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CRUSTAL THICKNESS IN NORTHERN NEVADA FROM SEISMIC REFRACTION PROFILES

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ABSTRACT

P_n arrival times were measured along three north-south profiles in northern Nevada and southeastern Oregon. Apparent arrival velocities of 8.0, 8.2, and 8.4 km/sec were observed on the southern ends of the profiles and are explained by crustal thinning of up to 8 km along the profiles. This interpretation is supported by the shape of the Bouguer gravity anomaly and a prominent second arrival interpreted to be a Moho reflection observed from a local quarry blast along one of the lines. The Battle Mountain heat flow high as outlined by the 2.5 HFU contour of Sass *et al.* (1976) does not correlate well with the area of thin crust in north central Nevada. However, the southern boundary of the heat flow high corresponds to a decrease in crustal thickness on all profiles— the crust inside the heat flow high is 5 to 8 km thinner than the crust to the south. The crustal thickness of 21 to 23 km in the Battle Mountain-Winnemucca area is compared to estimated depths to the wet and the dry basaltic solidus and no partial melting of the lower crust is expected if it is dry, while partial melting is expected if it is wet. A prominent later phase at distances greater than 550 km is modeled by an increase in P velocity of 0.2 to 0.3 km/sec at a depth between 70 and 90 km. A low-velocity zone may exist in the mantle above this velocity increase but is not required by our data.

INTRODUCTION

From Fall 1975 to Summer 1977 seismic body waves from nuclear events from the Nevada Test Site (NTS) were recorded in northern Nevada and southern Oregon by Stanford University and the University of Nevada. The area is predominately in the Basin and Range province and includes several features which indicate current tectonic activity. The Battle Mountain heat flow anomaly, defined by Sass *et al.* (1976) as the western end of a NE-SW trending zone with heat flow of over 2.5 HFU, extends into the studied area (see Figure 1). Heat flow measurements in this zone in the Battle Mountain-Winnemucca area are generally over 3 HFU. A second feature is the northern Nevada seismic zone, which extends south from Battle Mountain and Winnemucca. The seismic zone has been the location of 5 large ($m > 7$) earthquakes in the last 150 years (Ryall, 1977).

Previous seismic refraction work in northern Nevada consists of two reversed refraction lines (Figure 1), and a time-term analysis of NTS blasts and several earthquakes recorded at the University of Nevada network stations. The refraction line reported by Eaton (1963) runs east-west between Eureka and Fallon, Nevada to the south of the heat flow anomaly. The other, reported by Hill and Pakiser (1966), runs north-south to the east of our work. The time-term analysis of Batra (1970) includes two stations in the heat flow anomaly, at Battle Mountain and at Lovelock. The data presented here were obtained from profiles through the heat flow anomaly and, in conjunction with other data recorded by us from mine blasts near Battle Mountain, provide a look at changes in crustal structure in the area.

EXPERIMENT DESCRIPTION AND DATA REDUCTION

A variety of recording systems using 1 and 5 Hz vertical-component seismometers were used to obtain data. Most of the recordings made by Stanford University used

Sprengnether MEQ800 smoked-paper recorders with a timing accuracy of ±0.02 sec. Some recordings were obtained with a portable FM tape recording system which is being used for more extensive refraction experiments in the area using mine blasts. The timing accuracy of this system is also about ±0.02 sec. University of Nevada recordings were made with a short-period telemetered system with similar timing accuracy. The University of Nevada network station at Battle Mountain was used as a reference, so data from different NTS events could be combined, and is indicated on Figures 1 and 2.

