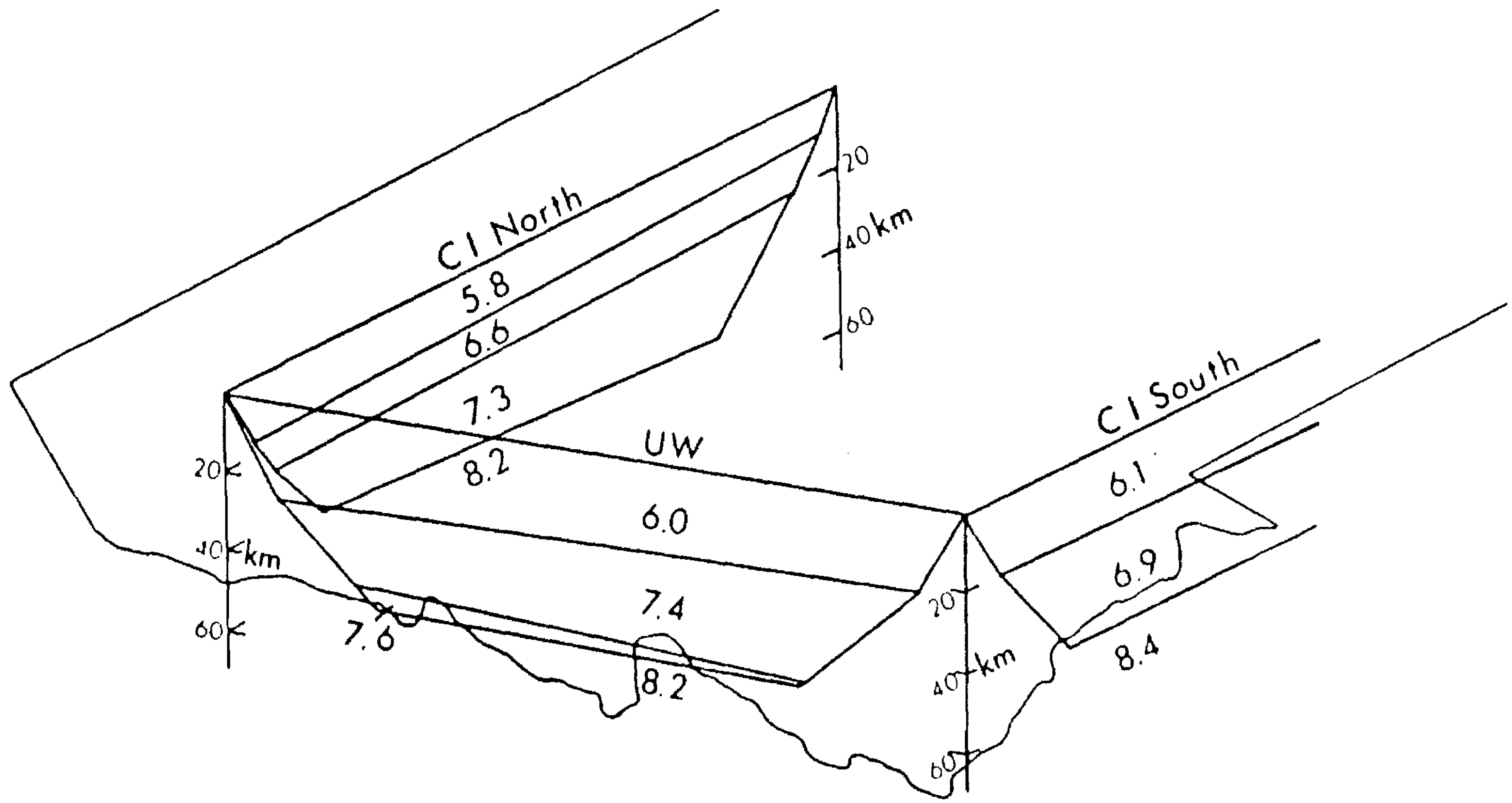

Figure 4. Crustal model for western Montana from McCamy and Myer (1964). C I North and South are unreversed lines from Carnegie Institute (1959) and U W is a reversed profile by Steinhart and Myer (1959), after McCamy and Myer (1964).

Figure 4 shows the crustal model derived by McCamy and Myer (1964). This model consists of an 20 km thick layer dipping to the northwest with a seismic velocity of 6.0 km/sec; an 20 km thick layer dipping to the southeast with a 7.4 km/sec velocity; a wedge of 7.6 km/sec material increasing in thickness from near 1 km in the southeast to about 5 km thick to the northwest. A 40 km to 50 km thick crust is indicated below the reversed line of McCamy and Myer (1964), (Figure 3, line d–e). The Pn velocity in the model is 8.2 km/sec in the west and north and 8.4 km/sec along the south line (C–I south line, Figure 4). The C–I south and north unreversed lines, shown in Figure 4, were employed by the Carnegie Institution (Asada and Aldrich, 1966) and included into McCamy and Myer's (1964) results. These two lines project east from each end point of McCamy and Myer's (1964) reversed profile (lines e–f and d–g, Figure 3). To the north, the M–discontinuity is inferred to dip in the eastward direction with the strike along the direction of the reversed line (Figure 4). The data and preliminary interpretation from these lines are published in an earlier report by Myer et. al. (1959). Interestingly, the initial determination from the reversed profile (Myer et. al., 1959), indicated a Pn velocity of 7.95 +–.02 km/sec, rather than the 8.2 km/sec as shown in Figure 4. Evidently, McCamy and Myer (1964) arrived at this higher Pn velocity by incorporating the Pn velocities from the Carnegie Institution's unreversed lines. The apparent Pn velocities recorded along these lines are: 8.15 km/sec from the line north and 8.40 km/sec from the line south (Myer et. al., 1959). Since higher apparent velocities are recorded in the updip direction, Asada and Aldrich (1966) contend that the high Pn velocities from these unreversed lines suggest a westward dipping M–

discontinuity, rather than eastward as indicated by McCamy and Myer (1964).

A reversed profile by Stickney and Sheriff (1983) between Butte, Montana and near Challis, Idaho (line c–b, Figure 3) also indicates: 1) a horizontal M-discontinuity, 2) an average Pg velocity of 5.9 km/sec, 3) an upper mantle velocity (Pn) of 8.0 km/sec, beneath a one layer, 33 km thick crust. This Pn velocity is approximately the same as recorded in the reversed profile by McCamy and Myer (1964); however, the crustal thickness between the two differs by approximately 25%. This wide disparity may result from the recognition and inclusion of intermediate layers in the analysis. Sheriff and Stickney (1984) used mainly first arrival times in their calculations which involved no intermediate crustal layers, whereas McCamy and Myer (1964) utilized second arrivals and included two intermediate layers in their analysis. McCamy and Myer (1964) also used an extensive method of phase correlation in an attempt to verify their results.

Ballard (1980) used earthquakes located in Montana and Yellowstone Park as a source and employed recording stations for three refraction profiles in southwestern Montana. His reversed profile indicated that the M-discontinuity dipped 0.56 degrees along this line to the northwest (Figure 3, line y–h). An apparent Pn velocity of 8.01 km/sec was recorded to the north and 8.16 km/sec recorded to the south. The other unreversed refraction lines resulted in low apparent Pn velocities, 7.92 km/sec (Figure 3, line y–b) and 7.69 km/sec (Figure 3, line y–m). This latter velocity was discounted and not used in the final analysis because it was inferred to be an average velocity of the lower crust and upper mantle (Ballard, 1980). Ballard (1980) combined his results with results from

McCamy and Myer (1964) and utilized gravity data to conclude that the Moho dips to the southwest. Figure 5 is a crustal model from Ballard (1980) between Helena, Montana and Yellowstone Park and includes: a 20 km thick, 5.98 km/sec layer, an intermediate 20 km thick, 6.55 km/sec crustal layer, and a Pn velocity of 8.08 km/sec. He infers that the crust thickens from 40 km at Helena to near 60 km at the southwestern border of Montana and Idaho. Ballard (1980) did not indicate whether he corrected for the hypocenters in the earthquake data. Without these corrections his intermediate crustal and Pn velocities are suspect as well as his calculated crustal thickness.

Hales and Nation (1973) conducted a crustal study using an unreversed refraction line stretching from British Columbia, Canada, through westernmost Montana to Texas. Figure 3, line t-u, shows the segment of the refraction line in Montana. Their interpretation from this section consists of: an assumed 0.2 km thick layer representing valley fill sediments with a 3.0 km/sec velocity; a upper crustal layer, approximately 22 km thick with a 6.0 km/sec velocity, a lower crustal layer about 14 km thick with a 6.41 km/sec velocity, and a Pn velocity of 8.04 km/sec. The station spacing in their Rocky Mountain segment averaged 20 km. Hales and Nation (1973) also report of an amplitude attenuation in the Pn phase within southwest Montana which may suggest a low velocity zone. If a low velocity layer did exist, the actual crustal thickness would be less than calculated from conventional seismic refraction analysis.

In our initial analysis (Carlson and Sheriff, 1983; Sheriff and Carlson, 1984; and Carlson, 1984) we obtained a relatively low Pn velocity of 7.6 km/sec from a

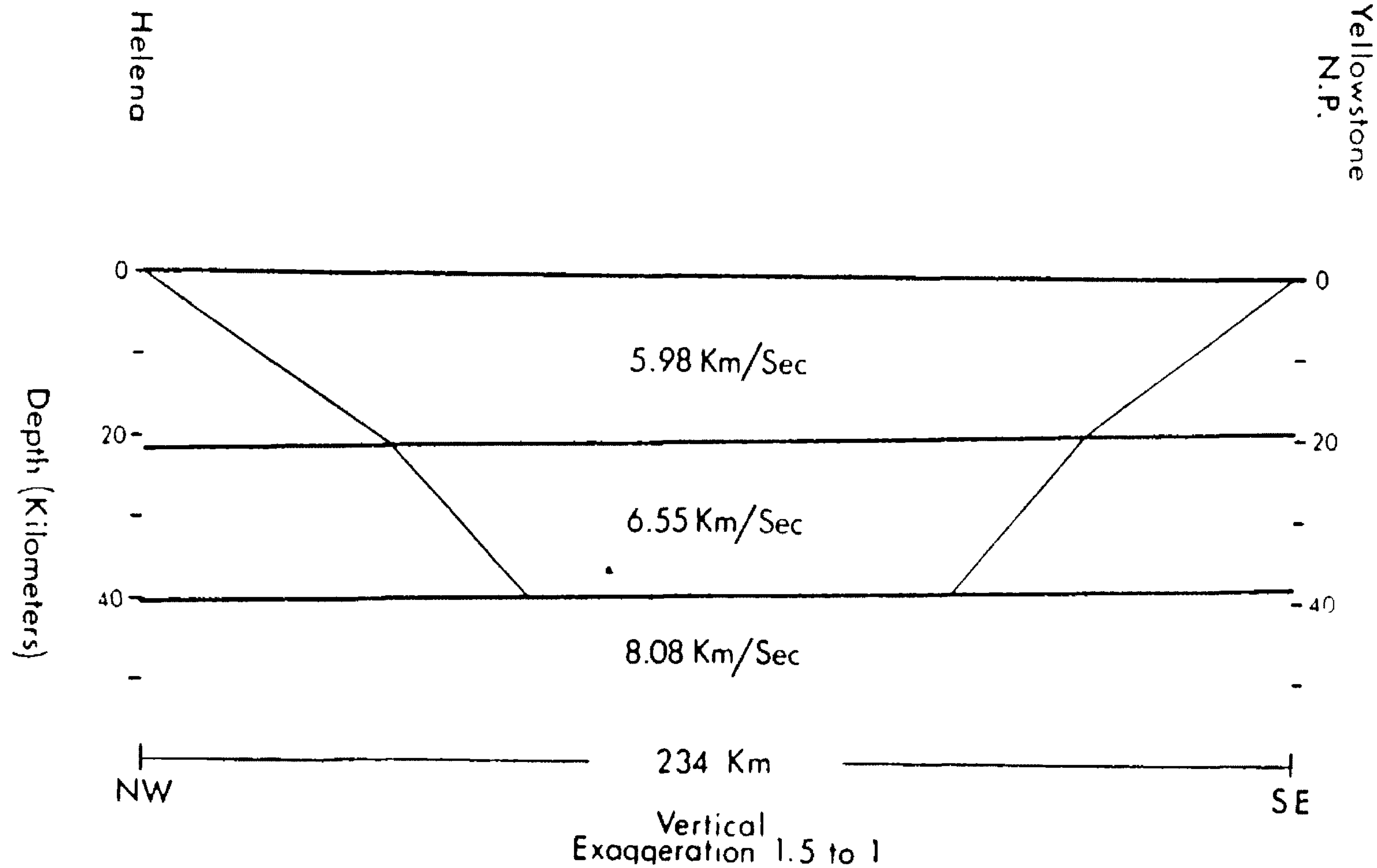

Figure 5. Crustal model between Helena and Yellowstone Park derived from a reversed profile by Ballard (1980).

one way refraction line extending from Butte, Montana to Wallace, Idaho (Figure 1, line A-B). We took this as an apparent velocity and assumed a true velocity of 8.0 km/sec and concluded that the M-discontinuity dipped to the northwest at about 3 degrees. In nearly the same location and direction, DeBoer (1984), arrived at the same apparent velocity of 7.6 km/sec from a one way refraction profile (Figure 3, line w-n). He supported our conclusion that the crust thickened from 33 km near Butte, Montana to about 50 km at the western end. DeBoer (1984) attempted to reverse this profile from a quarry blast near Missoula, but only recorded the Pg wave as first arrival in this 145 km line segment to the east. However, DeBoer (1984) was able to constrain a range of possible apparent Pn velocities for this line to the east by using the fact that both ends of the Pn travel time should be equal on his time distance graph for a reversed profile. Since the Pn phase was not recorded as a first arrival at 145 km, this point and the expected end point restricted a possible Pn velocity to a range of 8.20 km/sec to 8.40 km/sec. These velocities are within the range of expected apparent Pn velocities for the inferred updip direction (DeBoer, 1984).

Using aftershocks from the 1983 Borah Peak earthquake, Stickney (1985) constructed an unreversed refraction line extending northeast across southwest Montana (Figure 3, line j-o). This line is parallel to, but approximately 80 km east of, the reversed line of Sheriff and Stickney (1984). Average station spacing was approximately 12 km. Stickney (1985) recorded an apparent Pn velocity of 7.96 km/sec, nearly the same as the 7.97 km/sec Pn velocity recorded along the southeast to northeast segment of the reversed line of Sheriff and Stickney (1984).

However, his velocity fell to 7.78 km/sec after applying elevation corrections for hypocenter depths in the earthquake aftershock data. He calculated a crustal thickness of 25 km from a two layer model with a direct wave (Pg) velocity of 6.14 km/sec and the 7.78 km/sec Pn velocity. Stickney (1985) noted that this thickness was abnormally low because he probably missed a blind zone in his analysis. As evidence for this, Stickney (1985) indicated that his recorded Pg velocity of 6.14 km/sec is near the 6.15 km/sec velocity recorded by Sparlin (1978) for an intermediate crustal layer within the Snake River Plain to the south (Stickney, 1985). He pointed out that the refraction analysis by Sheriff and Stickney (1984) may have also missed a blind zone resulting in underestimating the thickness of the crust between Challis and Butte. Stickney (1985) further suggested using waveform analysis and wide angle reflections to avoid such pitfalls.

Residual times from six well located aftershocks recorded at 20 regional stations (> 650 km) from the Borah Peak earthquake, also give evidence for an intermediate crustal layer within the northern Rocky Mountains (Stickney, 1985, Richins et. al., 1985). The residual times were reduced when a 40 km thick crustal model was applied to the aftershock data as opposed to a 33 km thick model (Stickney, 1985). This 40 km thick model, shown in Figure 6, was also used to locate the hypocenters of the Borah Peak aftershocks (Richins et. al., 1985). The intermediate layers within the model were derived from unreversed refraction profiles by Sparlin et. al. (1982) with station spacings of 3-5 km, and unpublished University of Utah data with station spacings of 1 km. Yet, the refraction profile of Sparlin et. al. (1982) was across the Snake River Plain which shows the

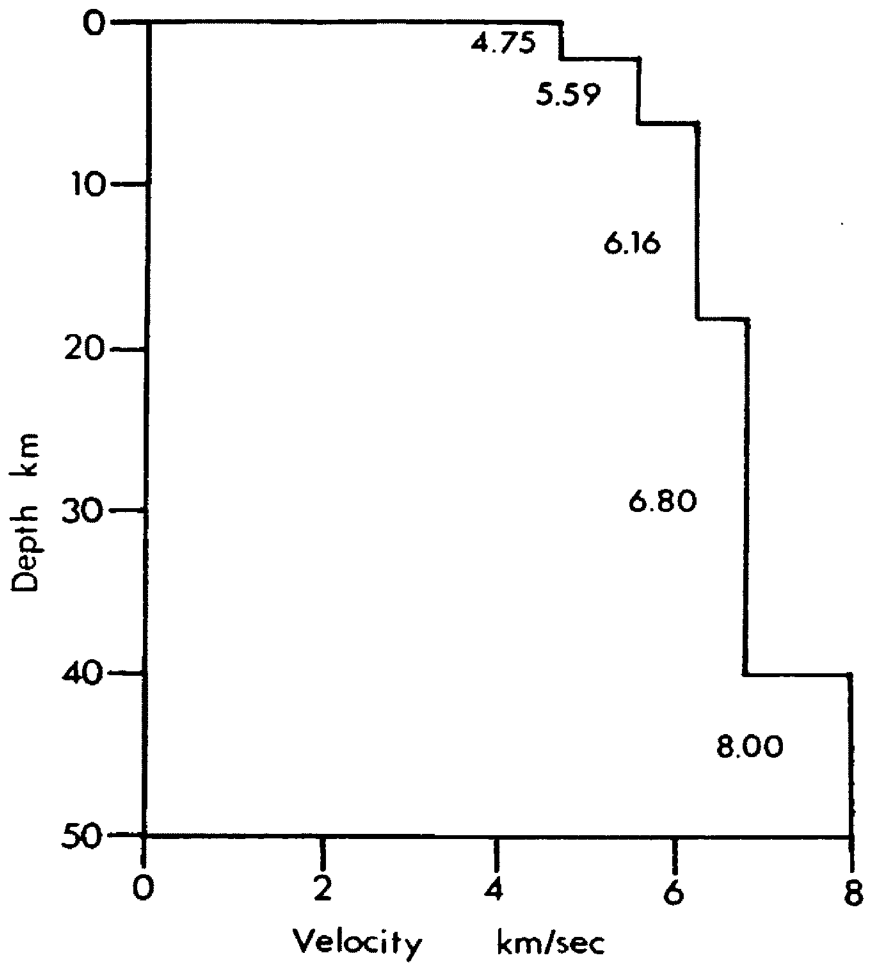

Figure 6. Crustal model for hypocenter corrections for the 1983 Borah Peak earthquake aftershocks (from Richins et. al., 1985).

intermediate layers to be localized within this physiographic province. The upper mantle velocity of 8.0 km/sec was taken from the reversed profile of Sheriff and Stickney (1984), (Richins et. al., 1985).

Crustal studies for the regions outlining the northern Rocky Mountains provide constraints for a crustal model within the study area. Sparlin et. al., (1982) achieved a detailed crustal model across the Snake River Plain by using close (3-5 km) station spacings (Figure 3, r-s). This reversed refraction profile was one of several employed in the Yellowstone-Snake River Plain (Y-SRP) investigation of crustal structure. Sparlin et. al., (1982) calculated a 40 km thick crust by using PmP phases and correlating with other refraction profiles in the area.

Figure 3, line p-q shows the location of a partially reversed profile across southern British Columbia, Canada by Cumming et. al., (1978). These workers indicated that the crust thinned, from 50 km thick at the eastern end to near 30 km at the western end. They recorded an upper mantle velocity of 7.8 km/sec.

Several reversed and unreversed lines indicate a 50 km thick crust for eastern Montana and western North Dakota (see McCamy and Myer, 1964; Allenby and Schnetzler, 1983). The Pn velocity recorded along these lines ranges from 8.2 km/sec to 8.4 km/sec (McCamy and Myer, 1964). The data for crustal thickness west of the study area are relatively sparse. Hill (1972) constructed a one way refraction line south from southernmost British Columbia, across the Columbia Plateau in eastern Washington and Oregon (Figure 3, line k-l). He recorded an apparent Pn velocity of 8.2 km/sec but assumed a true velocity of 7.9 km/sec from other regional studies. Based on these data and assumptions, Hill (1972) calculated a 30 km thick crust for eastern Washington and inferred that the crust thinned to approximately 18 km under the Columbia Plateau basalts.

Recently, Allenby and Schnetzler (1983) compiled numerous refraction studies and contoured expected crustal thicknesses and velocities for the conterminous United States (Figures 7 and 8). They use McCamy and Myer's (1964) results for the northern Rocky Mountains. The difference in crustal thickness from 50 km in eastern Montana to 20 km in eastern Washington, clearly suggests an east dipping M-discontinuity at the regional scale. However, only the reversed profile by Ballard (1980) indicates a dip to the M-discontinuity (line y-h, Figure 3). Although the reversed profiles by Sheriff and Stickney (1984) and McCamy and Myer (1964) are about 70 degrees from being parallel, both indicate a horizontal M-discontinuity (lines c-b and e-d, respectively, Figure 3).

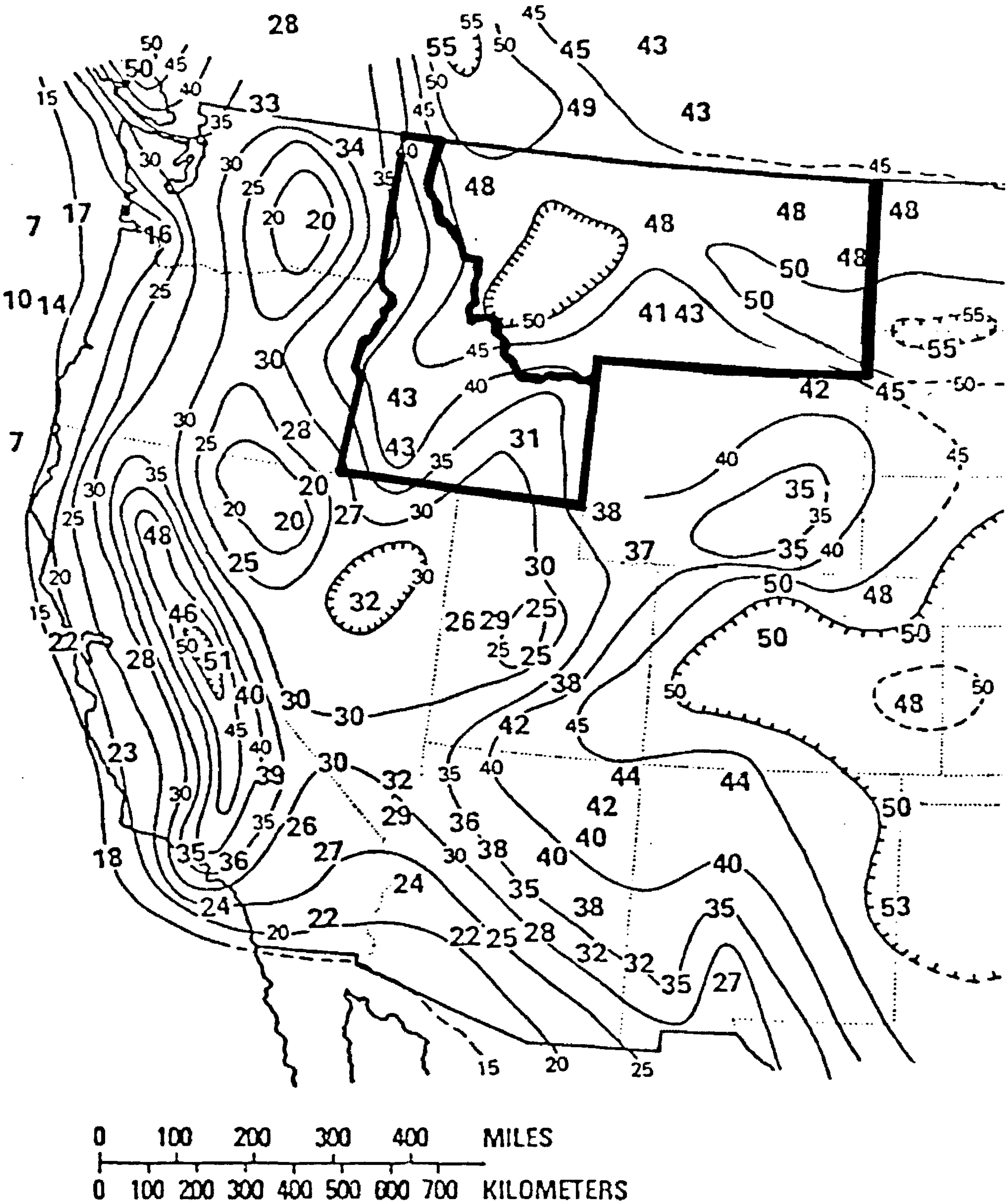

Figure 7. Crustal thicknesses for the western United States, compiled from seismic refraction studies by Allenby and Schnetzler (1983).

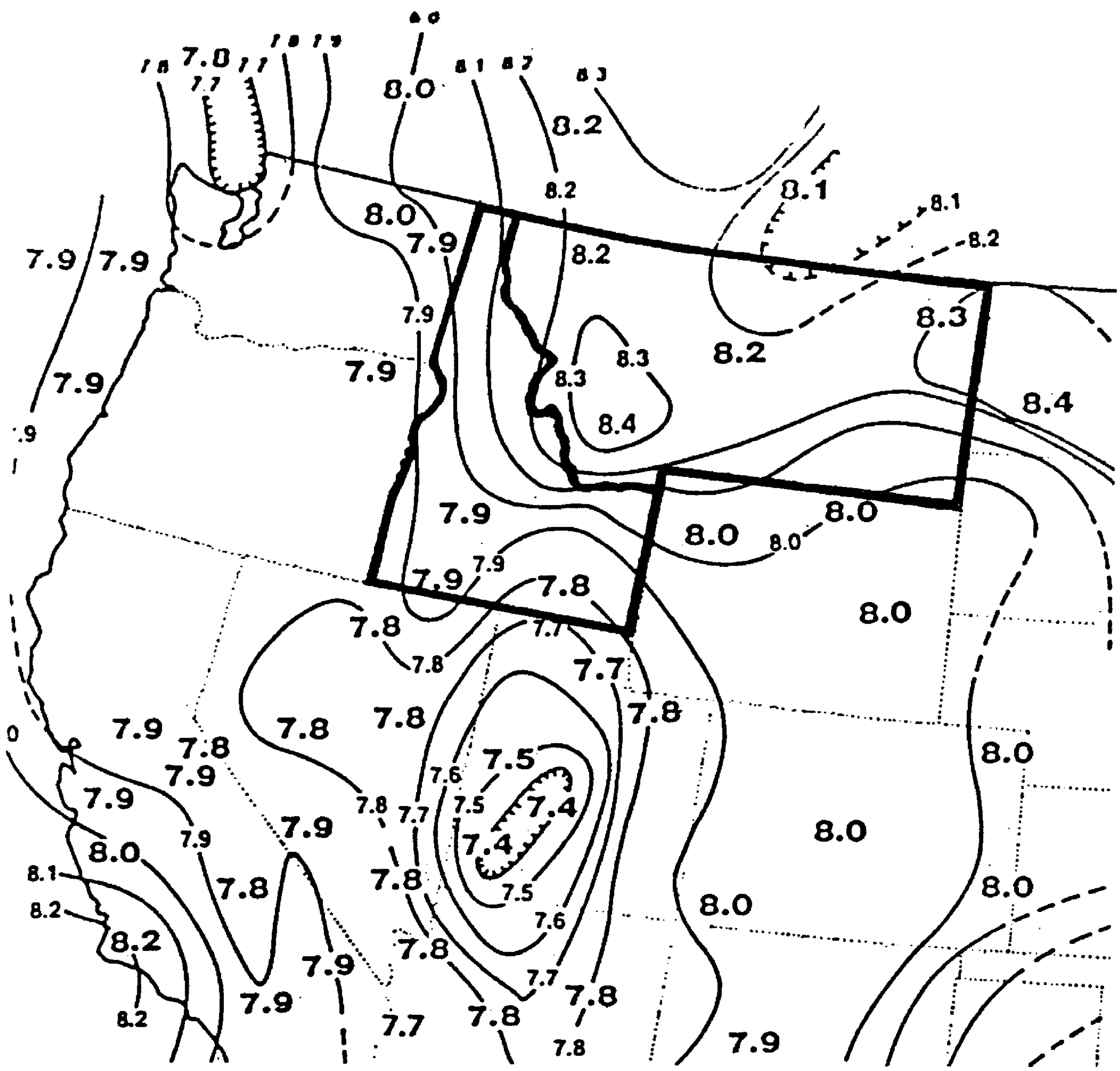

Figure 8. Upper-mantle velocities for the western United States, scale is same as in Figure 7. Compiled by Allenby and Schnetzler (1983).

Chapter 3

DATA COLLECTION

Crustal thickness is related to and provides a measure of the orogenic activity, and thus is critical in evaluating regional tectonics. The base of the crust is taken as the M-discontinuity and based on seismic reflection has been shown to be a relatively complex crust-mantle transition (Oliver, et. al., 1983). In seismic refraction, the complexity is generally averaged in the final analysis and therefore, indicates the average crustal thickness for the region. This is because there are several assumptions usually made in seismic refraction analysis.

Planar interfaces, whether dipping or horizontal are usually assumed in seismic refraction analysis. However, if an interface were dipping, the dip could not be ascertained from the results of a single refraction profile in one direction. An unreversed profile across dipping layers would yield only apparent velocities. If the profile extends in the direction of dip, the apparent velocity would be lower than the true velocity. In the updip direction, the apparent velocity would be higher. For a reversed profile displayed on a time-distance graph, the intersection of the line segments representing a dipping layer would not lie at the center of the graph, whereas if the layer is horizontal; the intersection would be centered.

Obviously, the resolution of the seismic refraction survey is governed by the station spacings. This is because using widely spaced stations averages lateral and horizontal velocity differences in crustal and upper mantle structure. It also becomes more difficult to recognize secondary phases representing intermediate layers which follow the initial arrival on the seismogram. If these later arrivals from an intermediate crustal layer are omitted in the analysis, as they often are in head wave or first arrival analysis, this becomes a blind zone as summarized by Won and Bevis (1984). The blind zone results in underestimating crustal thickness by as much as 40 percent (Won and Bevis, 1984). Certainly the further the stations are apart, the easier it is to miss an intermediate layer in the analysis, especially if the data are represented only as points on a time-distance plot.

To obviate these problems in seismic refraction analysis, Mueller and Landisman (1971) propose: 1) that the data be represented as traces on the time distance graph rather than as data points from a pick and plot method, 2) that the traces should be plotted on a reduced travel-time graph, 3) that wide angle reflections be used to support the refraction data, and 4) that the average station spacing in the survey should be 5 km or less. However, while many workers indicate this average interval spacing and less, they also show large gaps between some sites. It appears that several authors chose to interpret intermediate crustal layers by drawing lines within these gaps (eg. Smith et al., 1982, Braile et al., 1982, Richins et al., 1984), so that the layers are only supported by a few widely spaced points.

The locations of the three seismic refraction lines in this study are shown in Figure 1. On each line Sprengnether 800 MEQ recorders were deployed with vertical component seismometers. The data consist of analogue traces recorded on smoked paper. The internal time marks from the recorders were referenced to universal time from a signal directly input on the seismograms from radio station WWV. Time marks at the beginning and end of the records indicated no time drift among the instruments. Drum rotation speeds for all but four records were 120 mm/min.

These other four, at 60 mm/min, were among the thirty records obtained from instruments deployed at different locations along a 272 km profile from Butte, Montana to Wallace, Idaho (line A-B, Figure 1). Eight of these records were not used because of instrument failure or wind and cultural noise obliterating the traces. Figure 9 shows the twenty-two remaining stations along this profile which recorded clear traces from the Anaconda Company mine blast at Butte, Montana. Seven additional first arrival times, recorded by Hawley (1978) supplemented the twenty-two seismograms. The addition of these data provided an average station spacing of 9.3 km; however, no data were recorded between 228 km and 266 km.

Figure 10 displays the locations of the twenty-one out of the twenty-five seismograms which recorded good arrival times from the Cyprus mine blast located approximately 40 km southwest of Challis, Idaho. Stations along this line segment extended 185 km north, for a station spacing of 9.3 km, the same spacing as obtained along the Butte to Wallace profile. The largest gap between stations along the 185 line segment was approximately 15 km. Providing additional data for this profile were thirty-four recordings of independently located aftershocks from the 1983 Borah Peak earthquake located near Challis (U.S.G.S. Open File Report 85-290). These recordings were obtained from portable seismographs occupying seven sites and from two permanent stations (MSO and NMC) operated by the

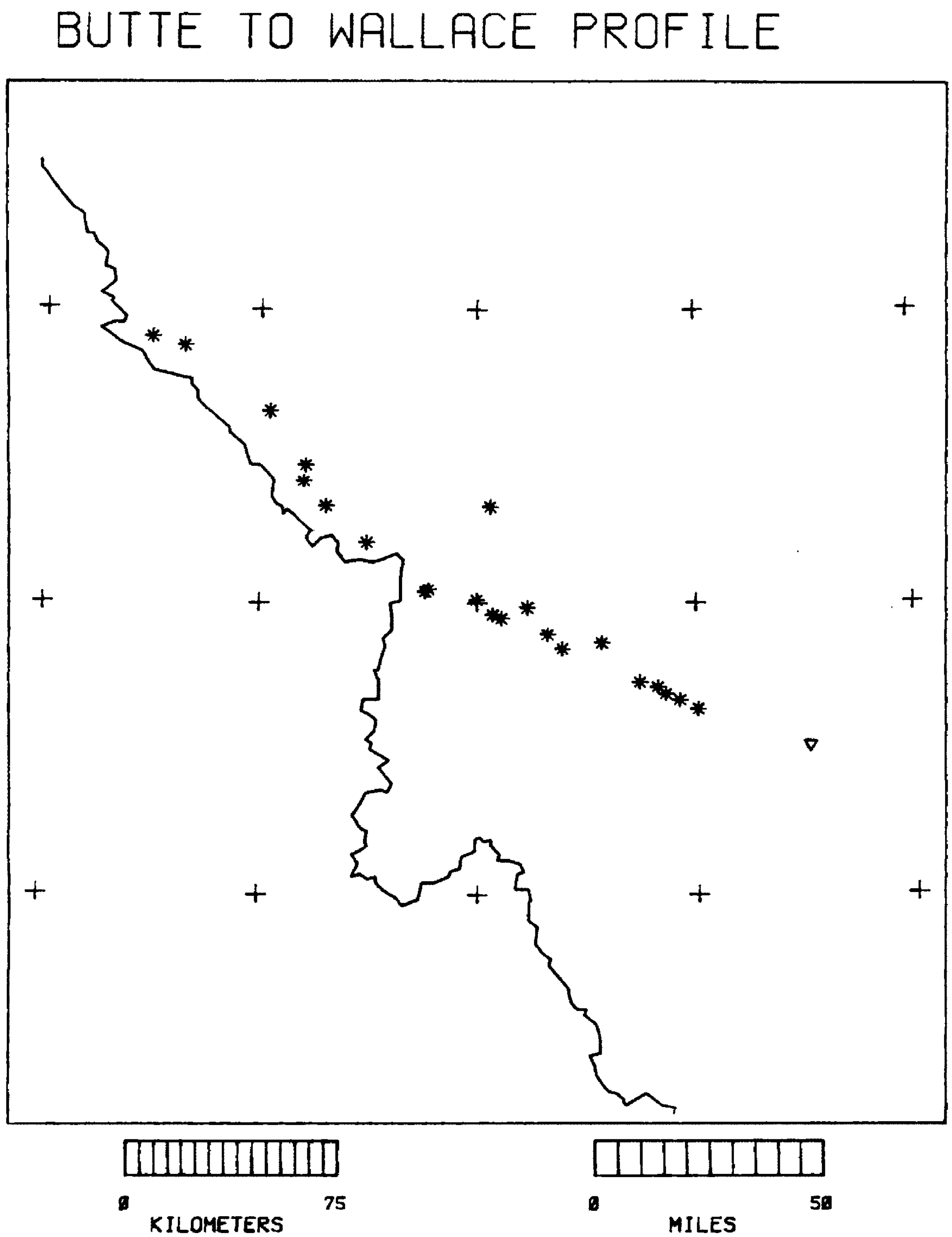

Figure 9. Map of western Montana depicting stations which recorded the Butte mine blast along the Butte to Wallace profile.

CHALLIS TO MISSOULA PROFILE

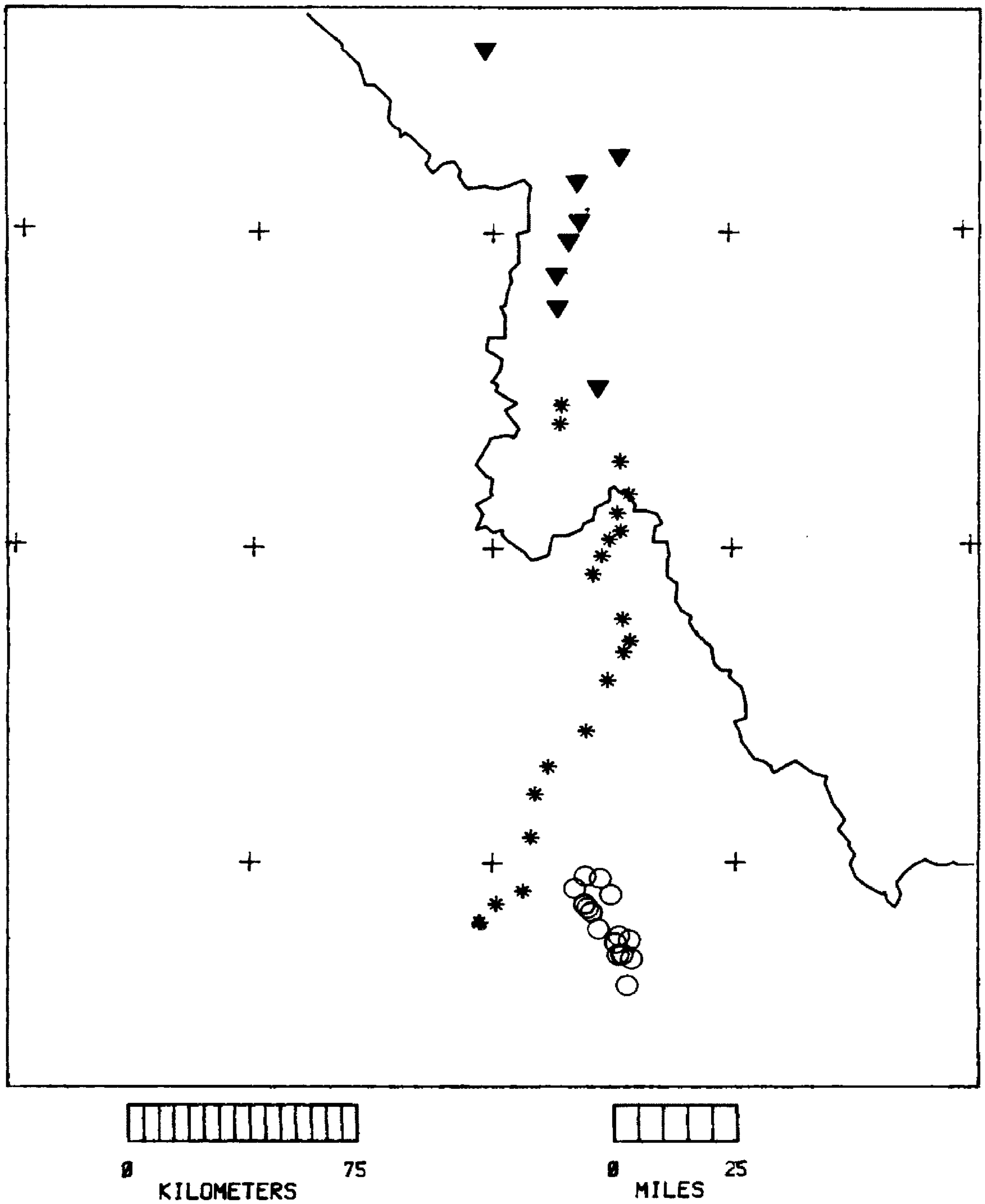

Figure 10. Map showing stations which recorded mine blasts and aftershocks along the Challis to Missoula profile. Asterisks depict stations which recorded the Challis mine blasts, circles show locations for earthquake aftershocks which were recorded from stations depicted by triangles.

University of Montana. Since the aftershocks varied in location, essentially each recording at any one individual site is a different data point. Distances between the aftershocks and the recording sites ranged from approximately 190 km to 350 km, so the nearest point was located near the end point of the data obtained from the blast.