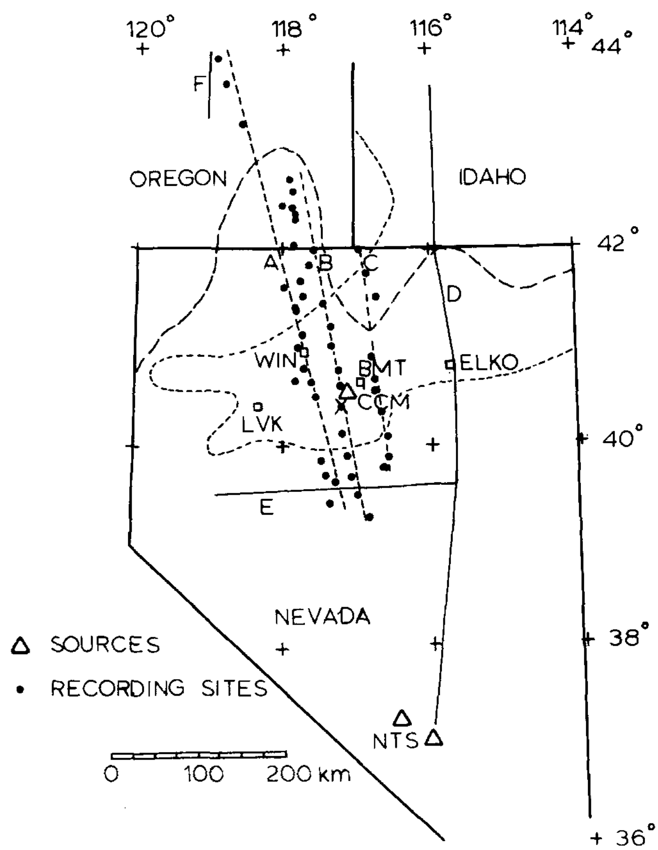

FIG. 1. Map showing location of refraction profiles: A, Winnemucca profile; B, Copper Canyon profile; C, Battle Mountain profile; D, Hill and Pakiser (1966); E, Eaton (1963); F, Hill (1972). The short dashed line is the boundary of the Battle Mountain heat flow high from Sass *et al.* (1976). The long dashed line is an approximate northern boundary for the Basin and Range province. The abbreviations are: BMT, Battle Mountain; CCM, Copper Canyon Mine; LVK, Lovelock; NTS, Nevada Test Site; WIN, Winnemucca. The University of Nevada network station near Battle Mountain is the station immediately south of CCM on the Copper Canyon profile.

The first-motion times were read from all the stations, and were corrected to a plane 1 km above sea level using a near-surface velocity of 4.0 km/sec. This velocity is in the middle of the range of velocities found in the area (3.5 to 4.5 km/sec), from our unpublished work and by the studies of Eaton (1963) and Hill and Pakiser (1966). The locations and origin times of the NTS sources were supplied by the Lawrence Livermore Laboratory.

DATA PRESENTATION

The first-arrival times for the Winnemucca, Copper Canyon, Battle Mountain profiles and first-peak times from Hill and Pakiser, line D, are plotted on reduced-time plots in Figure 2. The high-frequency forerunners between 400 and 450 km discussed by Hill and Pakiser (1966), are not plotted. The recording stations near the Oregon border and falling between profiles A and B were arbitrarily assigned to the closer of the two profiles. It should be noted that there is a scatter of the points of ±0.15 sec about any line drawn through them. This scatter is greater than the measuring accuracy of ±0.02 sec, and may be due to local geological structure.

A significant feature on both the Winnemucca and the Copper Canyon lines is the high apparent arrival velocity of 8.2 to 8.4 km/sec on the southern 100 to 200 km of the lines. The upper-mantle velocity determinations in the northern Basin and Range Province from other studies range from 7.3 to 8.0 km/sec (see Prodehl, 1970, Table 2). The area of high apparent velocity coincides with the southern half of the