Figure 11 shows the locations of the eleven stations from the Missoula-South profile which recorded the Janney Construction quarry blast from Clinton, Montana (approximately 40 km southeast of Missoula). This profile extends approximately 112 km south from Clinton along the western edge of the Sapphire Mountains; however, the distance is too short for a complete reversal of the Challis to Missoula profile. The stations, nearly equally spaced, were separated by approximately 10 kilometers.

The conventional method in seismic refraction interpretation is to reduce the data for a time versus distance plot. To do this, several standard calculations are needed. First, the distance between each recording station and energy source (blasts, earthquake aftershocks) must be determined.

The coordinates of the stations were initially taken from Bureau of Land Management (BLM) maps, except for two stations near Butte along the Butte to Wallace profile. These two were located using 7.5 minute U.S.F.S. topographic maps. The BLM maps afforded better control of roads and other cultural landmarks which were essential in determining the precise location of each station. The coordinates obtained from the BLM maps were cross checked using 7.5 and 15 minute U.S.F.S. topographic maps. In addition, elevations for each station were

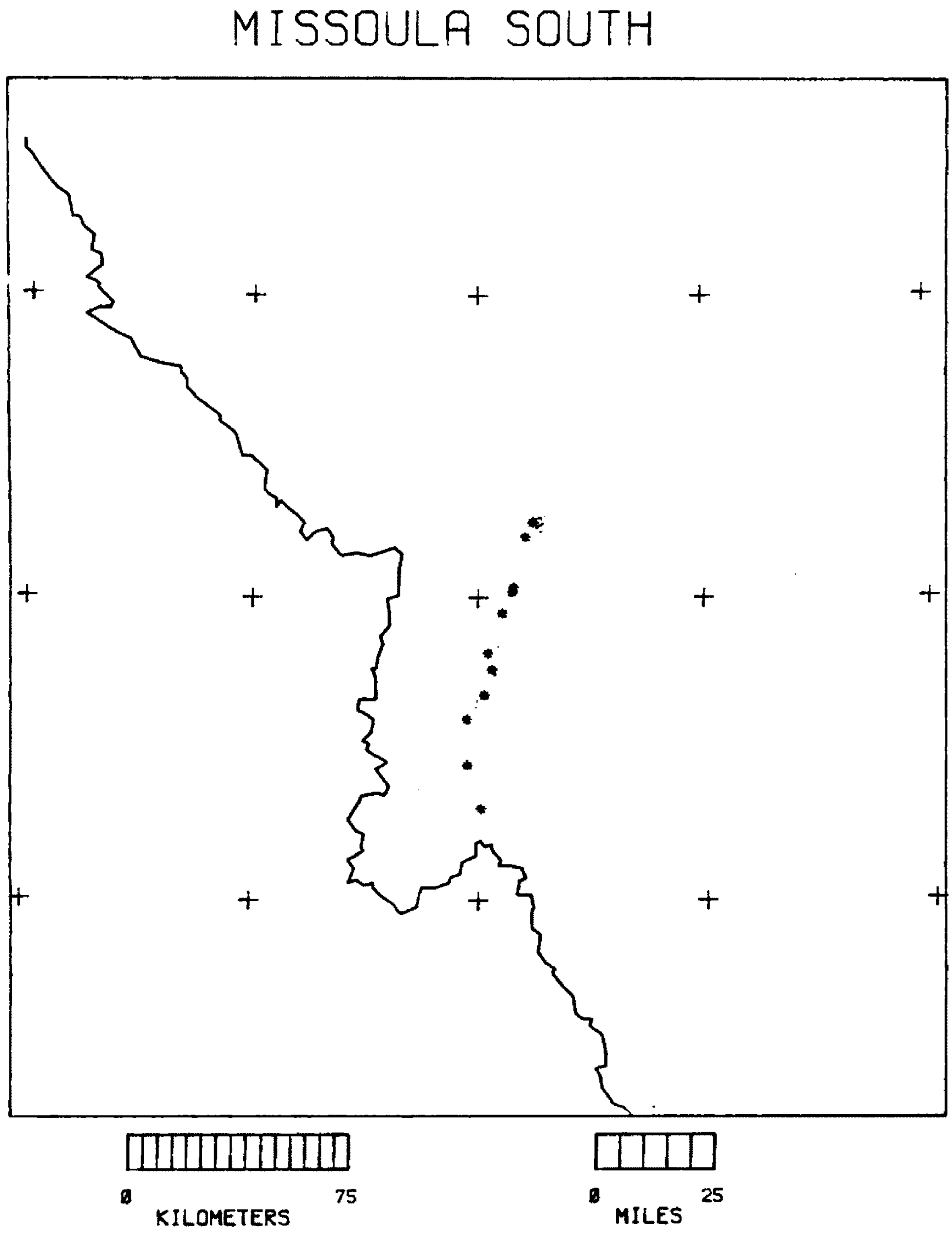

Figure 11. Stations which recorded Clinton quarry blast along the Missoula South profile.

determined from the topographic maps.

Several sources furnished locations for mine blasts and earthquake aftershocks used for each of the lines. The locations for the Butte blasts were provided by M. C. Stickney, Earthquake studies, Montana College of Mineral Science and Technology (personal communication). Cyprus company officials supplied precise locations and elevations for each Challis mine shot used in the Challis to Missoula profile (Table 1a). The coordinates for the quarry blast near Clinton, which did not vary in location by more than 50 m, were taken from a BLM map. Table 2a gives the coordinates and principle information for the aftershocks used in the Challis to Missoula profile. The hypocenter locations and origin times for the major aftershocks within the first twenty-one days after the main shock were provided by the University of Utah Seismology lab (unpublished report).

Another important quantity for the time versus distance plot is the time difference between the origin of the blast or aftershock and the onset arrival at the receiver station. I used several methods to determine origin times. Initially, all three blasts used in the study were timed on location by portable seismographs: three were timed at the Challis mine, two at the Butte mine and one at the Clinton quarry. For the days the blasts were timed at the site, they were also recorded at either a base station or a permenant station and on some days at both the base and permanent stations. Thus, other origin times were easily calculated since the precise blast locations and the travel times to these stations were known. The timing sources also provided cross checks for the calculated origin times and all were within +/- 0.1 sec of one another.

Subsequent origin times for both the Butte and Challis blasts were determined from arrival times supplied by M. C. Stickney (personal communication) from permanent stations operated by the Earthquake Studies Office in Butte, Montana. Idaho National Engineering Laboratory (INEL) also provided arrival times for the Challis mine blast from three permanent stations in Idaho. Later origin times for the Clinton quarry blast were determined from two permanent stations (MSO), (NCM), operated by the University of Montana. In addition to the permanent stations, base stations were set up for the Challis to Missoula and the Missoula South profiles; at 23.8 km from the Challis shot and at 5.3 km from the Clinton blast. Four shots were recorded at the Challis base station and two were recorded at the Clinton base station. On days the blasts were recorded at two or more of the stations used for timing, the origin time was determined by the closest station to the blast.

Only elevation corrections were applied to correct for the aftershock hypocenters; no elevation corrections were made for the shot data. These corrections for the blast data were insignificant (<0.06 sec) and may even add an error to the arrival times if applied. Normally, the higher elevations are assumed to have a delay time; however, in this study the inverse may exist where arrivals may be relatively earlier over higher stations.

The seismograms from all three profiles were digitized and plotted on a reduced time-distance graph using a computer program, TPLT (Appendix B). This facilitated recognition and comparison of later arrivals among the records. The amplitudes of each seismogram were uniformally scaled down to avoid lateral overlaps between records, or scaled up to provide good comparisons among the phases. The scaling was accomplished by trial and error to obtain the best display for the graph. The program, TPLT, also provides an option of inputing a theoretical crustal model to match the observed prominent phases. The program calculates expected distances and times for compressional (P) wave reflections and refractions from the input model, then it superimposes these lines on the seismograms. The optimum model was obtained by trial and error. After chosing a model, all second arrivals were re-examined to see if the model resulted in a good fit. The initial model was derived using first arrival times from the seismograms picked from the undigitized and thus unfiltered seismograms. Because of the excellent signal to noise ratio among the seismograms, the onset phases were particularly well distinguished.

In summary, utmost consideration was given to station spacing to obtain good correlation among prominent phases from the record sections. Timing and distance calculations were relatively accurate and several sources provided cross checks on the timing of the shot points. Elevation corrections were only needed to migrate the aftershock hypocenters to a common datum level and were insignificant (+/-0.06 sec) if applied to the blast data. Procedures outlined by Mueller and Landisman (1971) were followed to provide the optimum use of the data to interpret the results. These procedures involved plotting seismograms on a reduced time-distance graph and consideration of closely spaced stations. These methods allowed for a better correlation among second arrivals.

Chapter 4

RESULTS AND INTERPRETATION

4.1. BUTTE TO WALLACE PROFILE

Figures 12, 13 and 14 show the data used in this study. Tables 3b and 3c give the data used for the initial model in the Butte to Wallace profile. Calculations from these first arrival times yield three distinct best fit lines (Figure 15). The line representing a 4.75 km/sec velocity, taken as P1 velocity, consists of eight points with a correlation coefficent of .999 and intersecting the ordinate at 0.06 seconds. Twenty-one points and a correlation coefficent of .998, support a 6.05 km/sec line with an intercept of 1.00 sec. This velocity is taken as the Pg velocity. With a correlation coefficent of .998, four first arrivals from 200 km to 272 km indicate a Pn velocity of 7.57 km/sec with an intercept of 6.08 sec. The Sg velocity of 3.55 km/sec is derived from nineteen points yielding a correlation coefficent of .996, and the Sn velocity of 4.26 is calculated from eight points giving a correlation coefficent of .973. With the exception of four second arrivals supporting the Pg velocity between 200 km and 270 km, all these data were first arrivals.

Figure 12 shows the compressional wave travel time curves from the derived crustal model superimposed on the plotted seismograms from the Butte to Wallace profile. This best fit model, shown in Figure 15, was calculated from the data

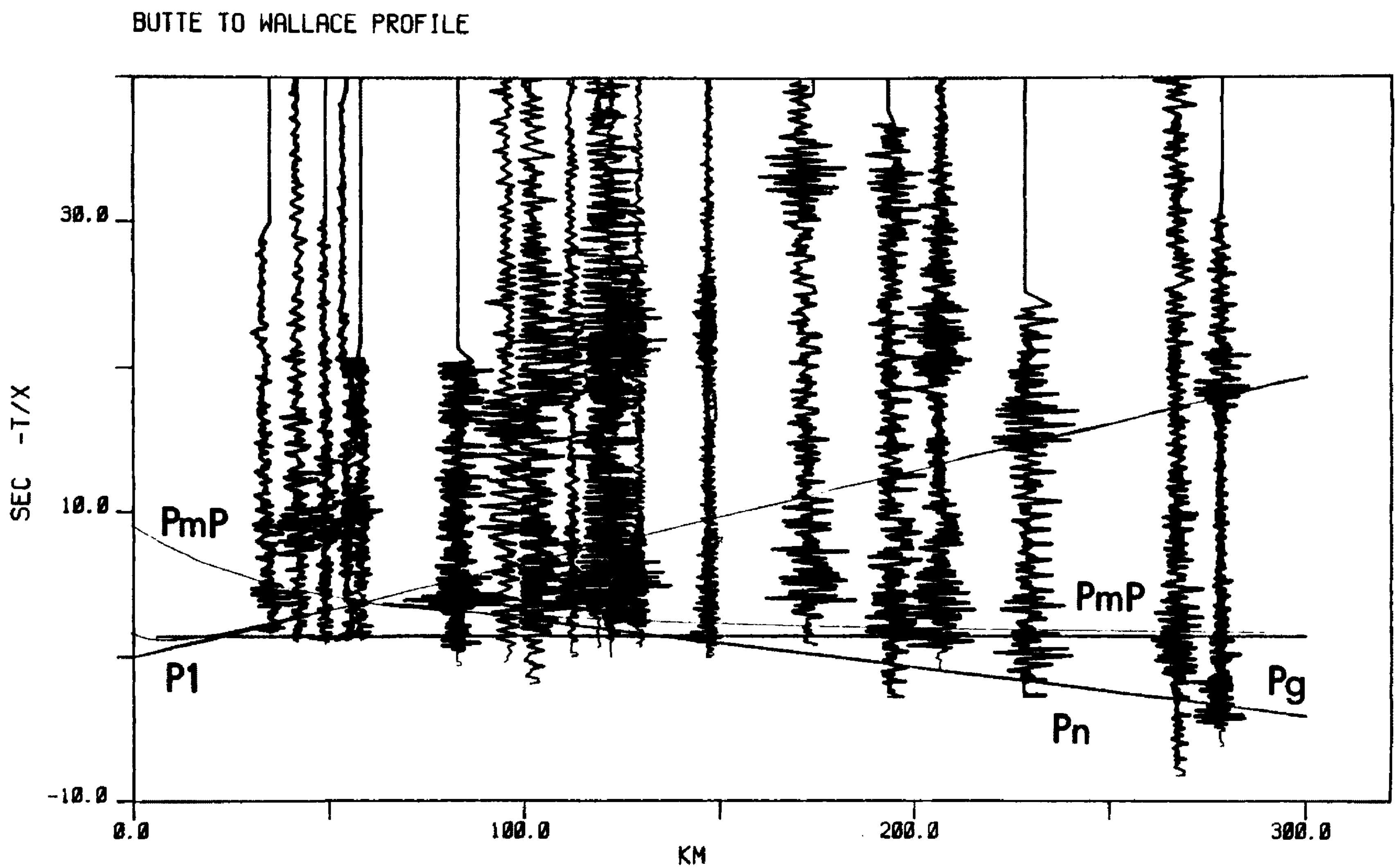

Figure 12. Plot of traces recorded for Butte to Wallace refraction line with superimposed travel-time curves from best fit model

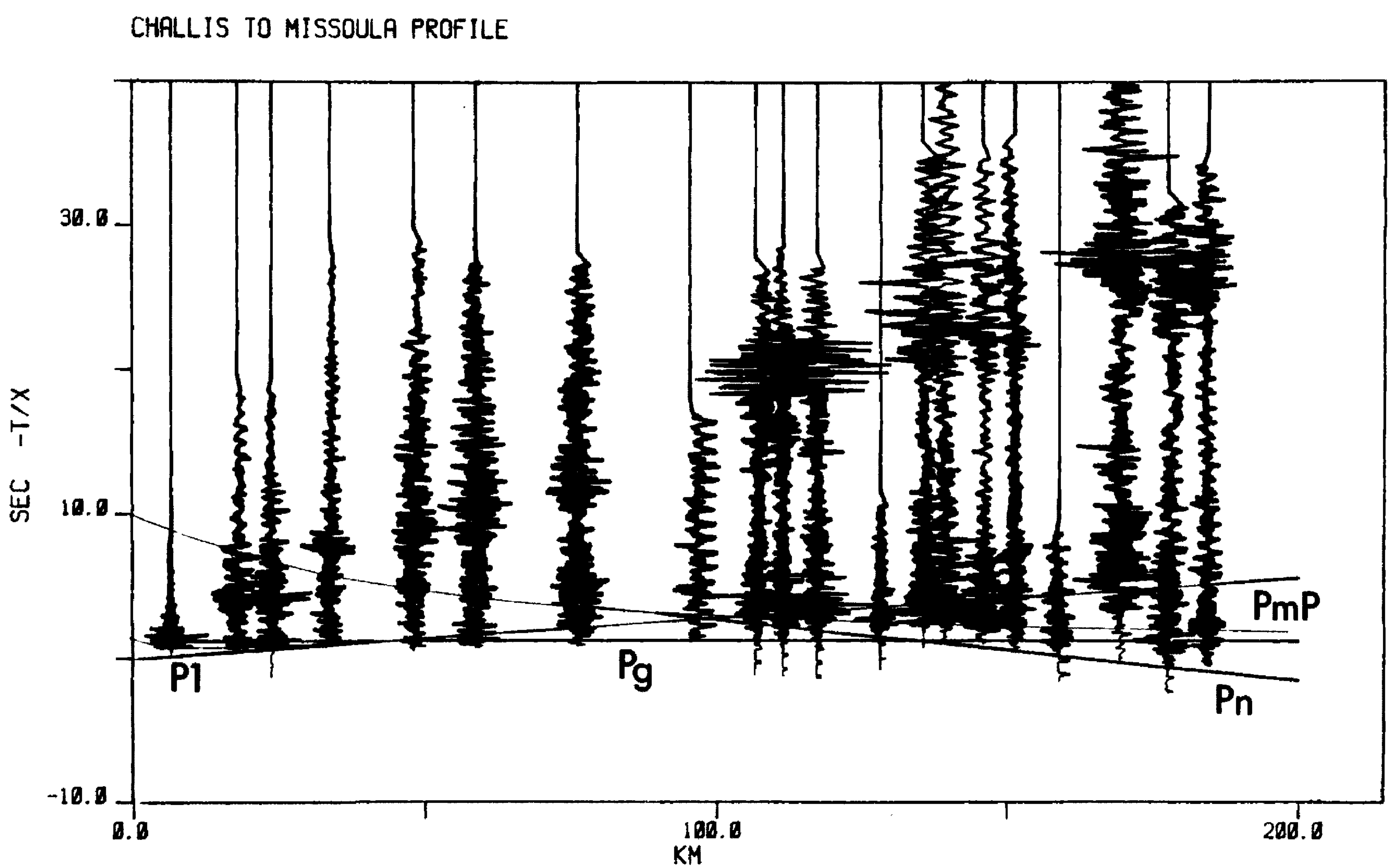

Figure 13. Plot of traces recorded from Challis mine blast along Challis to Missoula profile with travel-time curves derived from best fit model.

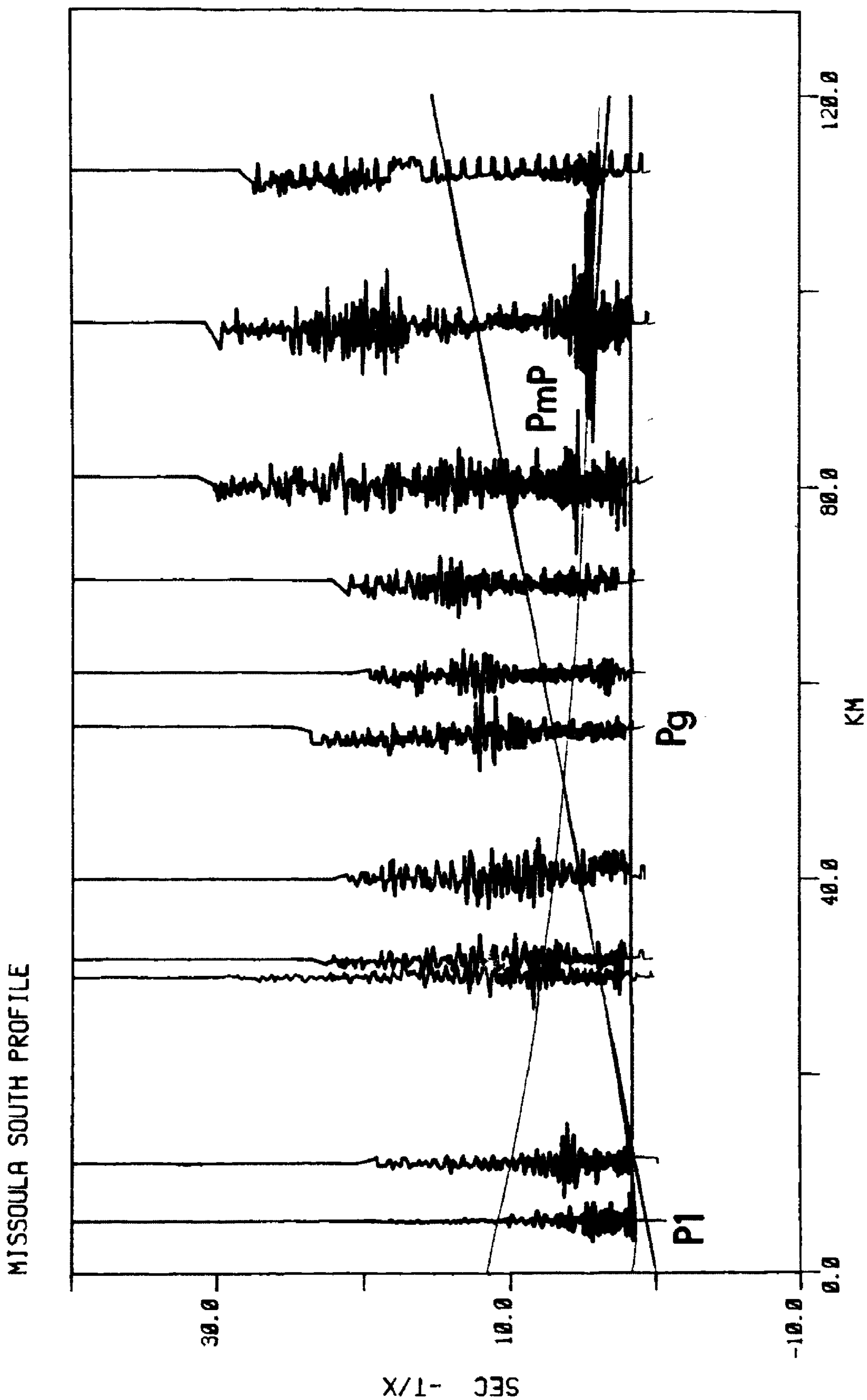

Figure 14. Plot of traces from Missoula South profile with travel-time curves from best fit model.