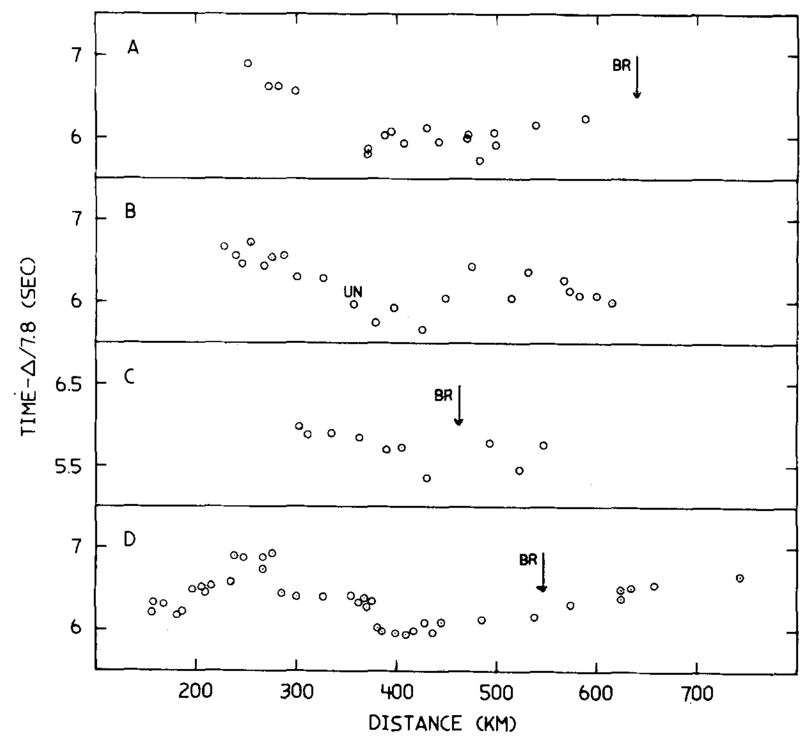

FIG. 2. Reduced travel times: A, Winnemucca; B, Copper Canyon; C, Battle Mountain; D, Hill and Pakiser (1966). University of Nevada network station near Battle Mountain is marked by UN on Copper Canyon profile. Northern boundary of the Basin and Range province indicated by arrows labeled BR. Error bars are smaller than the symbols.

Battle Mountain heat flow high. On our Battle Mountain profile, the maximum apparent velocity over a comparable distance range is about 8.0 km/sec.

On the north end of the Winnemucca profile, the P_n branch dies out and a large-amplitude, low-frequency phase 1 to 2 sec later becomes prominent. A record section for the northern end of the Winnemucca profile is shown in Figure 3. This section was constructed from the smoked-drum recordings by measuring zero-crossing times and peak and trough amplitudes. The wave form was then sketched to fit these points and to look like the original records. Some of the larger peaks are clipped. The recordings shown on the record section were made with two types of geophones, and no amplitude calibration was performed. The four recordings between 400 and 700 km were made with 4.5 Hz geophones, and the other two stations used 1 Hz geophones. A large-amplitude and longer period phase is evident at a reduced time of 7.7 sec on all the records at distances greater than 500 km. The amplitude of the first arrival (P_n) decreases rapidly with distance and is not clear beyond 600 km.

Additional recordings were made along a southward extension of the Copper Canyon line using quarry blasts at Copper Canyon Mine (CCM in Figure 1). This

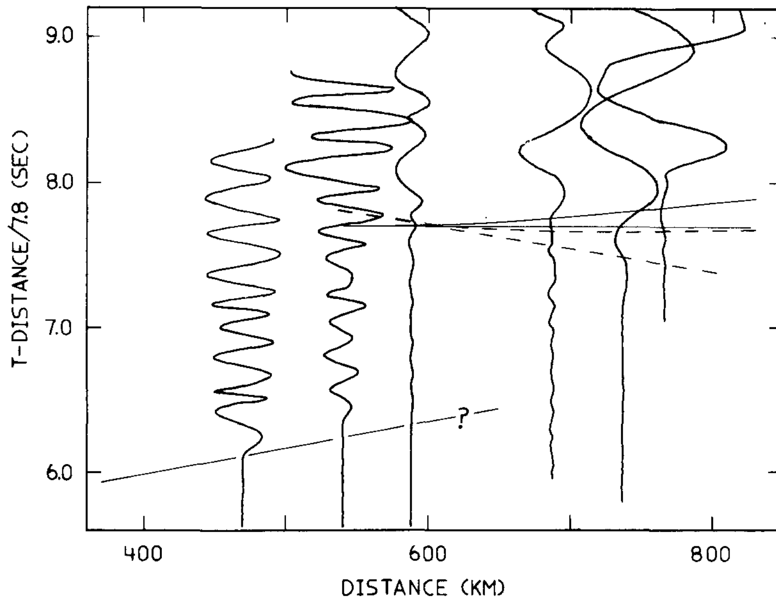

FIG. 3. Record section for north end of Winnemucca profile. Travel times for Model A (with LVL) shown with solid lines and travel times for model B (without LVL) are dashed. Models A and B are listed in Table 1.

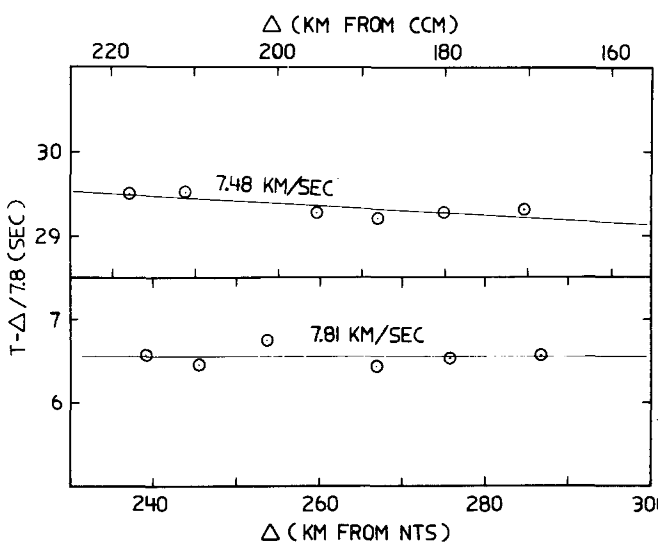

FIG. 4. Reversed refraction data at south end of Copper Canyon profile. *Top* is for Copper Canyon mine shot and are relative times only. *Bottom* is for an NTS source. The two halves are offset horizontally to the approximate position from which the *Pn* waves leave the crust-mantle boundary.

provides reversed refraction coverage of the southern 50 km of the mantle path sampled by waves coming from the Nevada Test Site and recorded on profile B. The data in the region of overlap are shown in Figure 4. Least-square linear fits yield apparent velocities of 7.48 ± 0.17 km/sec for the north to south direction and

7.81 ± 0.13 km/sec for the opposite direction. The apparent velocities are consistent with an upper mantle velocity of 7.64 km/sec and a Moho dip of 0.8° to the south. Because the recordings for the two directions were not made at the same surface locations, the pertubations of the travel times due to near-surface geology do not cancel when using the reversed coverage to determine the true P_n velocity. Systematic variations in geological structure could cause a variation of ±0.30 km/sec in the computed "true" *Pn* velocity.

Interpretation

Since most of the travel-time data in Figure 2 are unreversed, the high apparent velocities on the southern halves of the lines could be explained in several ways, as follows: (1) the average crustal velocities increase systematically to the north; (2) the crust thins from south to north; (3) they represent true, high, upper-mantle velocities.

The first hypothesis requires a mean crustal velocity of 7.0 km/sec in the area of