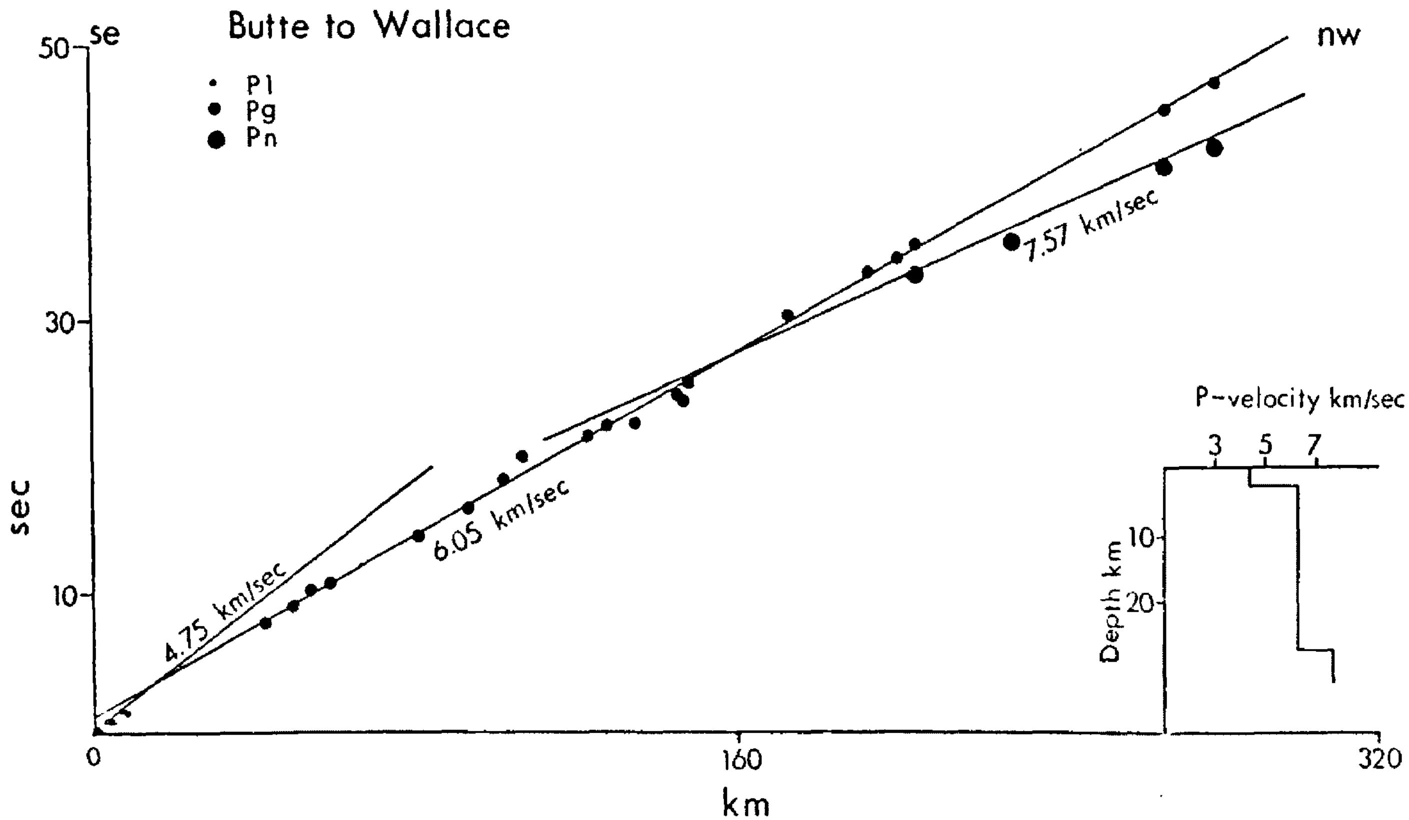

Figure 15. Time-distance plot of data along with best fit model for Butte to Wallace refraction line.

given for the best fit lines above, which are mostly first arrivals. Several prominent phases are evident in the observed data and most of these are explained from the model calculated solely from first arrival data. Other pronounced phases are seen among the traces but are not coherent when followed from trace to trace. These other phases may represent S-to-P conversions or localized variations in crustal structure.

The Pg phase is conspicuous as a first arrival to approximately 180 km. From 180 km to the end of the profile, the Pn phase is well distinguished as a first arrival. Several prominent later phases are also explained by the crustal model. A high amplitude phase is obvious at approximately 80 km and follows the Pg phase by nearly 3 seconds. This point is near the predicted critical distance where a high amplitude phase is expected due to constructive interference between the refracted and reflected wave from the M-discontinuity (Braile and Smith, 1975). This modelled wide angle reflection from the M-discontinuity, the PmP phase, matches well with secondary phases, except for a slight offset before 50 km. Perhaps this discrepancy can be explained by a dip to the crust-mantle boundary. If there is a dip to the Moho, the travel time curve depicting the mantle reflection would not be represented as a hyperbola, but rather as a higher order curve (Slotnick, 1959). In the downdip direction, this curve would be flatter toward the origin.

4.2. CHALLIS TO MISSOULA PROFILE

Figure 16 is a plot illustrating the first arrival times of the mine blast data from the Challis to Missoula profile. Three lines are evident, representing breaks in compressional first arrivals on the time-distance plot. The correlation coefficents near unity for each line strongly support these breaks. The first determined velocity of 5.03 km/sec, taken as P1, is supported by a line consisting of five points with a correlation coefficent of .999 and an intercept of 0.1 sec. The line indicating a Pg velocity of 5.81 km/sec is determined from nine points with a correlation coefficent of .999 and intercept of 0.8 sec. The Pn velocity of 7.75 km/sec is particularly well supported by five first arrivals forming a line with a correlation coefficent of 1.000 and an intercept of 7.02 sec. Seven points represent the Sg velocity of 3.67 km/sec, and ten points support the Sn velocity of 4.15 km/sec, with a correlation coefficent of .994 for both lines.

Figure 13 illustrates the fit of the theoretical crustal model with the blast data obtained along the Challis to Missoula line. Similar to the Butte and Wallace profile, the model which best fits the data is derived from first arrival times. The P1 phase becomes an apparent second arrival beyond 50 km where it and the Pg phase diverge. The Pg phase is evident by low amplitude first arrivals from approximately 30 km to 140 km. After 140 km, well defined first arrivals mark the Pn phase to 180 km. Never a first arrival, the PmP phase is particularly distinguished as a later arrival from approximately 100 km to 180 km.

Thirty-four arrival times were recorded along the Challis to Missoula profile using aftershocks from the Borah Peak earthquake. The aftershock data represent

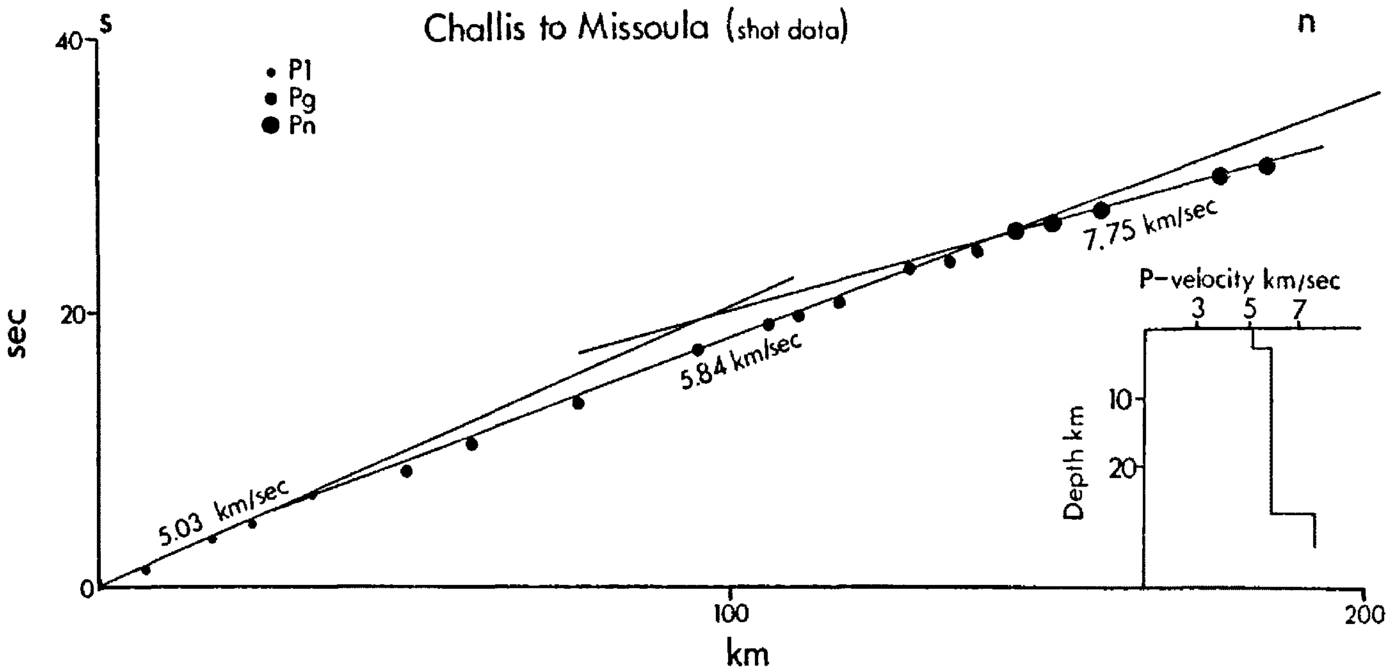

Figure 16. Time-distance plot of mine blast data with best fit model for Challis to Missoula profile.

a line segment of the Challis to Missoula profile from approximately 185 km to 350 km; thus only the Pn phase is the recorded first arrival (Table 2c, Figure 17). The thirty-four data points of the Pn phase yield a line with a correlation coefficent of .995, indicating a 7.75 km/sec velocity and a 5.98 sec intercept (Table 2d). The velocity is exactly the same as determined from the blast data, however, the intercept is nearly one second lower. Using this intercept value would result in calculating a significantly thinner crust than using the intercept value derived from the blast data. However, the range of error in this intercept at the ninety-five percent confidence interval is +/-1.6 sec, which may account for the discrepancy. The input model used in this study to migrate the hypocenters to a datum level is the same model applied to originally determine the hypocenters. This crustal model by Richins et. al., (1985) was chiefly derived from a combination of crustal models (Sparlin et al., 1978 and Sheriff and Stickney, 1984) from two widely contrasting geologic regions. To arrive at their generalized crustal model, Richins et. al., used a trial and error method to minimize residual times of the aftershock recordings from broadly dispersed permanent stations (< 650 km from epicenter) throughout the northwestern United States. Thus their model averages disparate major geological provinces (ie. Basin and Range, craton, oceanic crust). Residual times from these stations were within +-.15 sec (Richins et. al., 1985). Since an error in the migrations of the hypocenters would be uniformally applied to all the data, an erroneous crustal model would modify the intercept but not significantly affect the velocity, which only depends on the slope of the best fit line to the data. For this reason, the velocity calculated from the aftershock data strongly support

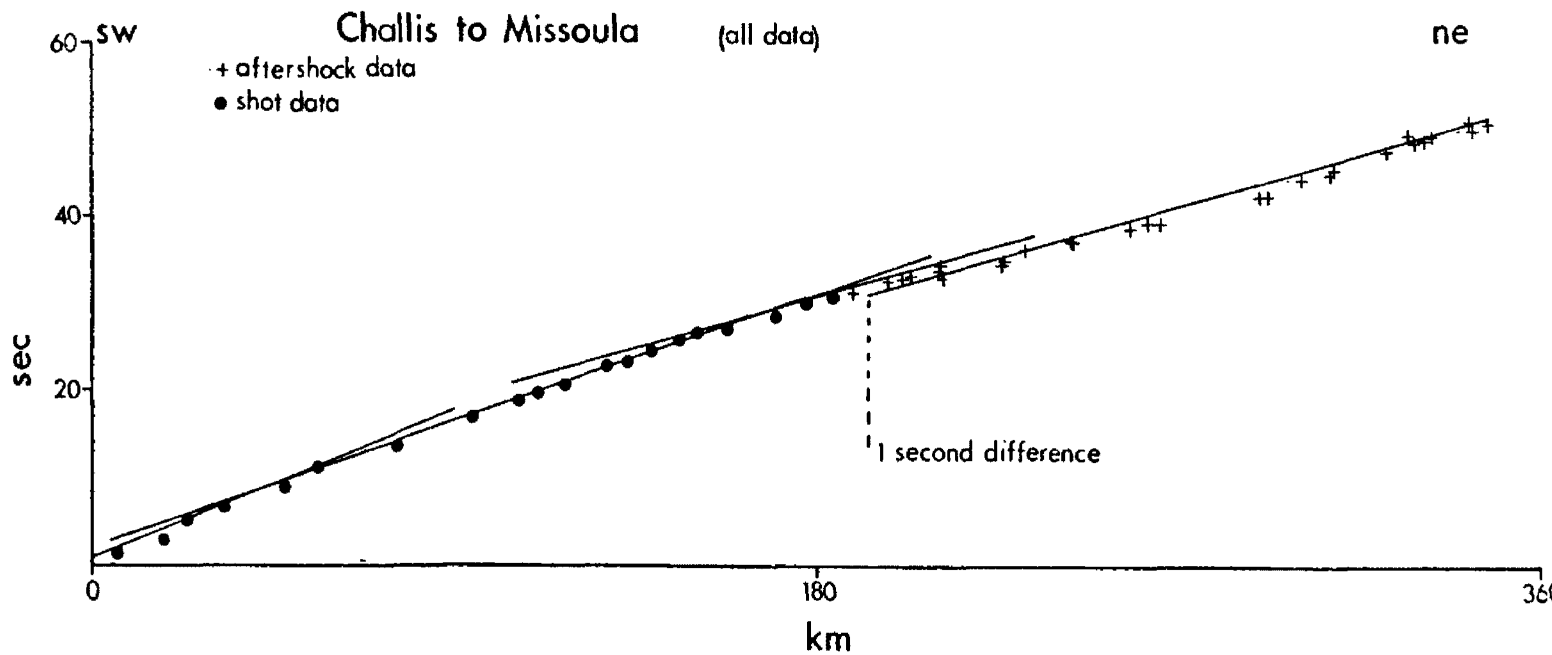

Figure 17. Time-distance plot of mine blast and aftershock data for Challis to Missoula profile.

that derived from the blast data and the intercept was not used. A time-distance plot of all these data is shown in Figure 17.

4.3. MISSOULA SOUTH PROFILE

Figure 18 shows the first arrival data and the best fit lines obtained for the Missoula South line. Although this profile only extends from Clinton to Darby, a distance of 112 km, there is a break in the data which indicates different velocities. Most of the first arrivals indicate a 5.94 km/sec layer. A correlation coefficent of .999 supports this best fit line with an intercept of 1.2 seconds. This intercept is the result of the near source rocks. The first two stations as well as several second arrival times show that a 3.4 km/sec layer is also present. Eight points support an Sg velocity of 3.08 km/sec with a correlation coefficent of .996 and an intercept of 1.06 seconds. Large, prominent amplitudes are distinguished as second arrivals on the last three records at the southern end of the profile (Figure 14).

Figure 18 portrays the crustal model which best fits the data for the Missoula South profile. The travel time curves for P1 and Pg were derived from first arrival analysis, however, the crustal thickness was derived by considering a northwest dipping M-discontinuity as reported by Carlson and Sheriff (1983), Sheriff and Carlson (1984), Carlson (1984). The large amplitude second arrivals correlate extremely well with the theoretical crustal model and are most likely as phases recorded at the critical distance for a regional northwest dipping M-discontinuity. The critical distance is the distance where the reflected and refracted wave arrive

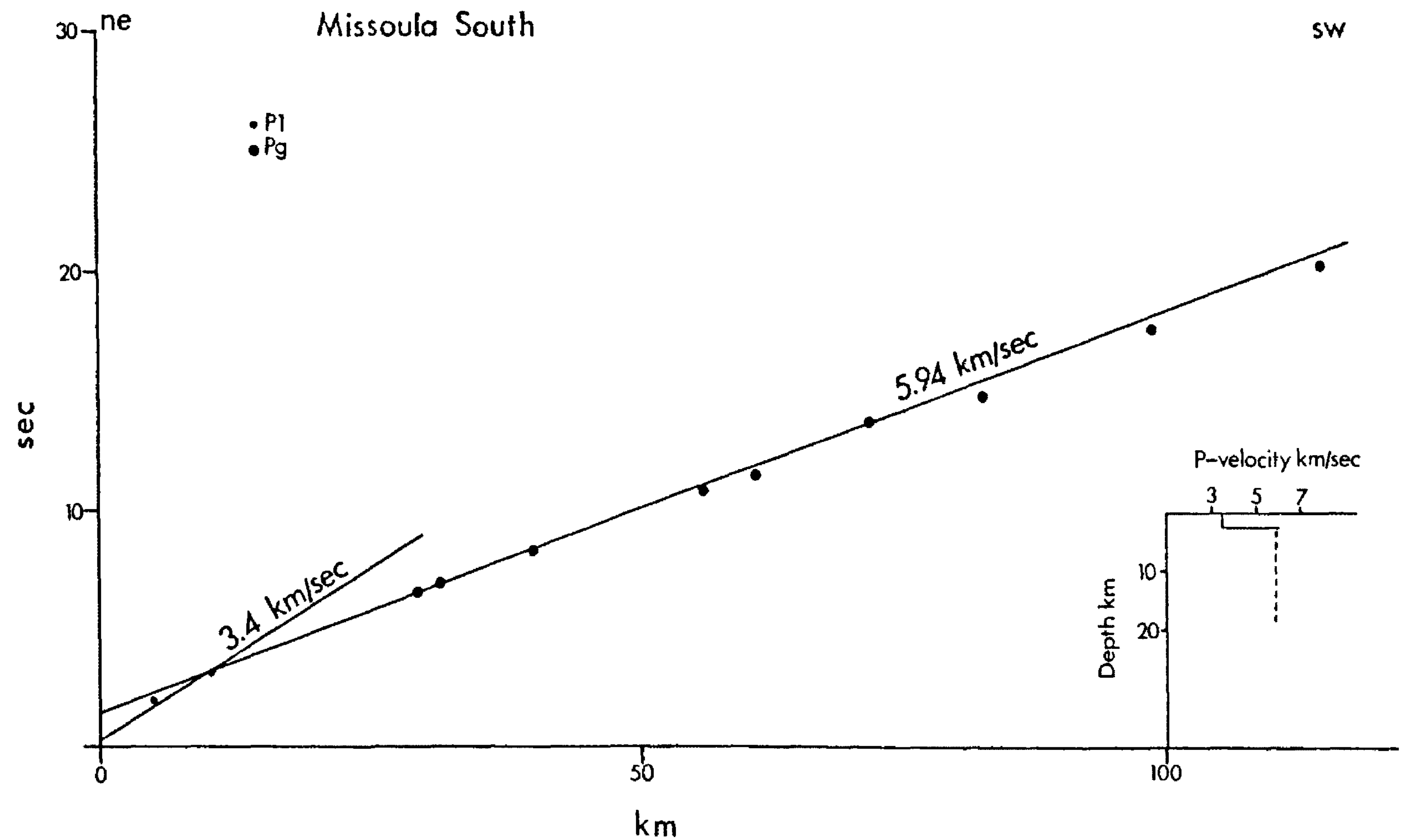

Figure 18. Time-distance plot of Clinton quarry blast data and crustal model from Missoula South line.

at the same time to interfere constructively. The best fit model for the this profile consists of a 34 km thick crust with an 8.17 km/sec apparent Pn velocity. This apparent velocity is higher than those values recorded along the Butte to Wallace and Challis to Missoula profiles and consistent with a value expected in the apparent updip direction of an M-discontinuity dipping approximately 3 degrees to the northwest.

The interpretation of all three lines is shown in Figure 19. The Butte to Wallace profile has an apparent Pn velocity of 7.57 km/second. The previous refraction data indicate an upper mantle velocity of 7.95 km/sec (McCamy and Myer, 1964; Ballard, 1980; Stickney and Sheriff, 1983) for the northern Rocky Mountains. With a true velocity of 7.95 km/sec, the low apparent velocity along this profile can be explained by a 3 degree dip to the Moho. Using the recorded and assumed velocities, the intercepts and equations for dipping interfaces by Mota (1954), yields a 26 km thick crust below Butte. This thickness is too low and inconsistent with other results near Butte (Stickney and Sheriff, 1983). Using DeBoer's (1985) data of a Pg velocity of 5.95 km/sec and an apparent Pn velocity of 7.59 km/sec, with a 6.3 second intercept, the calculated crustal thickness is a somewhat more acceptable 30 kilometers. Stickney and Sheriff (1983) arrived at a 33 km to 34 km thick crust from their recorded data along line from Challis to Butte (line c-b, Figure 3). A reasonable estimate for the the thickness of the crust at Butte is the average of these values, or about 30 kilometers.

There are several reasons for the wide range of values of crustal thickness obtained at Butte. There could be a low velocity zone missed along Sheriff and

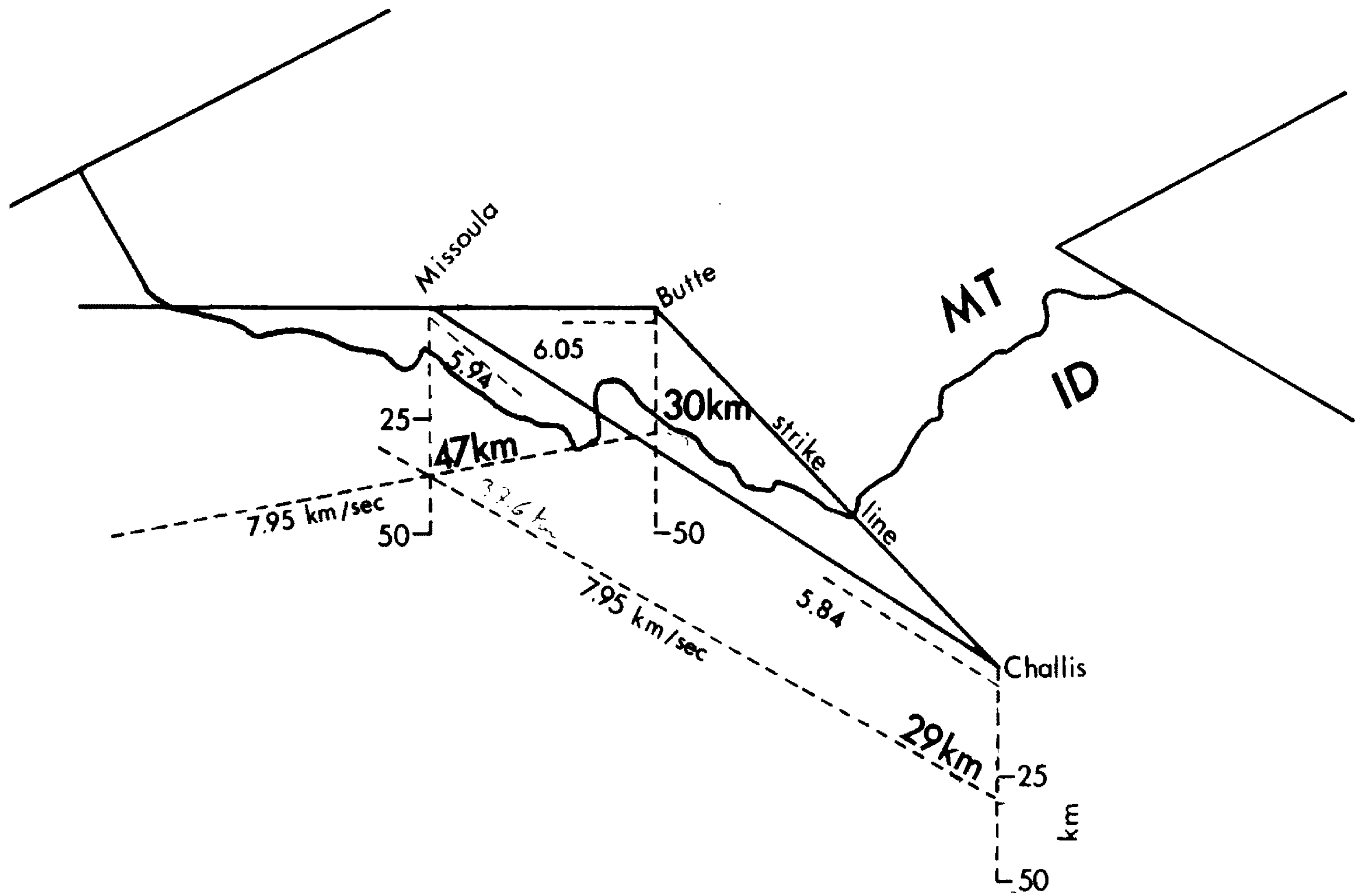

Figure 19. Crustal model for study area derived from the Butte to Wallace, Challis to Missoula and Missoula South refraction profiles.

Stickney's (1984) line or a blind zone (Won and Bevis, 1985) along the Butte to Wallace profile. Also, an incorrect general location for the Butte blasts could account for a low intercept for the Pn line and thus a low value for thickness. However, the location of this blast was provided by Montana Bureau of Mines and Geology (Mike Stickney, personal communication) and double checked on a 7.5 U.S.F.S. topographic map. Since the distances between blasts did not vary by more than 0.38 km, this also would not result in a significant error in the intercept. These thickness discrepancies may simply reflect the limitations of seismic refraction data. However, the data from the Challis to Missoula profile provides a check and verification for the crustal thickness.

Using the average crustal thickness of 30 km at Butte and a 3 degree dip to the M-discontinuity along the Butte to Wallace profile, calculations give a 37.6 km thick crust below Missoula and approximately 47 km thick crust at Wallace. With the 3 degree dip to M-discontinuity to the northwest and assuming the standard planar interfaces, the predicted apparent dip in the direction of the Challis to Missoula profile is 1.6 degrees. The recorded apparent Pn velocity from this profile is 7.75 km/sec. Given this apparent velocity and considering a true velocity of 7.95 km/sec; calculations by Mota (1954) for dipping interfaces yield a value in the direction of the line of exactly 1.6 degrees, thus providing additional support for the crustal model.

Since all three lines cross or lie near Missoula, this location can be used as a pivot point to also test the proposed crustal model. Using the intercepts and velocities obtained for the Challis to Missoula profile the model yields a 29.9 km thick crust at Challis. Using this thickness and the 1.6 degree dip, calculations reveal that the crust thickens to 37.1 km at Missoula, nearly identical to the 37.6 km value obtained from the Butte to Wallace profile. Therefore, while the Butte to Wallace and Challis to Missoula profiles are one-way refraction lines, because they cross they are independent checks for the derived crustal model.

The crustal model for the Missoula South profile consists of a 33 km thick crust and an apparent 8.17 km/sec Pn velocity, which is primarily supported by second arrivals near the critical distance. The calculated thickness of the crust at Missoula based on the other two refraction profiles is approximately 37 km, which is 4 km thicker than the model for the Missoula South profile. However, because the PmP wave reflects off the Moho about 30 km south of Clinton at the critical distance and the Clinton blast is 16 km east of Missoula, the actual thickness of the crust predicted from the model should be 35.7 km for the Missoula South profile. Considering the level of precision in the survey and calculations, the thickness predicted from the crustal model is relatively close to the 33 km value from the Missoula South profile.

Additional support for the crustal model derived from all three profiles is provided by the excellent correlation of large amplitude second arrivals and the predicted mantle reflection. If a blind zone or low velocity layer was missed in the analysis in this study, the predicted and observed models would not indicate such a good correlation. This is because the PmP phase represents the average velocity of the crust. Although only horizontal interfaces are considered in the predicted travel time curves, the actual PmP wave for the slight dip of 3 degrees differs only by about +/-.2 sec near the intercept (Slotnick, 1959).

Some conclusions about the local geology can be drawn from the analysis of the recorded P1 phases along all three profiles. The velocities obtained from stations close to the source reflect the seismic parameters of the local geology. Data analysis from the Butte to Wallace profile (Figure 15) indicates a 4.75 km/sec, 3.8 km thick layer west of Butte within the granitic rocks of Boulder batholith. This velocity is within the range of values for granitic rocks (Birch, 1961). The thickness of the Boulder batholith has been the subject of much controversy. Hamilton and Myers (1974a, 1974b) contend that the batholith is a 5 km thick, tabular body. Klepper et al. (1971, 1974) suggest it is a mushroom shape body, 15 km or thicker. Hyndman (et al., 1975) infer that the thickness may lie between these estimates. Both the studies of Hamilton and Myers (1974a, 1974b) and Klepper (et al., 1971, 1974) rely on gravity modelling and field contacts to support their interpretations. In the gravity modelling, different density contrasts were used in both studies to arrive at the two widely disparate values for the thickness. The thickness calculated in this study favors the interpretation by Hamilton and Myers (1974a, 1974b) for a relatively thin batholith.

The 5.03 km/sec velocity, 3.42 km thick layer near Challis probably represents the average seismic parameters of the Challis volcanics and associated granitic plutons (Foster, 1983). The 5.03 km/sec velocity is relatively high for near surface geology and could well be an apparent velocity in the updip direction of the base of the Challis volcanic package. The map of the general regional geology (Figure 1), shows that these volcanics give way to Precambrian belt rocks to the north which supports dip and therefore apparent velocity. However, Figure 13 indicates that the high amplitudes correlated with the P1 phase from this layer are continuous to approximately 125 km north of Challis. Thus, the volcanic layer appears relatively continuous to the north.

A relatively low 3.4 km/sec apparent velocity of an approximate 3 km thick layer is indicated in the Missoula South profile (Figure 18). This velocity is in the range of expected sedimentary fill. This line segment of the refracton line crosses sediments deposited within the Clark Fork river valley. However, another explanation for this layer is that it could represent southward dipping thrusts of Paleozoic and Mesozoic sedimentary rocks. Desormier (1975) has shown that most thrusts along the northern boundary of the Sapphire Tectonic block dip to the south, which could result in a low apparent velocity.

The Missoula South profile crosses this northern edge of this block which is inferred to be approximately 17 km thick in the center and resulted from sliding off the Bitterroot dome, a metamorphic core complex (Hyndman, 1983). The base of this block is probably composed of mylonites representing this decollement. However, there are no coherent phases among the Missoula South records which may indicate the depth of the Sapphire block. This may be the result of a small velocity contrast between the mylonites and the underlying Belt Supergroup rocks compared to the resolution in this profile. Closer station spacings along this profile may resolve this problem.

Chapter 5

SIGNIFICANCE OF THE RESULTS

The crustal model derived in my study (Figure 19), is consistent with our earlier interpretation (Carlson and Sheriff, 1983; Sheriff and Carlson, 1984; Carlson, 1984). This model includes and compliments the results from Sheriff and Stickney (1984) and is also strongly supported by the crustal study of DeBoer (1984). Although the crustal studies by Ballard (1980), Hales and Nation (1973) and McCamy and Myer (1964) are within the study area, their crustal models appear to contradict my interpretation. Ballard (1980) incorporated the results from his seismic refraction lines with those from McCamy and Myer (1964). He also used gravity modelling to support his conclusions (Ballard, 1980). Upon closer examination of Ballard's (1980) study though, his refraction data actually lend support to my conclusions. For example, in his reversed profile between Yellowstone Park and Helena (Figure 3, line y-h) Ballard reported a northwest dipping M-discontinuity. The data from his one-way refraction lines also support this dip. The line extending from Yellowstone Park to Butte, Montana (Figure 3, line y-b) shows an apparent velocity of 7.92 km/sec and another from Yellowstone Park to Missoula (Figure 3, line y-m) indicates an apparent velocity of 7.69 km/second. Although Ballard discounted the 7.69 km/sec velocity, it is nearly the value in the direction predicted from the crustal model presented here (Figure 19). Ballard (1980) also inferred that the trend of decreasing Bouguer gravity values to the southwest supported his model of an M-discontinuity dipping to the southwest. However, the Basin and Range province, with a thin crust (< 30 km) is outlined by a regional gravity low. In fact similar to the Basin and Range province, the low gravity values lie within the thinner crust (30 km) in the study area. Thus, while Ballard (1980) used low gravity values to support a thickening of the crust, they actually imply a thin crust.

The southern end of the reversed profile by McCamy and Myer (1964) crosses the study area (Figure 3, line e-d). For the most part, this profile lies to the north and trends northwest, parallel to the general strike of the fold and thrust belt. Therefore, it is not suprising they show no dip to the M-discontinuity here, in the direction of their line. Similar to Ballard's (1980) study, the unreversed refraction lines in McCamy and Myer's (1964) study support our (Carlson and Sheriff, 1983; Sheriff and Carlson, 1984; and Carlson, 1984) interpretation. The unreversed line in southern Montana incorporated in their study (Figure 3, line e-f), recorded an apparent velocity of 8.40 km/sec. This line is approximately 150 degrees from the Butte to Wallace profile and extends in a west-east direction from approximately 50 km southeast of Butte to near Billings, Montana. The high apparent velocity of 8.40 km/sec is nearly the value expected from our model in the updip direction (Figure 19). The other west to east line deployed by the Carnegie Institute (Figure 3, line d-g), also shows a high apparent Pn velocity of 8.20 km/sec in northwest Montana. This may indicate that the crust in northern Montana also dips to the west but not by as much as in western central Montana (this study).

The dip upward of the M-discontinuity to the east at approximately 50 km southeast of Butte as indicated by the Carnegie Institute's southern line (Figure 3, line e-f) is also consistent with the results of the unreversed line by Stickney (1985), (Figure 3, line j-o). However, Stickney (1985) arrived at a 25 km thick crust from his one-layered crustal model by using aftershock data from the Borah Peak earthquake of 1983. Similar to the aftershock data from Challis to Missoula profile, the line representing the Pn velocity in Stickney's (1985) study has a low intercept on the time-distance graph. The low intercept results in a relatively low value for crustal thickness and may simply reflect a problem in using the aftershocks as a source.

The refraction line of Hales and Nation (1973) extends over 2000 km south from British Columbia, Canada to Texas (Figure 3, line t-u). This profile covers westernmost Montana with station spacings of approximately 20 km. The results from the line segment in Montana therefore, would be an average over different geologic regions. Despite averaging the crustal structure here, Hales and Nation (1973) obtained a relatively high upper mantle velocity of 8.04 km/sec for western Montana. This value is in the realm of the predicted apparent velocity for a northwest dipping Moho in the direction of their line.

These previous studies (Ballard, 1980; McCamy and Myer, 1964; Hales and Nation, 1973), also differ from my study by including intermediate crustal layers. Most of these layers have velocities between the Pg and Pn recorded velocities. While the recording sites from Sheriff and Stickney (1984) averaged 25 km apart, which may preclude the determination of intermediate layers and Stickney (1985) used only head wave analysis; the station spacing in my study should provide the detail to identify phases from these layers. Yet, the seismograms do not reveal any additional correlatatble phases other than those included in the analysis, especially between the Pg and Pn phases. If these phases, which are possibly undetected, have unusually low relative amplitudes, the crust would be thicker than the interpretation presented here. Interestingly, Hales and Nation (1973) suggest a low velocity layer from their analysis. An undetected low velocity layer would yield a thinner crust. However, the results from all three refraction lines exhibit a remarkable fit with the derived crustal model. This fit suggests that no significant intermediate layers, whether low-velocity or not, were missed in my analysis.

Additional support for my crustal model can be gained by comparing it with the regional crustal thickness. Based on a one-way refraction line, Hill (1972) infers that the crust is about 20 km thick in eastern Washington (Figure 3, line k-l). Certainly, the majority of the data from the seismic refraction lines suggest a regional dip of the crust-mantle boundary. If a 40 km or more thick crust is considered at Butte, as inferred from the studies of McCamy and Myer (1964), Ballard (1980), then with a 3 degree dip to the Moho to the northwest, the crust would be about 60 km thick at Wallace. Although it is possible for the crust to thin from 60 km at Idaho to 20 km in eastern Washington, my model with a 47 km thick crust at Idaho proposes a more reasonable, gradual transition across this region. This transition from a thick (50 km) crust, with the crust thinning eastward is also evident in a crustal study in southern British Columbia, Canada (Cumming et al., 1978; Figure 3, line p-q). These workers suggest a 50 km thick crust at the eastern end of their profile (see line p-q, Figure 3) which lies northwest, with the general strike of regional structures, from the end of the Butte to Wallace profile. The westernmost end of my Butte to Wallace line (Figure 1, line A-B) also indicates nearly 50 km of crustal thickness. The profile by Cumming et al. (1978) extends 360 km westward and shows the crust thinning in this direction from the 50 km to about 30 km, similar to the crustal transition from western Montana to eastern Washington.

The relatively thick 47 km crust in my model is at the western edge of the Idaho batholith, compatible with a model explaining metamorphic core complexes within the western Cordillera. Coney and Harms (1984) suggest that a crustal welt formed as a result of Laramide compression within the hinterland behind the fold and thrust belts where thickening of the crust resulted from shortening. The northern metamorphic core complexes of the western Cordillera apparently formed as a result of deep seated extension during a pulse of Eocene volcanic activity. The Tertiary extension migrated towards the coast from the fold and thrust belt, superimposing the extensional structural grain onto the Laramide structures (Coney and Harms, 1984). The thicker crust towards the west in the study area then, could reflect a remnant of the Laramide crustal welt and define the limit of the westward extensional migration. The maximum crustal thickness in this study is also coincident with the region of the rich mineral deposits within the Cour d'Alene district and the thickest part of Belt Supergroup stratigraphic package. Harrison (1968) describes a 60,000 ft section of Belt Supergroup rocks near Alberton, Montana at the western end of the Butte to Wallace profile.

My two layer crustal model for southwestern Montana (Figure 19) is derived mainly from first arrival analysis and therefore, is less complex than some other recent crustal models determined from seismic refraction analysis (eg. Braile et al., 1982; Smith et al., 1982; Mueller and Landisman, 1971; Mueller, 1977). However, studies by Sinno et al. (1981) and Braile et al. (1974) in the Basin and Range province support my model. Sinno et al., (1981) indicate a simple three layer crustal model for the Basin and Range province within west-central Arizona (Figure 20). This model also illustrates the same ambiguities in seismic refraction interpretation. For example, using a simple two layer crustal model with Sinno et al.'s (1981) data the crust appears to be 25 km thick. Their model, with three layers, shows a 24.0 +/-1.0 km thick crust. Likewise, more stations along my lines may provide more detail in determining intermediate layers. However, if these layers do exist they are denoted by subtle velocity contrasts and may slightly refine my model but would not significantly change my interpretation. The correlation between prominent phases and the PmP travel-time curve derived from the model further supports this arguement.

The 24 km thick crust reported by Sinno et al., (1981) also typifies the relatively thin crust within the Basin and Range province and is close to my value for the eastern part of the study area. Braile et al. (1974) also indicate a thin, 28 km thick crust for the Basin and Range province in northern Utah based on seismic refraction. Similar to my study, they show a transition to a thicker crust away from the Basin and Range province. Regional high heat flow (62.7-104.5 mW/m^2) and low Bouguer gravity values characteristic of the Basin and Range province are

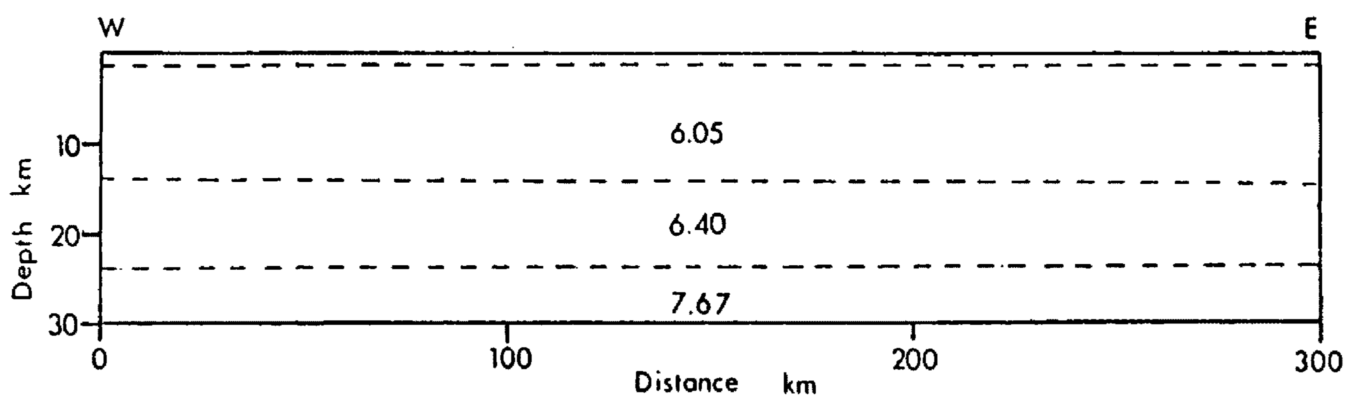

Figure 20. Crustal model for west-central Arizona, Basin and Range, from Sinno et. al., (1981).

included within the study area. Therefore, the major portion of my study area should be included within the Basin and Range province. Thin crust, high heat flow and low gravity values, and prevalant seismic activity with normal faulting are all indicative of Tertiary extension. Earlier workers (eg. Hamilton and Myers, 1966) recognized the structural features of the area and included it within the Basin and Range province (Figure 21).