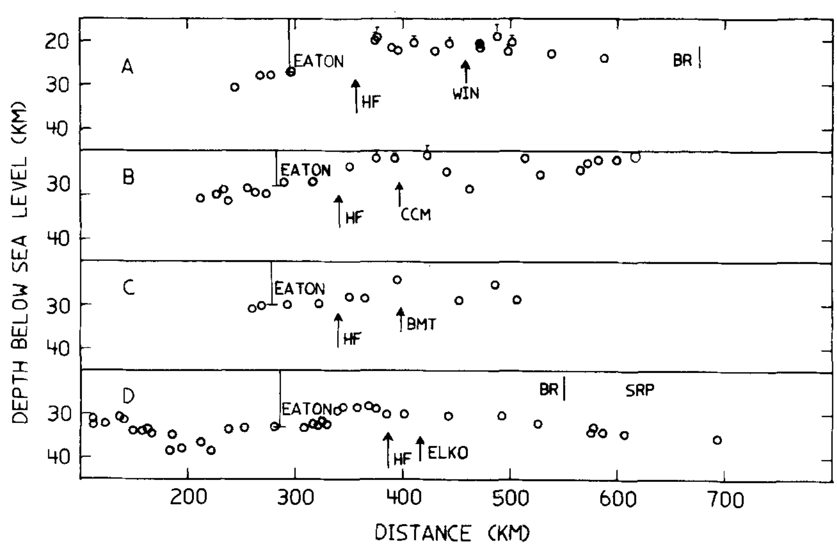

FIG. 5. Crust-mantle boundary profiles for data in Figure 2. Arrows marked HF indicate approximate southern boundary of the heat flow high. Error bars shown when larger than symbols.

earliest arrivals of Figure 2 if the crustal thickness remains constant and if we use the crustal velocities found by Eaton (1963), with mean of 6.25 km/sec, at the southern end. The refraction data from chemical explosions presented by Hill and Pakiser (1966) rules this out for the profile in Figure 2d. Also, preliminary interpretation of an unreversed refraction line south from the Copper Canyon Mine (see Figure 6) indicates that at least the upper 10 km of crust has a *P* velocity of 6.0 km/sec or less, ruling out a systematic increase in crustal velocities of sufficient size to explain the high apparent velocity on the Copper Canyon profile.

The second hypothesis, that of changing crustal thickness, is used in constructing the models shown in Figure 5. The upper-mantle and crustal *P* velocities needed for the construction were based on the profiles of Eaton (1963) and Hill and Pakiser (1966), described earlier. The upper-mantle velocity was taken as 7.8 km/sec, and a simple crustal model with *P* velocities of 6.0 and 6.7 km/sec in the upper two-thirds and the lower third of the crust, respectively, was used. For this model, the change in crustal thickness, in kilometers, is approximately ten times the change in reduced travel time in seconds. Other simple crustal models yield factors of 9 to 13 depending on the behavior of the thickness of the lower crustal layer. In the absence of other information, the factor of 10 was used. The error bars on the depths shown on Figure 5 reflect this uncertainty. The base of the crust is fixed at the depths determined by Eaton (1963) where his line crosses our lines. Error in this depth is not included in the error bars, and all depths may be changed by a constant amount, retaining the shape of the crust-mantle boundary.

The data of Hill and Pakiser (1966) were reinterpreted by us using the above method, and the resulting crustal thickness profile is plotted in Figure 5d for comparison with our lines. On our western two profiles the base of the crust rises from 30 km below sea level at the south end to 22 km in the Battle Mountain-Winnemucca area. Our results agree with those of Batra for his estimate of crustal thickness at a point about 30 km south of the University of Nevada network station near Battle Mountain. The shallowest depth to the crust-mantle boundary increases eastward to 25 km on our Battle Mountain line and to 29 km on the line of Hill and Pakiser through Elko (Figure 5).

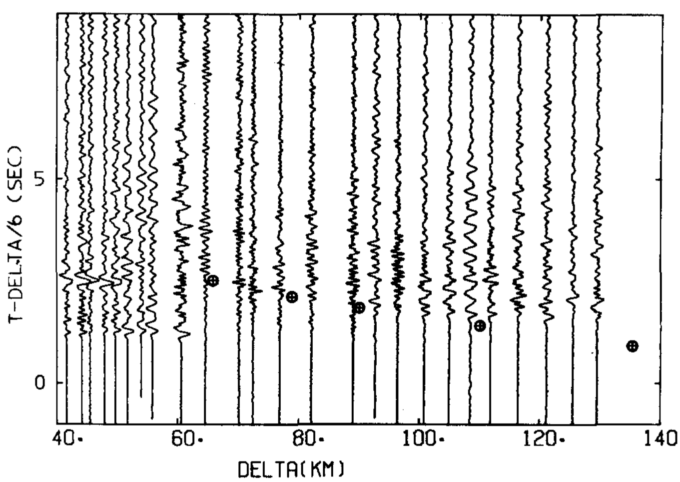

FIG. 6. Record section from Copper Canyon Mine shots recorded south along the Copper Canyon profile. Model Moho reflection times shown as circles. The critically reflected ray is at 64 km.