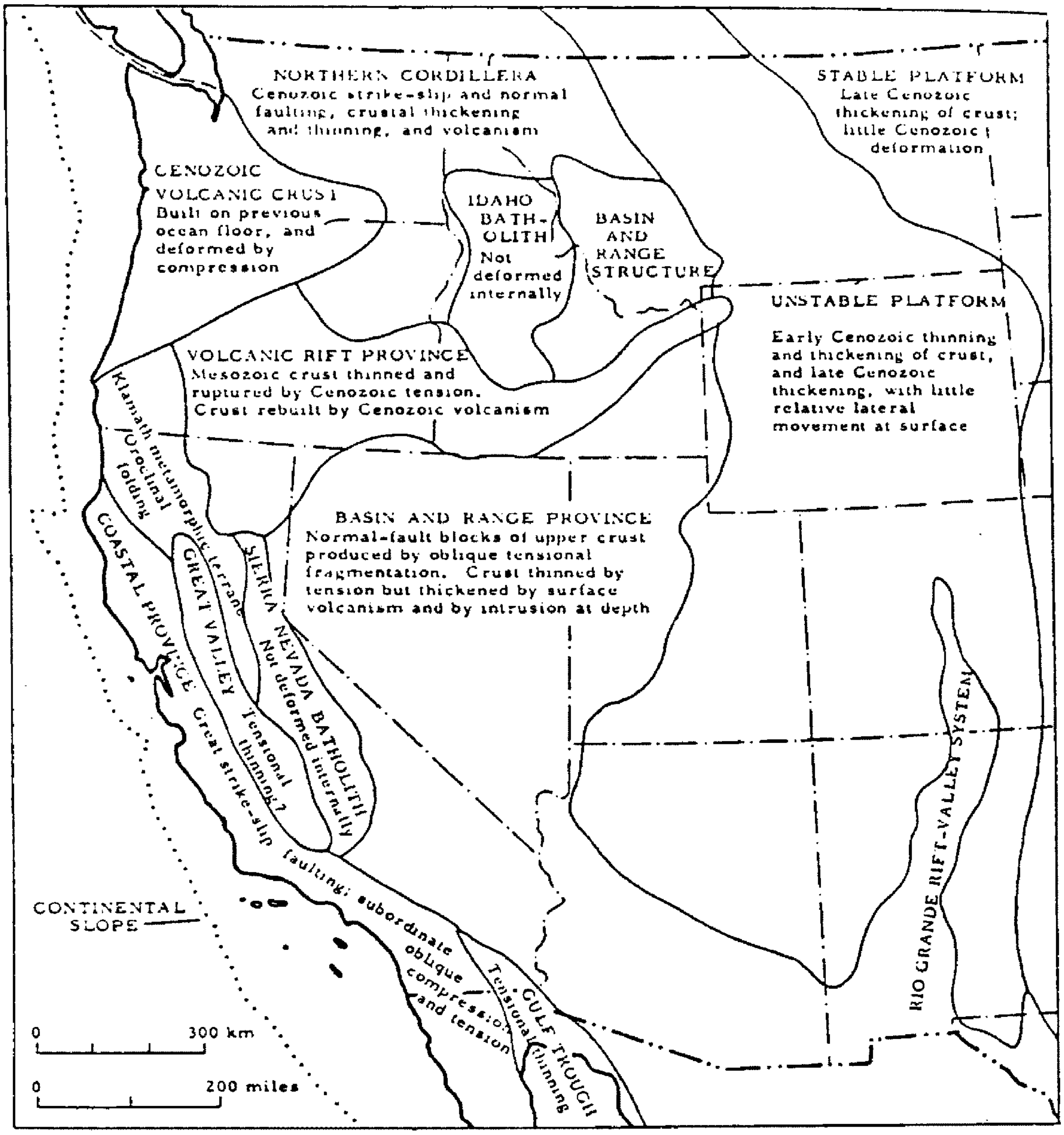

Figure 21. Generalized tectonic map of western United States as proposed by Hamilton and Myers, (1966).

Chapter 6

SUMMARY and CONCLUSIONS

I collected explosion and earthquake aftershock data along three seismic refraction lines in western Montana and part of adjacent Idaho to determine regional crustal and upper mantle velocity structure. The results indicate a regional 3 degree dip to the M-discontinuity to the northwest with crustal thickness increasing from 30 km at Butte, Montana to 47 km at Wallace, Idaho. The thin crust (30 km) in west-central Montana and the adjacent part of Idaho is coincident with the axis of the intermountain seismic belt, high heat flow and low Bouguer gravity values. These features are characteristic of the Basin and Range province, thus west-central Montana and adjacent Idaho should be included within this province. Such a thin crust indicates considerable extension during Tertiary time and Recent seismic activity reflects this extension. The thickest crust in my study area lies near key regional features of the northwesternmost end of the Bitterroot lobe of the Idaho Batholith metamorphic core complex, the Coer d'Alene mineral district and near the thickest package of Belt Supergroup rocks of the Belt Basin.

The crustal structure within western Montana and the adjacent part of northeastern Idaho can be closely approximated by a simple crustal model. Analyis of the PmP phases recorded among the records verifies this model; which includes a near surface layer of variable thickness and velocity depending on the local geology, and a crustal layer with velocities ranging from 5.84 km/sec in the south to 6.05 km/sec in the north. The upper mantle velocity is approximately 7.95 km/sec, but with a northwest dip to the M-discontinuity, apparent upper mantle velocities deviate from this value. This upper mantle velocity is higher than established within the Basin and Range province but significantly lower than in eastern Montana and thus is consistent with the crustal extension for the region.

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Appendix A

Tables

1a. CHALLIS BLAST INFORMATION

Date Yr Mo Dy	No.	Origin Time UTC	Lat. N. Deg.	Long. W. Deg.	Elev. Meters
84/7/11	1	2152:41.6	44.32	114.55	2576
84/7/12	2	2100:31.6	44.31	114.55	2271
84/7/13	3	2129:25.5	44.31	114.55	2286
84/7/16	4	1734:12.1	44.31	114.55	2423
84/7/17	5	2144:32.6	44.31	114.55	2271
84/7/18	6	2141:32.4	44.31	114.55	2286
84/7/26	7	1908:03.6	44.31	114.55	2271
84/8/17	8	1847:48.9	44.31	114.56	2423
84/8/17	9	2118:17.7	44.31	114.56	2374

1b. RECORDED DATA FROM CHALLIS BLAST

Sta No.	Date Yr Mo Dy	Lat. N. Deg.	Long. W. Deg.	Elev. Meters	Dist. Km	P1	Pg	Pn	Sg	Sn
1	84/7/12	44.37	114.48	1905	6.62	1.6			4.2	
2	84/7/12	44.41	114.38	2438	17.86	3.6			7.2	
3*	84/7/12	44.46	114.33	2057	23.78	4.9			10.9	
4	84/7/11	44.58	114.34	1841	33.68	6.8	6.8		12.9	
5	84/7/11	44.72	114.33	2170	48.04		8.8		16.0	
6	84/7/11	44.81	114.27	2201	58.66		10.8		19.3	
7	84/7/17	44.92	114.11	1762	76.12		13.9		23.4	
8	84/7/17	45.08	114.02	1737	95.35		17.5			
9	84/8/17	45.17	113.96	1609	106.72		19.1			37.1
10	84/8/17	45.21	113.93	1426	111.41		19.8			37.8
11	84/7/16	45.28	113.96	1990	117.32		20.7			38.7
12	84/8/17	45.42	114.08	1600	128.28		23.1			41.1
13	84/7/18	45.48	114.04	1451	135.45		23.9			43.0
14	84/7/18	45.53	114.01	1684	139.92		24.9			45.4
15	84/7/18	45.56	113.96	1622	145.88		26.0			45.0
16	84/7/18	45.61	113.98	1609	151.37			26.6		46.1
17	84/7/26	45.62	113.92	2249	158.99			27.6		
18	84/7/26	45.78	113.96	1561	164.29			28.9		
19	84/7/13	45.89	114.22	1705	177.68			30.0		54.0
20	84/7/26	45.96	114.21	1463	184.62			30.9		55.5

* base station for timing

1c. STATISTICS FOR CHALLIS TO MISSOULA PROFILE

	Cor. Cof.	int sec	Slope	Std.Err. sec	*Max(95%) int	Min(95%) int	Max(95%) slope	Min(95%) slope
P1	0.999	0.11	0.199	0.0046	0.28	-0.05	0.2135	0.1841
Pg	0.999	0.78	0.172	0.0016	0.86	0.70	0.1757	0.1684
Pn	1.000	7.02	0.129	0.0004	7.48	6.64	0.1305	0.1277
Sg	0.994	3.07	0.272	0.1368	3.30	2.85	0.3084	0.2380
Sn	0.994	10.70	0.241	0.0092	11.10	10.30	0.2619	0.2196

2a. AFTERSHOCK LOCATIONS AND INFORMATION

#	Date Yr Mo Dy	Origin Time UTC	Lat. N. Deg.	Long. W. Deg.	Depth	Mag.	No.	Gap	Dmn.	RMS
1	83/10/28	1406:06.69	43.97	113.91	16.0	7.3	19	10	70	.27
2	83/10/28	1951:25.02	44.07	113.89	10.0	5.8	18	10	74	.36
3	83/10/29	1147:02.25	44.14	113.89	10.8	3.1	15	8	7	.41
4	83/10/29	1737:41.12	44.08	113.89	8.3	3.1	10	10	1	.17
5	83/10/30	1314:43.94	44.21	114.04	5.0	3.0	13	263	7	.18
6	83/10/31	1032:41.80	44.23	114.04	7.4	3.2	17	191	3	.29
7	83/10/31	2114:17.42	44.27	114.08	6.0	2.8	12	24	4	.19
8	83/11/01	0059:08.13	44.22	114.04	7.8	2.7	22	76	4	.13
9	83/11/01	0105:28.15	44.24	114.05	8.9	2.9	29	82	3	.12
10	83/11/02	1241:13.51	44.27	114.07	4.5	3.5	15	206	3	.17
11	83/11/02	2224:04.56	44.24	114.07	9.9	3.2	14	204	4	.14
12	83/11/02	2342:01.74	44.27	114.09	7.6	3.2	14	120	3	.19
13	83/11/03	0105:20.17	44.25	114.11	7.9	3.8	20	222	6	.16
14	83/11/03	1414:17.91	44.26	114.10	7.0	3.4	17	23	5	.15
15	83/11/03	1547:29.56	44.26	114.04	6.8	3.6	17	181	1	.21
16	83/11/03	2337:08.64	44.35	114.08	8.0	2.7	25	163	5	.16
17	83/11/04	0500:14.81	44.14	113.94	9.3	3.5	28	73	3	.10
18	83/11/04	0708:19.09	44.22	114.03	10.8	3.4	28	69	4	.13
19	83/11/04	0904:12.76	44.16	113.93	8.1	3.1	25	67	4	.18
20	83/11/04	0916:09.45	44.15	113.94	5.2	2.9	18	102	3	.23
21	83/11/04	1343:00.92	44.20	114.04	11.4	2.6	24	74	5	.12
22	83/11/04	1730:44.18	44.26	114.02	5.9	3.2	25	102	4	.15
23	83/11/11	2250:47.82	44.10	113.92	11.5	2.8	29	66	5	.13
24	83/11/12	2232:27.50	44.18	114.02	11.7	2.4	28	84	2	.16
25	83/11/13	1201:16.92	44.08	113.94	12.6	2.4	23	69	3	.12
26	83/11/13	1523:07.79	44.35	114.02	5.1	2.6	13	141	9	.14

Mag. is aftershock magnitude in estimated coda length or from Wood-Anderson seismograph. No. is number of readings in hypocenter solution. Gap is largest azimuthal station separation. Dmn. is distance from closest station to epicenter, RMS is root mean square of travel-time residuals.

2b. STATIONS RECORDING AFTERSHOCKS

Site	Lat. N. Deg.	Long. W. Deg.	Elev. Km.
BG	46.04	114.03	1341
MC	46.31	114.22	1463
SH	46.42	114.23	1463
KC	46.54	114.15	1281
BC	46.60	114.13	1312
MCK	46.74	114.13	1280
MSO	46.83	113.94	1204
NCM	47.19	114.56	1173

2c. AFTERSHOCK RECORDINGS FOR CHALLIS TO MISSOULA PROFILE

Site	Event* No.	Depth Km.	Time Cor. Sec.	Time Dif. Sec.	Dist. Km.
BG	16	8.0	1.12	30.58	188.05
BG	22	5.9	0.90	32.37	198.01
BG	18	10.8	1.41	32.82	203.31
BG	21	11.4	1.47	33.25	204.04
BG	19	8.1	1.13	34.22	210.91
BG	20	5.2	0.81	31.96	211.16
BG	17	9.3	1.25	32.89	211.74
MC	7	6.0	0.91	35.21	227.91
MC	9	8.9	1.21	36.21	228.77
SH	26	5.1	0.80	38.81	231.72
MC	8	7.8	1.10	36.07	232.50
KC	16	8.0	1.12	37.48	244.17
SH	24	11.7	1.51	42.41	250.73
KC	18	10.8	1.41	38.91	259.36
BC	9	8.9	1.21	39.61	262.90
KC	17	9.3	1.25	39.51	267.71
MSO	6	7.4	1.05	42.25	290.77
MSO	5	5.0	0.78	42.34	292.74
MCK	25	12.6	1.56	44.74	298.63
MSO	3	10.0	1.32	44.67	300.60
MSO	4	8.3	1.15	45.23	308.38
MSO	2	10.0	1.32	45.30	308.92
NCM	10	4.5	0.72	47.05	321.57
NCM	12	7.5	1.08	48.84	327.08
NCM	14	7.0	1.01	48.40	328.75
NCM	13	7.9	1.11	48.74	328.91
NCM	15	6.8	0.99	48.93	329.17
NCM	11	9.9	1.31	49.35	331.03
NCM	18	10.8	1.41	49.51	334.25
NCM	19	8.1	1.13	51.03	342.41
NCM	17	9.3	1.25	50.25	343.09
NCM	23	11.5	1.48	51.46	347.25

* Event no., correlates with event (#) recorded in Table 2b.

2d. STATISTICS FOR AFTERSHOCK DATA

	Cor. Cof.	int sec	Slope	Std.Err. sec	Max(95%) int	Min(95%) int	Max(95%) slope	Min(95%) slope
Pn	0.995	5.98	0.129	0.00319	7.58	4.38	0.1331	0.1200

3a. ORIGIN TIMES OF BUTTE BLASTS

Date Yr Mo Dy	Shot No.	Origin times UTC
82/5/04	1	1801:35.2
82/5/11	2	1801:47.6
82/5/18	3	1805:25.6
83/3/23	4	1904:11.4
83/3/31	5	1906:48.0
83/4/05	6	1903:49.4
83/4/15	7	1910:11.3
83/4/19	8	1904:41.9
83/5/20	9	1801:08.6
83/6/09	10	1805:28.7

3b. DATA FROM B. HAWLEY

Station	Dist.	P1
But	0.00	0.00
Bbt	4.27	0.93
Bbt	4.13	1.00
Shg	8.88	2.00
Shg	8.86	2.08
Bgh	14.62	3.00
Bgh	14.76	3.10

3c. BUTTE TO WALLACE PROFILE, DATA

Coordinates for Butte Blast: 46.01 N., 112.48 W. (deg.)

Sta No.	Date Yr Mo Dy	Lat. N. Deg.	Long. W. Deg.	Elev. Meters	Dist. Km	P1	Pg	Pn	Sg	Sn
1	82/5/04	46.23	113.26	1524	34.7	7.4			9.4	
2	82/5/11	46.13	112.99	1768	41.8		8.0		13.6	
3	82/5/11	46.16	113.08	1890	49.0		9.1		15.9	
4	82/5/18	46.19	113.14	2134	54.4		10.1		17.3	
5	82/5/04	46.21	113.18	2073	58.1		10.8		18.8	
6	83/4/15	46.36	113.43	1768	82.9		14.1		24.1	
7	83/4/15	46.34	113.61	1524	94.2		16.4		32.2	
8	83/4/05	46.39	113.68	1463	101.4		18.4		31.0	
9	83/4/05	46.68	113.77	1295	112.3		20.0		36.1	
10	83/3/31	46.45	113.89	1570	118.7		22.2			41.1
11	83/3/23	46.46	113.93	1768	122.0		21.2		37.9	39.5
12	83/3/31	46.51	114.00	1280	129.5		22.1		37.6	41.5
13	83/3/31	46.54	114.24	1280	146.6		24.8		44.4	44.7
14	83/3/23	46.55	114.22	1707	147.3		24.4		44.0	45.4
15	83/5/20	46.83	113.94	1264	148.6		25.5		43.8	47.0
16	83/5/20	46.71	114.51	1463	173.9		30.5		51.8	53.6
17	83/5/20	46.83	114.70	1280	190.0		33.6		53.7	59.6
18	83/5/20	46.91	114.80	1311	204.3		34.8			
19	83/4/19	46.97	114.79	1158	206.6		35.8	33.6		
20	83/4/19	47.15	114.96	914	228.1		37.4	35.8	65.3	
21	83/6/09	47.38	115.36	1184	267.0		45.4	41.5		
22	83/6/09	47.40	115.51	1722	278.4		47.5	42.8		

3d. STATISTICS FOR BEST FIT LINES, BUTTE TO WALLACE PROFILE

	Cor. Cof.	int. sec	Slope	Std.Err. sec
P1	0.999	0.06	0.211	0.0137
Pg	0.998	1.06	0.165	0.0021
Pn	0.998	6.08	0.132	0.0061
Sg	0.996	2.04	0.282	0.0058
Sn	0.990	12.56	0.235	0.0127

4a. CLINTON BLAST INFORMATION

Date Yr Mo Dy	Shot No.	Origin time UTC
84/7/30	1	2208:39.9
84/8/22	2	2211:29.6
84/9/06	3	2201:20.5
84/9/21	4	2301:43.2

4b. MISSOULA SOUTH PROFILE DATA

Coordinates of Clinton blast: 46.80 N., 113.74 W. (deg.)