Although the third hypothesis, that the upper-mantle velocity in the southern portion of our lines is 8.0 to 8.4 km/sec, cannot be excluded by the unreversed travel-time data alone (we lack sources north of Copper Canyon Mine to provide reversed coverage of the high apparent velocities), there are other data which support the crustal thinning case. The first is an estimate of crustal thickness in the Battle Mountain area from a reflection seen on the unreversed refraction line running south along the Copper Canyon line. This reflection begins at a distance of 64 km, about 2 sec after the first arrival (see Figure 6). Using a preliminary interpretation of upper-crustal velocity from this data, a lower-crustal velocity of 6.7 km/sec beginning at a depth of 11 km in the Battle Mountain area, and the Moho depth and dip calculated from the NTS data, the calculated Moho reflection times are shown on Figure 6 (circles). The increase in amplitude expected at the critical reflection distance is seen in the data, and it matches the calculated critical reflection distance. The calculated travel times also fit the observed times. Variations in Moho depth change the travel times at a given distance by roughly 0.15 sec/km. A change of greater than 3 km in Moho depth would not fit the travel-time data.

The second piece of evidence supporting the changing crustal-thickness model over the high-velocity upper-mantle model is the Bouguer gravity. In the high-velocity upper-mantle case, one would expect a gravity anomaly to be centered over the area exhibiting high velocities, while in the crustal-thinning case a gravity high is expected over the area of thin crust. A Bouguer gravity profile is plotted in Figure 7 for the Winnemucca line. Each point of the gravity profile represents the mean of a perpendicular profile extending 35 km on each side of the refraction line. This procedure removes the effects of individual basins and ranges by averaging over 3 or 4 basin and range pairs. The gravity data is taken from Erwin (1974 and 1977) and Woollard and Joesting (1964). The gravity high observed on the Winnemucca line extends well north of the region of high apparent P_n velocities, supporting the crustal-thinning model.

An apparent inconsistency with this argument is the gravity high over the western Snake River Plain, where Hill and Pakiser (1966) found a thicker crust than in the

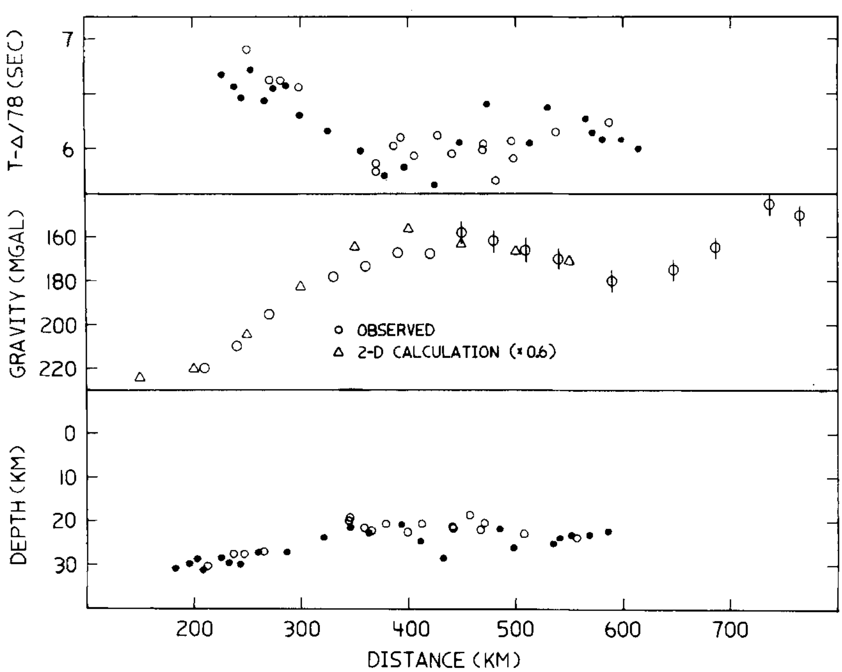

FIG. 7. Reduced travel times, observed Bouguer gravity and crustal section for Winnemucca profile, open circles; Copper Canyon profile reduced travel times and crustal profile shown with closed circles for comparison. The calculated two-dimensional gravity anomaly for the Winnemucca crustal profile has been multiplied by 0.6 and is shown with triangles for comparison of shapes. Vertical error bars are shown when larger than the symbols.