Sta No.	Date Yr Mo Dy	Lat. N. Deg.	Long. W. Deg.	Elev. Meters	Dist. Km	P1	Pg	Sg
1*	84/7/30	46.75	113.76	1280	5.25	2.3		
2	84/7/30	46.70	113.79	1509	11.07	3.3		
3	84/9/21	46.54	113.84	1905	29.94		6.6	
4	84/9/21	46.52	113.85	1859	31.82		7.0	
5	84/9/21	46.45	113.89	1768	40.00		8.4	14.3
6	84/9/06	46.32	113.96	1920	55.60		11.0	18.0
7	84/9/06	46.26	113.94	2073	61.60		11.6	19.7
8	84/9/06	46.18	113.97	2164	70.60		14.0	24.3
9	84/8/22	46.10	114.05	1890	81.08		15.0	26.0
10	84/8/22	45.95	114.05	1768	96.79		17.7	
11	84/8/22	45.80	113.35	2164	111.75		20.5	38.0

* base station for timing

4c. STATISTICS FOR BEST FIT LINES, MISSOULA SOUTH PROFILE

	Cor. Cof.	int sec	Slope	Std Err. sec
Pg	0.999	1.20	0.168	0.0051
Sg	0.996	1.06	0.324	0.0184

Appendix B

Programs

```
C********************TPLT.FOR**********************************

C  TPLT IS A PROGRAM WHICH PLOTS SEISMIC TRACES FROM DIGITIZED POINTS
C  ON A TIME DISTANCE GRAPH...ALSO INCLUDED IS THE OPTION TO USE A
C  FORWARD MODELLING APPROACH IN FITTING LINES TO THE PHASES OF THE
C  TRACES..THE LINES DERIVED FROM THE INPUT OF THE MODEL INCLUDE
C  RELECTIONS AS WELL AS REFRACTIONS...IN PLOTTING BOTH THE TIME
C  DISTANCE GRAPH OF THE TRACES AND THE LINES A REDUCED TRAVEL TIME
C  PLOT CAN BE USED...THIS PROGRAM WAS WRITTEN BY GARRY CARLSON WITH
C  SUBROUTINES: LBAXLI, FRAME, TEXT AND TITLE WRITTEN BY TONY QAMAR
C  AND JERRY SAYERS (FROM COMPUTER GRAPHICS)...ZTRACE HAS BEEN
C  MODIFIED FROM SUBROUTINE PLLINE....PLEASE ACKNOWLEDGE THE
C  AUTHORS NAMES (GIVEN ABOVE) IN ANY PUBLICATIONS USING TPLT

        DIMENSION TIME(50),DIST(50),XX(10005),YY(10005)
        DIMENSION X(10005),Y(10005),XLAB(5),YLAB(5)
        DIMENSION IY(10005),IX(10005)
        DIMENSION ZX(500),ZY(500),V(50),H(50),CRDIST(50)
        DIMENSION TI(50),SLP(50),AI(50),ZTHET(50),ZP(50)
C**************************************************************
C SPECS DETERMINES THE DIMENSIONS OF THE FRAME AND PLOT
C FOR FURTHER INFO ON SPECS SEE COMPUTER GRAPHICS/TONY QAMAR
C S(1)....NO. OF INCHES ALONG X DIRECTION TO ORIGIN
C S(2)....NO. OF INCHES ALONG Y DIRECTION TO ORIGIN
C S(3)....LENGTH OF X AXIS IN INCHES
C S(4)....LENGTH OF Y AXIS IN INCHES
C S(5)....LEFT X VALUE IN USER COORDINATES
C S(6)....RIGHT X VALUE IN USER COORDINATES
C S(7)....BOTTOM Y VALUE ON Y AXIS IN USER COORDINATES
C S(8)....TOP Y VALUE ON Y AXIS IN USER COORDINATES
C S(9)....TICK OR GRID LINES, 0=NO TICKS, 1=TICKS, 2=GRID
C S(10)...TICK OR GRID LINES ON Y AXIS,
C S(11)...NO. OF SUBDIVISIONS ON X AXIS
```

```
C S(12)...NO. OF SUBDIVISIONS ON Y AXIS
C S(13)...SIZE OF PLOTTED SYMBOLS IN INCHES
C S(14)...1,2 OR 3 SPECIFIES INTERVALS OF TICKS TO BE NO.
C S(15)...SAME AS S(14) ONLY FOR Y AXIS
C***********************************************************
C FOR DIFFERENT DIMENSIONS IN PLOTS, USER CAN USE EDIT TO CHANGE
C THE SPECS.
        COMMON/SPECS/S(35)
        S(1)=1.
        S(2)=1.
        S(3)=7.
        S(4)=4.
        S(5)=0.
        S(6)=300.
        S(7)=-10.
        S(8)=40.
        S(9)=1.
        S(10)=1.
        S(11)=6.
        S(12)=5.
        S(13)=.1
        S(14)=2.
        S(15)=2.
C***********************************************************
7       FORMAT(F)
        WRITE(5,251)
251     FORMAT(1X,'DO YOU WANT PEN CURVATURE CORRECTION FOR MEQ,
     *  Y OR N?  ',$)
        READ(5,246) QUES
        WRITE(5,245)
245     FORMAT(1X,'DO YOU WANT A REDUCED TRAVEL TIME PLOT,
     *  Y OR N?  ',$)
        READ(5,246) ANS
246     FORMAT(A3)
        OPEN(UNIT=24,DEVICE='DSK',ACCESS='SEQIN',FILE='BUTDIS.DAT')
        OPEN(UNIT=23,DEVICE='DSK',ACCESS='SEQIN',FILE='NEWBUT.DAT')
        READ(24,7)ZNUM
        REDFAC=0.
        RDUC=1.
        RAD=57.295
        IF(ANS .EQ. 'N' .OR. ANS .EQ. 'NO') GOTO 247
```

```
      IF(ANS .EQ. 'Y' .OR. ANS .EQ. 'YES') B=1.
      WRITE(5,248)
248   FORMAT(1X,'WHAT IS THE REDUCTION VELOCITY? =  '$)
      READ(5,249) RDUC
249   FORMAT(F)

247   X2=(S(6)-S(5))/S(3)

C  OPTION OF INPUTING A MODEL TO PLOT TRAVEL TIME CURVES
C  ABC EQUALS ANSWER, YES OF NO
      WRITE(5,77)
77    FORMAT(1X,'DO YOU WANT A MODEL?, Y OR N  ',$)
      READ(5,222) ABC
222   FORMAT(A3)
      IF(ABC .EQ. 'N' .OR. ABC .EQ. 'NO') GOTO 770
      WRITE(5,2002)
2002  FORMAT(1X,'HOW MANY LAYERS IN THE MODEL? ',$)
      READ(5,2003)LYR
2003  FORMAT(I)
      DO 2004 NI=1,LYR
      WRITE(5,2005)NI
2005  FORMAT(1X,'VELOCITY OF LAYER  ',I,'=  ',$)
      READ(5,2006)V(NI)
2006  FORMAT(F)
2004  CONTINUE
      LIM=LYR-1
      DO 2008 JB=1,LIM
      WRITE(5,2007) JB
2007  FORMAT(1X,'THICKNESS OF LAYER ',I,'  =  ',$)
      READ(5,3333) H(JB)
3333  FORMAT(F)
2008  CONTINUE
C PLOTS SHOULD BE FIRST PLOTTING CALLING ROUTINE TO INITIATE PLOTTER
770   CALL PLOTS(0,0,0)
      CALL FRAME
      XLAB(1)='KM'
      YLAB(1)='SEC'
      YLAB(2)='-T/X'
      NND=9
      MMD=5
      CALL LBAXLI(2,2,1,1,YLAB,NND)
```

```
        CALL LBAXLI(1,2,1,1,XLAB,MMD)

C TITLE PLOTS TITLE OF REFRACTION LINE ABOVE THE PLOT
C NEEDS TO BE EDITED FOR EACH PLOT,  NUMBER AFTER TITLE IS
C THE NUMBER OF CHARACTERS IN TITLE INCLUDING BLANK SPACES
C LAST NUMBER IS WHETHER X (1) OR Y (2) AXIS TITLE IS PLACED

        CALL TITLE('BUTTE TO WALLACE PROFILE',24,1)

        NUM=INT(ZNUM)

        DO 1001 JL=1,NUM
        ZLIM=S(8)-2.
        READ(24,7) EXP
        READ(24,1) X1,F1
        XFAC=X1*X2
C  SINCE PAPER CHANGES USER COORDINATES TO PAPER COORDINATES ONE INCH
C  HAS TO EQUAL ONE SECOND IN OUR INPUT
        YFAC=2.54/F1
        READ(24,1) TIME(JL),DIST(JL)
1       FORMAT(2F)
        IF(B .NE. 1.) GOTO 223
        REDFAC=DIST(JL)/RDUC
223     L=1
        READ(23,90) CUL
90      FORMAT(1X,A4)

C READ DIGITIZED POINTS..FROM DIGITIZED TABLE IN SOCIOLGY DEPT
C THE NUMBERS NEED TO BE CONVERTED TO INCHES BY DIVIDING BY 100
C 9999 AND 0 ARE THE FLAGS MARKED TO MOVE ON TO NEXT TRACE
C INPUT FROM THE DIGITIZING MACHINE
C PROGRAM READS 5 SETS OF X,Y DATA FROM DATA FILE

        DO 203 I=1,2000
        READ(23,2) (IX(K),IY(K),K=L,L+4)
        DO 201 JK=L,L+4
        IF(IX(JK) .EQ. 9999 .AND. IY(JK) .EQ. 1) GOTO 202
        IF(IX(JK) .EQ. 0 .AND. IY(JK) .EQ. 0) GOTO 202
        IF(IX(JK) .EQ. 9999 .AND. IY(JK) .EQ. 2) GOTO 52
        XX(JK)=FLOAT(IX(JK))/100.
        YY(JK)=FLOAT(IY(JK))/100.
```

```
201     CONTINUE
52      L=L+5
203     CONTINUE
2       FORMAT(10I)

202     JJ=0
        MM=0
C QUES IS YES OR NO DEPENDING ON PEN CORRECTION
C PEN IS 5 INCHES LONG..CORRECTION FACTOR TAKES ARC INTO ACCOUNT

        IF(QUES .EQ. 'N') GOTO 302
        IF(EXP .EQ. 1.) GOTO 301
        DO 304 N=2,JK
        MM=MM+1
        YY(N)=YY(N)-YY(1)
        XX(N)=XX(N)-XX(1)
        IF(YY(N) .EQ. 0.) GOTO 45
        YY(N)=YY(N)/EXP
        A=SQRT(ABS(25.-YY(N)**2))
        Z=(YY(N)/A)
        ANG=ATAN(Z)
        YY(N)=(5.*ANG)*EXP
        XX(N)=XX(N)-((5.-A)*EXP)
45      X(N)=(YY(N)*XFAC)+DIST(JL)
        Y(N)=(XX(N)*YFAC)+(TIME(JL)-REDFAC)
304     CONTINUE
        GOTO 46
301     DO 300 N=2,JK
        MM=MM+1
        YY(N)=YY(N)-YY(1)
        XX(N)=XX(N)-XX(1)
        IF(YY(N) .EQ. 0.) GOTO 144
        A=SQRT(ABS(25.-YY(N)**2))
        Z=(YY(N)/A)
        ANG=ATAN(Z)
        YY(N)=5.*ANG
        XX(N)=XX(N)-(5.-A)
144     X(N)=(YY(N)*XFAC)+DIST(JL)
        Y(N)=(XX(N)*YFAC)+(TIME(JL)-REDFAC)
300     CONTINUE
        GOTO 46
```

```
C DO SUBROUTINE WITHOUT PEN CORRECTION

302     DO 303 N=2,JK
        MM=MM+1
        YY(N)=YY(N)-YY(1)
        XX(N)=XX(N)-XX(1)
        X(N)=(YY(N)*XFAC)+DIST(JL)
        Y(N)=(XX(N)*YFAC)+(TIME(JL)-REDFAC)
303     CONTINUE
46      X(0)=DIST(JL)
        Y(0)=TIME(JL)-REDFAC
        X(1)=DIST(JL)
        Y(1)=TIME(JL)-REDFAC
        X(MM)=DIST(JL)
        Y(MM)=Y(MM-1)+1.
        GB=DIST(JL)
        DO 150 JI=MM+1,MM+3
        X(JI)=GB
        ZLIM=ZLIM+1.
        Y(JI)=ZLIM
150     CONTINUE

        NLAST=1

C ZTRACE IS PLOTTING SUBROUTINE WHICH PLOTS THE TRACES

        CALL ZTRACE(X,Y,JI,1,1,1,0)
1001    CONTINUE
C***************************************************************
        IF(ABC .EQ. 'N' .OR. ABC .EQ. 'NO') GOTO 400
C ABC DETERMINES WHETHER TRAVEL TIME CURVES FROM MODEL IS PLOTTED
C******************************************************************
        AZ=S(6)
        IK=INT(S(6))

C TRAVEL TIME CURVES FROM REFLECTIONS PLOTTED FIRST
C USING RAY PARAMETER AND EQUATIONS FROM SLOTNICK, 1959

        DO 1005 I=1,LYR-1
        K=1
        DO 1006 JK=0,89
```

```
      C=FLOAT(JK)
      A=C/RAD
      P=(SIN(A))/V(I)
      XR=0.0
      YR=0.0
      DO 1007 N=1,I
      YR=H(N)/(V(N)*(SQRT(ABS(1.-(P**2)*(V(N)**2)))))+YR
      XR=(H(N)*V(N))/(SQRT(ABS(1.-(P**2)*(V(N)**2))))+XR
1007  CONTINUE
      ZY(K)=2.*YR
      ZX(K)=2.*P*XR
      IF(K.EQ.1)GOTO 44
      UT=ZX(K)-ZX(K-1)
      IF(B .EQ. 1.) ZY(K)=ZY(K)-(ZX(K)/RDUC)
      IF(UT.LT. 1.) GOTO 1006
      IF(UT.LT.3.) GOTO 44

C INCREASE RESOLUTION OF CALCULATED POINTS FOR BETTER CURVE

      K=K+1
      CD=0.
      DO 432 KP=1,19
      CD=CD+.5
      A=((FLOAT(JK))+CD)/RAD
      P=(SIN(A))/V(I)
      XR=0.0
      YR=0.0
      DO 898 N=1,I
      YR=H(N)/(V(N)*(SQRT(ABS(1.-(P**2)*(V(N)**2)))))+YR
      XR=(H(N)*V(N))/(SQRT(ABS(1.-(P**2)*(V(N)**2))))+XR
898   CONTINUE
      ZY(K)=2.*YR
      ZX(K)=2.*P*XR
      IF(B.EQ.1.) ZY(K)=ZY(K)-(ZX(K)/RDUC)
      RT=(ZX(K)-ZX(K-1))
      IF(RT .LT. 1.) GOTO 432
      IF(ZX(K).GT. S(6) .OR. ZY(K) .GT. S(8)) GOTO 44
      IF(KP .EQ. 19) GOTO 432
      K=K+1
432   CONTINUE
```

```
C IF ZX OR ZY LIES OF PLOT..PLOTTING FOR THE PARTICULAR TRACE IS
C DISCONTINUED AND PROGRAM MOVES ON TO PLOT NEXT TRACE BY DEFAULT

44      IF(ZX(K).GT. S(6) .OR. ZY(K) .GT. S(8)) GOTO 155
        K=K+1
1006    CONTINUE
C NEWPEN DETERMINES WHAT COLOR TRAVEL TIME CURVE IS ON CALCOMP
C BLACK = 1   RED = 2....ETC

155     CALL NEWPEN(2)
        CALL ZTRACE(ZX,ZY,K,1,1,1,1)
1005    CONTINUE
C*********************************************************************
        J=0
        K=0

C PLOT TRAVEL TIME CURVES FOR REFRACTIONS...GIVEN BY SLOPE-INTERCEPT
C FORM DETERMINED FROM INPUT MODEL

        DO 1111 I=1,LYR
        SLP(I)=1./V(I)
1111    CONTINUE
        N=0
        TI(1)=0.0
        DO 1160 J=2,LYR
        N=N+1
        DO 1150 I=1,N
        TI(J)=2.*H(I)*SQRT((V(LYR)**2)-(V(I)**2))/(V(LYR)*V(I))+TI(J)
1150    CONTINUE
1160    CONTINUE
        M=0
C CRDIST IS WHEN THE FIRST REFRACTION WILL COME IN ON THE PLOT
        DO 2001 N=1,LYR
        DO 1002 JJ=1,M
        CRDIST(N)=2.*H(N-1)*SQRT(1.-(V(JJ)**2/V(N)**2))+CRDIST(N)
1002    CONTINUE
        M=M+1
2001    CONTINUE

C GO THROUGH NUMBER OF LAYERS GIVEN IN MODEL
```

```
      DO 1010 I=1,LYR
      NA=0
      DO 1012 KK=0,1000,2
      A=FLOAT(KK)
      IF(A .LT. CRDIST(I)) GOTO 1012
      NA=NA+1
      ZX(NA)=A
      ZY(NA)=SLP(I)*A+TI(I)
      IF(B.EQ.1.) ZY(NA)=ZY(NA)-(ZX(NA)/RDUC)
      IF(ZX(NA) .GT. S(6)) GOTO 156
1012  CONTINUE

C NEWPEN CAN BE CHANGED FOR DIFFERENT COLOR
156   CALL NEWPEN(1)
      CALL ZTRACE(ZX,ZY,NA,1,1,1,1)
1010  CONTINUE
400   CALL PLOT(0,0,999)
      STOP
      END
C*****************************************************************
C END OF MAIN PROGRAM
C PLOTTING SUBROUTINES FOLLOW
C FRAME DRAWS BOUNDARIES DETERMINED BY SPEC ARRARY
C LBLAXI PLOTS Y AND X AXES
C INFORMATION IS IN CALCOMP PLOT MANUAL BY QAMAR AND SAYERS
C UNIVERSITY OF MONTANA
C****************************************************************
      SUBROUTINE FRAME
      COMMON/SPECS/S(35)
      XC=S(1)
      YC=S(2)
      CALL PLOT(XC,YC,3)
      XC=S(1)+S(3)+.5
      CALL PLOT(XC,YC,2)
      YC=S(2)+S(4)
      CALL PLOT(XC,YC,2)
      XC=S(1)
      CALL PLOT(XC,YC,2)
      YC=S(2)
      CALL PLOT(XC,YC,2)
      RETURN
```

```
      END
C*******************************************************************
C ZTRACE PLOTS TRACES AND TRAVEL TIME CURVES
C********************************************************************
      SUBROUTINE ZTRACE(X,Y,N,NOPX,NOPY,NDOWN,J)
      COMMON/SPECS/S(35)
      DIMENSION X(N),Y(N)
      S(35)=0.
      IF(S(6) .GT. S(5)) GOTO 10
      X1=S(6)
      X2=S(5)
      GOTO 12
 10   X1=S(5)
      X2=S(6)
 12   CONTINUE
      IF(S(8) .GT. S(7)) GOTO 23
      Y1=S(8)
      Y2=S(7)
      GOTO 24
 23   Y1=S(7)
      Y2=S(8)
 24   CONTINUE
      NLAST=0
      IF(NDOWN .NE. 1) GOTO 30
 30   CONTINUE

      DO 977 I=J,N
      IF((X(I).GT.X2) .OR.(X(I).LT.X1).OR.(Y(I).GT.Y2)
     * .OR.(Y(I).LT.Y1)) GOTO 90
      XC=PAPER(X(I),1,NOPX)
      YC=PAPER(Y(I),2,NOPY)
      IF(NLAST.NE.1) GOTO 80
      CALL PLOT(XC,YC,2)
      GOTO 95
 80   CONTINUE
      CALL PLOT(XC,YC,3)
      GOTO 95
 90   NLAST=0
      S(35)=S(35)+1.
      GOTO 500
 95   NLAST=1
```

```
500     CONTINUE
977     CONTINUE
        RETURN
        END
C*****************************************************************
        FUNCTION PAPER(Z,NOP1,NOP2)
C...RETURNS PAPER COORDINATE(INCHES) CORRESPONDING TO USER
C...      NOP1=1 AXIS IS AN X AXIS
C...      NOP1=2 AXIS IS A  Y AXIS
C...      NOP2=1 AXIS IS LINEAR
C...      NOP2=2 ASIS IS LOG
        COMMON/SPECS/S(35)
        GOTO(100,200),NOP1
100     GOTO(110,120),NOP2
110     PAPER=S(1)+S(3)*(Z-S(5))/(S(6)-S(5))
        RETURN
120     PAPER=S(1)+S(3)*ALOG10(Z/S(5))/ALOG10(S(6)/S(5))
        RETURN
200     GO TO(210,220),NOP2
210     PAPER=S(2)+S(4)*(Z-S(7))/(S(8)-S(7))
        RETURN
220     PAPER=S(2)+S(4)*ALOG10(Z/S(7))/ALOG10(S(8)/S(7))
        RETURN
        END
C************************************************************
C************************************************************
        SUBROUTINE LBAXLI(KIND,NUMB,LBL,NFIG,TXT,NTXT)
C...NUMBERS A LINEAR ABSCISSA(KIND=1) OR ORDINATE(KIND=2) AXIS
C...SEE COMPUTER GRAPHICS/BY TONY QAMAR FOR OTHER VARIABLES
C...NUMB SPECIFIES NUMBERING
C...         =0  NO NUMBERING
C...         =1  INTEGER NUMBERING
C...         =2  FLOATING PT NUMBERING
C...         =3  EXPONENTIAL NUMBERING
C...LBL SPECIFIES LABELING
C...         =0  NO LABELING
C...         =1  LABELING
C...KIND SPECIFIES X OR Y AXIS
C...         =1  X AXIS
C...         =2  Y AXIS
C...SIZE OF SYMBOLS IN LABELS GIVEN BY S(13).  SIZE OF NUMBERS
```

```
C...IS .833333*(SIZE OF SYMBOLS)
      COMMON /SPECS/S(35)
      DIMENSION TXT(10)
      DATA TIKSIZ/.1/
      SAVE=S(13)
      SIZTXT=S(13)
      SIZNUM=.83333*SIZTXT
      S(13)=SIZNUM
      NWAY =2
      IF(KIND.NE.2)GOTO 777
      GOTO 888
777   NWAY=1
888   TL=0.
      GO TO (3,4),NWAY
3     CONTINUE
      ATK=S(9)
C...MINUS SIGN WAS INSERTED ON NEXT LINE TO MAKE TICKS COME
C...OUTSIDE FRAME.
      IF(ATK.EQ.1.)TL=-TIKSIZ
      IF(ATK.EQ.-1.)TL=TIKSIZ
      IF(ATK.EQ.2.)TL=S(4)
      NOP=2
      NT=S(11)+1+.0001
      IF(S(11).LT.0.)NT=-S(11)+.0001
      GO TO 5
4     CONTINUE
      ATK=S(10)
C...NEXT MINUS SIGN FOR TICKS OUTSIDE FRAME
      IF(ATK.EQ.1.)TL=-TIKSIZ
      IF(ATK.EQ.-1.)TL=TIKSIZ
      IF(ATK.EQ.2.)TL=S(3)
      NOP=1
      NT=S(12)+1+.0001
      IF(S(12).LT.0.)NT=-S(12)+.0001
5     CONTINUE
C...CHECK TO SEE IF TICKS OR GRID LINES ON AXIS ARE DESIRED
      IF(ATK.NE.1..AND.ATK.NE.2..AND.ATK.NE.-1.)GO TO 50
C...CHECK FOR ILLEGAL VALUES
      GO TO (6,7),NWAY
6     IF(ABS(S(11)).LT..99)GO TO 50
      GO TO 8
```

```
7        IF(ABS(S(12)).LT..99)GO TO 50
8        CONTINUE
         L=1
         XC=S(1)
         YC=S(2)
         GO TO(201,202),NWAY
201      SINC=S(3)/ABS(S(11))
         XC=S(1)-SINC
         IF(S(11).LT.0.)XC=S(1)-SINC/2.
         GO TO 205
202      SINC=S(4)/ABS(S(12))
         YC=S(2)-SINC
         IF(S(12).LT.0.)YC=S(2)-SINC/2.
205      CONTINUE
         DO 40 I=1,NT
         GO TO (10,20),NWAY
10       XC=XC+SINC
         GO TO 22
20       YC=YC+SINC
22       CONTINUE
         CALL PLOT(XC,YC,3)
         IF(L.LT.0)GO TO 30
         GO TO(23,24),NWAY
23       YC=S(2)+TL
         GO TO 38
24       XC=S(1)+TL
         GO TO 38
30       GO TO (31,32),NWAY
31       YC=S(2)
         GO TO 38
32       XC=S(1)
38       CONTINUE
         CALL PLOT(XC,YC,2)
         L=-L
40       CONTINUE
50       CONTINUE
C...CHECK FOR NUMBERING OF AXIS
         IF(NUMB.NE.1.AND.NUMB.NE.2.AND.NUMB.NE.3)GO TO 100
C...CHECK FOR ILLEGAL VALUES
         GO TO (55,56),NWAY
55       IF(ABS(S(14)).LT..99)GO TO 100
```

```
      GO TO 57
56    IF(ABS(S(15)).LT..99)GO TO 100
57    CONTINUE
      GO TO (63,64),NWAY
63    YP=S(2)-TIKSIZ-1.25*S(13)
      NTIME=S(11)+1+.00001
      IF(S(11).LT.0.)NTIME=-S(11)+.0001
      GO TO 65
64    XP=S(1)-TIKSIZ
      NTIME=S(12)+1+.00001
      IF(S(12).LT.0.)NTIME=-S(12)+.0001
65    CONTINUE
      GO TO (301,311),NWAY
301   SINC=S(3)/ABS(S(11))
      FACTOR=(S(6)-S(5))/ABS(S(11))
      IF(S(11).LT.0.)GO TO 305
      XPAPR=S(1)-SINC
      XVALU=S(5)-FACTOR
      GO TO 320
305   XPAPR=S(1)-SINC/2.
      XVALU=S(5)-FACTOR/2.
      GO TO 320
311   SINC=S(4)/ABS(S(12))
      FACTOR=(S(8)-S(7))/ABS(S(12))
      IF(S(12).LT.0.)GO TO 315
      YPAPR=S(2)-SINC
      XVALU=S(7)-FACTOR
      GO TO 320
315   YPAPR=S(2)-SINC/2.
      XVALU=S(7)-FACTOR/2.
320   CONTINUE
      GO TO(331,332),NWAY
331   NSKIP=S(14)
      GO TO 340
332   NSKIP=S(15)
340   CONTINUE
      DO 73 I=1,NTIME,NSKIP
      GO TO(66,67),NWAY
66    XP=XPAPR+SINC*I
      GO TO 68
67    YP =YPAPR+SINC*I
```

```
68      CONTINUE
        XV=XVALU+FACTOR*I
        GO TO (70,71),NUMB
C SUBROUTINE INUM PLOTS INTEGER NUMBERS ON X Y AXIS
70      CALL INUM(XP,YP,XV,0.,NOP)
        GO TO 73
71      CONTINUE
C SUBROUTINE FLTNUM PLOTS FLOATING POINT NUMBERS ON X Y AXIS
        CALL FLTNUM(XP,YP,XV,0.,NOP,NFIG)
73      CONTINUE
100     CONTINUE
C...CHECK FOR LABELING OF AXIS
        IF(LBL.NE.1)GO TO 350
        S(13)=SIZTXT
        GO TO (120,150),KIND
120     CONTINUE
C...CONTINUE HERE FOR X AXIS LABELING
        XPAPR=S(1)+S(3)/2.
        YPAPR=S(2)-TIKSIZ-2.5*S(13)
C SUBROUTINE TEXT LABELS AND PLOTS THE AXIS
        CALL TEXT(XPAPR,YPAPR,TXT,0.,NTXT,2)
        GO TO 350
150     CONTINUE
C...CONTINUE HERE FOR Y AXIS LABELING
        NWAY=NUMB+1
C...DYNAMICALLY POSITION Y AXIS LABEL DEPENDING ON MAX
C...NO. OF DIGITS IN THE NUMBERS ON THE AXIS.
        YPAPR=S(2)+S(4)/2.
        AMAX=ABS(S(8))
        AMIN=ABS(S(7))
        IF(AMAX.GT.AMIN)GO TO 199
        TEMP=AMAX
        AMAX=AMIN
        AMIN=TEMP
199     CONTINUE
        NEG=0
        IF((S(7).LT.0.).OR.(S(8).LT.0.))NEG=1
        XSPACE=1.25
        GO TO(250,220,230),NWAY
C...Y LABELING WITH INTEGER NUMBERING
220     CONTINUE
```

```
      NNN=ALOG10(AMAX)+1.
      XSPACE=XSPACE+NNN
      GO TO 250
C...Y LABELING WITH FLOATING POINT NUMBERING
230   CONTINUE
      XSPACE=XSPACE+NFIG+1.
      IF(AMAX.LT.1.)GO TO 250
      NNN=ALOG10(AMAX)+1.
      XSPACE=XSPACE+NNN
250   CONTINUE
      IF(NEG.EQ.1)XSPACE=XSPACE+1.
      XPAPR=S(1)-XSPACE*SIZNUM-TIKSIZ
      S(13)=SIZTXT
      CALL TEXT(XPAPR,YPAPR,TXT,90.,NTXT,2)
350   CONTINUE
      S(13)=SAVE
      RETURN
      END
C*******************************************************
      SUBROUTINE FLTNUM(X,Y,VALUE,THETA,NOP,NRIGHT)
C...PLOTS A FLOATING POINT NUMBER WITH NRIGHT DIGITS TO RIGHT OF
C...DECIMAL POINT.  FOR OTHER PARAM. SEE ENUM
      COMMON /SPECS/S(35)
      IF(NOP.EQ.3)GO TO 200
      NR=NRIGHT
      IF(NRIGHT.LT.0)NR=0
C...TEST ACCOUNTS FOR ROUNDOFF
      TEST1=5.00001*10**(-NR-1)
      TEST=1.-TEST1
      AVAL=ABS(VALUE)
      IF(AVAL.GE.1.)GO TO 3
C...CONTINUE HERE FOR ABS(VALUE) .LT. 1.
      NSPACE=NR+2
      GO TO 6
3     CONTINUE
      YY=ALOG10(AVAL)
      NY=YY+.000001
      NSPACE=NR+2+NY
C...ADD 1 TO NSPACE IF NECESSARY BECAUSE OF ROUNDOFF
      NY1=ALOG10(AVAL+TEST1)
      IF(NY1.GT.NY)NSPACE=NSPACE+1
```

```
C...ADD I TO NSPACE IF VALUE IS NEGATIVE
6       IF(VALUE.LT.O.)NSPACE=NSPACE+1
C...POSITION PEN
200     CONTINUE
        GO TO (202,203,204),NOP
202     XMOV=NSPACE
        GO TO 205
203     XMOV=NSPACE/2.
        GO TO 205
204     XPOS=X
        YPOS=Y
        GO TO 250
205     CONTINUE
        XPOS=X-XMOV*S(13)*COSD(THETA)
        YPOS=Y-XMOV*S(13)*SIND(THETA)
250     CALL NUMBER(XPOS,YPOS,S(13),VALUE*1.000001,THETA,NRIGHT)
        RETURN
        END
C************************************************************
        SUBROUTINE INUM(X,Y,VALUE,THETA,NOP)
C...PLOTS THE TRUNCATED( INTEGER) PART OF NUMBER VALUE.
C...FOR THETA SEE SUBROUTINE SYMBOL
        COMMON /SPECS/S(35)
        IF(INT(VALUE).EQ.0)GO TO 50
        PVAL=ABS(VALUE)*1.00001
        NDIGIT=ALOG10(PVAL)+1
        IF(VALUE.LT.O.)NDIGIT=NDIGIT+1
        GO TO 55
50      CONTINUE
        NDIGIT=1
55      CONTINUE
        GO TO(1,2,3),NOP
1       XMOV=NDIGIT
        GO TO 5
2       XMOV=NDIGIT/2.
        GO TO 5
3       XMOV=0.
5       CONTINUE
        XPOS=X-XMOV*S(13)*COSD(THETA)
        YPOS=Y-XMOV*S(13)*SIND(THETA)
        CALL NUMBER(XPOS,YPOS,S(13),VALUE,THETA,-1)
```

```
      RETURN
      END
C*************************************************************
      SUBROUTINE TITLE(TITL,NTITL,NP)
C...PLOTS A TITLE ABOVE THE FRAME DEFINED BY S(1)--S(4)
C...   TITL   TEXT TO BE PLOTTED(1ST NTITL CHARACTERS)
C...   NP =1  START TITLE AT TOP LEFT OF FRAME
C...      =2  TITLE IS CENTERED OVER FRAME
C...      =3  END OF TITLE IS AT TOP RIGHT OF FRAME
C...THE TITLE IS ALWAYS SPACED ABOVE FRAME SO THAT BOTTOM OF LETTERS
C..IN TITLE ARE 2.5*S(13)INCHES AWAY FROM FRAME.  SIZE OF CHARACTERS
C...IS S(13) INCHES.
      COMMON/SPECS/S(35)
      DIMENSION TITL(10)
      XC=S(1)
      YC=S(2)+S(4)+2.5*S(13)
      IF(IABS(2-NP).GT.1)NP=2
      GO TO (10,20,30),NP
10    NPP=3
      GO TO 40
20    NPP=2
      XC=XC+S(3)/2.
      GO TO 40
30    NPP=1
      XC=XC+S(3)
40    CONTINUE
      CALL TEXT(XC,YC,TITL,0.,NTITL,NPP)
      RETURN
      END
C*************************************************************
      SUBROUTINE TEXT(X,Y,ASC,THETA,NASC,NOP)
C...PLOTS NASC CHARACTERS OF ARRAY ASC(5 CHARACTERS PER WORD)
C...FOR OTHER PARAMETERS SEE SUBROUTINE SYMBOL
      COMMON /SPECS/S(35)
      DIMENSION ASC(10)
      IF(NASC.LE.0)RETURN
      GO TO (2,3,4),NOP
2     XMOV=NASC
      GO TO 5
3     XMOV=NASC/2.
      GO TO 5
```

```
4       XMOV=0.
5       CONTINUE
        XPOS=X-XMOV*S(13)*COSD(THETA)
        YPOS=Y-XMOV*S(13)*SIND(THETA)
        CALL SYMBOL(XPOS,YPOS,S(13),ASC,THETA,NASC)
        RETURN
        END
```

```
C***************************DIST.FOR*******************************
C       THIS PROGRAM CALCULATES EPICENTER DISTANCES--WRITTEN BY
C       GARRY CARLSON JUL25,83 FOR REFRACTION SURVEY
C       EQUATION FOR CALCULATION TAKEN FROM BULLEN, INTRO
C       TO SEISMOLOGY PAGE 155, AND IS GOOD FOR CALCULATING
C       SHORT DISTANCES AND NOT WITHIN 20 DEGREES OF POLES
C       ERROR IS LESS THAN 1 KM IF DELTA IS < 6.5 DEGREES\\\\\
C  DATA IS SET UP IN DATA FILE--REF.DAT, FIRST NUMBER IN FILE
C  IS THE NUMBER OF STATIONS FOR THE DISTANCE CALCULATION
C  EXAMPLE:
C  2
C  SAM 45.32543 113.5678
C********************
C  INPUT DATA IN FILE IN DEGREES MINUTES AND SECONDS, FOR EXAMPLE
C 45 DEGREES 32 MINUTES AND 43 SECONDS EQUALS 45.3243.... THE
C PROGRAM THEN CALCULATES THE DECIMAL EQUIVALENT

      DOUBLEPRECISION ZLOC(50,3),ZDEG(50),PHI(50),THETA(50)
     * ,DIST(50),DEL(50),ATHETA(50)

      OPEN(UNIT=20,DEVICE='DSK',ACCESS='SEQIN',MODE='ASCII',
     * FILE='REF.DAT')
      OPEN(UNIT=21,DEVICE='DSK',ACCESS='SEQOUT',FILE='OUT.DAT')
C*****************************************************************
C  SET THE BASE STATION IN DECIMAL DEGREES AND COLATITUDE
C  THIS CASE THE STATION IS THE BUTTE PIT TO RECORD THE BUTTE
C  MINE BLAST
      TPRI=43.99
      PHPRI=112.48
      READ (20,1) NUM
1      FORMAT(I)
      DO 100 I=1,NUM
      READ(20,2) ZLOC(I,1),ZLOC(I,2),ZLOC(I,3)
2      FORMAT(A3,2F)

      SHIF=ZLOC(I,2)*100.
      OVER=ZLOC(I,3)*100.
      IG= INT(SHIF)
      JG= INT(OVER)
      KG= INT(ZLOC(I,2))
```

```
      LG= INT(ZLOC(I,3))
      MG=KG*100
      NG=LG*100
      SECA=(SHIF-FLOAT(IG))/36.
      SECB=(OVER-FLOAT(JG))/36.
      ZNEW=(FLOAT(IG-MG))
      XNEW=(FLOAT(JG-NG))
      DECA=ZNEW/60.
      DECB=XNEW/60.
      ZDEG(I)=FLOAT(KG)+DECA+SECA
      PHI(I)= FLOAT(LG)+DECB+SECB
      THETA(I)=90.-ZDEG(I)

      ATHETA(I)=THETA(I)/57.29578
      ATPRI=TPRI/57.29578
      DEL(I)=((THETA(I)-TPRI)**2.+(((PHI(I)-PHPRI)**2.)*
     * ((SIN((ATHETA(I)+ATPRI)/2.))**2.)))**(1./2.)
      DIST(I)=DEL(I)*111.17
C     WRITE(5,44) DEL(I)
C44    FORMAT(1X,F)
100   CONTINUE

      DO 300 I=1,NUM
      WRITE(5,4) ZLOC(I,1),DIST(I)
      WRITE(21,4) ZLOC(I,1),DIST(I)
4      FORMAT(1X,'#',A3,'=',F)
300   CONTINUE
      STOP
      END
```

```
C***************************HYP.FOR*********************************

C****HYP.FOR, WRITTEN BY GARRY CARLSON, OCTOBER, 1985
C       MIGRATES HYPOCENTERS TO A DATUM LEVEL PICKED BY USER
C       HAS OPTION OF WRITTING RESULTS TO OUTPUT FILE
C       USER INPUTS CHOSEN DATUM LEVEL
        DIMENSION Z(500),TI(500),DIST(500),COR(500),CTI(500)
        DIMENSION H(100),DEP(100),V(100),ZZ(100),STA(100)
        OPEN (UNIT=22,DEVICE='DSK',ACCESS='SEQIN',FILE='CORAFT.DAT')
        READ(22,17)ZNUM
1       FORMAT(I)
        NUM=INT(ZNUM)
        DO 100 I=1,NUM
        READ(22,3,END=100) ZZ(I),TI(I),DIST(I),STA(I)
100     CONTINUE
3       FORMAT(3F,A5)
        WRITE(5,700)
700     FORMAT(1X,'DO YOU WANT THE RESULTS IN AN OUTPUT FILE? ',$)
        READ(5,710) ANS
710     FORMAT(A3)
        WRITE(5,11)
C****INPUT DATUM LEVEL TO MIGRATE HYPOCENTERS
11    FORMAT(1X'WHAT IS DATUM FOR CORRECTIONS(-IF BELOW SEA LEVEL) ',$)
        READ(5,17) DATUM
        WRITE(5,99)
17      FORMAT(F)
C****DATUM LEVEL OF MODEL MAY DIFFER TO USER DATUM LEVEL
C****OPTION OF CHOOSING DIFFERENT DATUM LEVELS
99     FORMAT(1X'WHAT IS DATUM OF INPUT MODEL  ',$)
        READ(5,17) DATMDL
        WRITE(5,20)
20      FORMAT(1X,'HOW MANY LAYERS BELOW DATUM LEVEL?(TYPE IN AS
     *  INTEGER NOT FLOATIN PT) ',$)
        READ(5,1) LYR
        DAT=DATUM-DATMDL
C****************************************************************
        DO 300 J=1,LYR-1
        WRITE(5,12)J
12      FORMAT(1X,'VELOCITY AND DEPTH OF LAYER',I,'= '$)
        READ(5,9) V(J),DEP(J)
9       FORMAT(2F)
```

```
      DEP(J)=DEP(J)+DAT
      H(J)=DEP(J)-DEP(J-1)
300   CONTINUE
      WRITE(5,13)
13    FORMAT(1X,'VELOCITY OF THE LAST LAYER? ',$)
      READ(5,17) V(LYR)
      JJ=LYR-1
      WRITE(5,14)
14    FORMAT(10X,'SITE',9X,'DEPTH',8X,'TIME COR',6X,'TIME DIF',/)
C  THE DEPTHS OF THE HYPOCENTERS ARE GIVEN WITH REFERENCE TO THE
C  DATUM IN THE MODEL...THEREFORE THE DEPTHS MAY NOT BE DEPTHS
C  BELOW SEA LEVEL BUT BELOW THE DATUM OF THE MODEL
C  DAT IS THE CORRECTION OF ELEVATION OR DEPTH BETWEEN THE DATUM
C  OF THE SURVEY AND THAT OF THE MODEL
      DO 400 I=1,NUM
      Z(I)=ZZ(I)+DAT
      D=0.
      FAC=0.
      DO 500 K=1,JJ
      IF(Z(I) .GE. DEP(K-1) .AND. Z(I) .LT. DEP(K)) GOTO 10
      D=H(K)+D
      FAC=(H(K)*(SQRT(V(LYR)**2-V(K)**2))/(V(LYR)*V(K)))+FAC
      GOTO 500
10    COR(I)=FAC+(Z(I)-D)*(SQRT(V(LYR)**2-V(K)**2))/(V(LYR)*V(K))
      CTI(I)=TI(I)+COR(I)
      GOTO 410
500   CONTINUE
410   WRITE(5,16) I,ZZ(I),COR(I),CTI(I)
400   CONTINUE
C***************************************************************
16    FORMAT(8X,I4,8X,F7.2,8X,F7.2,8X,F7.2)
      IF(ANS .EQ. 'N' .OR. ANS .EQ. 'NO') GOTO 144
C****OPEN FILES FOR OPTIONAL OUTPUT
      OPEN(UNIT=23,DEVICE='DSK',ACCESS='SEQOUT',FILE='AFTSHK.DAT')
      OPEN(UNIT=20,DEVICE='DSK',ACCESS='SEQOUT',FILE='AFTNUM.DAT')
      WRITE(20,88) ZNUM
88    FORMAT(1X,F)
C***************************************************************
      DO 800 I=1,NUM
      WRITE(23,55) CTI(I),DIST(I),STA(I),ZZ(I)
C***************************************************************
```

```
55      FORMAT(1X,F,1X,F,1X,A5,1X,F)
800     CONTINUE
        WRITE(23,52) DATUM
52      FORMAT(1X,F5.2)
        WRITE(23,17) DATMDL
        DO 750 J=1,LYR-1
        WRITE(23,66) V(J),DEP(J)
66      FORMAT(1X,2F5.2)
750     CONTINUE
        WRITE(23,52) V(LYR)
144     STOP
        END
```