Basin and Range to the south. Our argument assumes that the mean crustal density does not have a significant lateral variation. Seismic velocity structures from refraction profiles in the northern Basin and Range province show no large changes in mean crustal velocities, suggesting that the densities are similarly well behaved. The crustal velocity structure determined by Hill and Pakiser (1966) for the western Snake River Plain is very different than that found in the Basin and Range to the south, and therefore, one would not expect the same relation between crustal thickness and Bouguer gravity values to hold in the western Snake River Plain as in the Basin and Range province.

A two-dimensional gravity profile was calculated for the Winnemucca crustal profile from 200 to 650 km, using a density of 2.7 gm/cm^3 for the upper two-thirds of the crust, 2.9 gm/cm^3 for the lower third, and an upper-mantle density of 3.20 gm/cm^3. The calculated anomaly has a maximum amplitude of 98 mgal instead of the observed 60 mgal. The shape of the calculated two-dimensional anomaly, however, matches the observed anomaly well as can be seen in Figure 7 where the calculated gravity anomaly values have been multiplied by 0.6 for ease of comparison. Small modifications of the calculated shape are expected when three-dimensional effects are included. The Winnemucca profile is located near the eastern edge of a large, positive gravity anomaly in northwestern Nevada, with an amplitude of 70 mgal. Approximate three-dimensional gravity calculations show that the shape of the crust-mantle boundary to the east of the Winnemucca and Copper Canyon profiles can account for about one-third of the discrepancy between the two-dimensional calculation and the observed gravity. The amplitude of the calculated gravity anomaly also depends strongly on the amount of lower crustal rocks ($\rho = 2.9 - 3.0$ gm/cm^3) which are included in the crust in the Battle Mountain-Winnemucca area. Analysis of more detailed refraction lines from mines in the Battle Mountain area and use of the Battle Mountain refraction profile should allow more quantitative gravity interpretation.

The large-amplitude, long-period, second arrival at the north end of the Winnemucca profile may be a reflection from a velocity increase in the mantle at a depth of 70 to 90 km. A velocity increase of 0.2 to 0.3 km/sec at this boundary produces a critical reflection distance of 550 km as observed. Travel-time curves for two models, one with a low-velocity zone above the discontinuity, and one without, are shown on Figure 3. The velocity models used are listed in Table 1. The rapid amplitude decay of the P_n branch suggests a negative velocity gradient near the top of the mantle, but we cannot be quantitative because of lack of amplitude calibration. The long-period nature of the second arrival indicates an increase in attenuation with depth in the mantle, which is expected for a LVZ caused by partial melting.

TABLE 1

VELOCITY MODELS SHOWN IN FIGURE 3

Layer Thickness (km)	V_p (km/sec)
Velocity Model A, with low-velocity zone	
18.8	6.0
9.4	6.7
29.6	7.7
15.4	7.5
—	7.8
Velocity Model B, without low-velocity zone	
18.8	6.0
9.4	6.7
53.5	7.7
—	7.9

A similar arrival was reported by Hill (1972) on a north-south profile from a source in southern Canada, line F on Figure 1. His profile runs south into central Oregon and overlaps our Winnemucca profile. One model presented by Hill (CP1) to explain this phase was a velocity increase from 8.0 to 8.4 km/sec at a depth of about 100 km. Julian (1970) found velocity increases of 0.3 km/sec at 100 km depth on a profile northeast and east from NTS but not on a profile north from NTS. A velocity increase at a depth of 100 km is apparently a common feature, but is not evident on all profiles in the western U.S., as it is in the eastern U.S. (see Hales, 1969).

SUMMARY AND DISCUSSION

Nuclear events have been recorded along three lines in Nevada and Oregon to the north of NTS, one which passes through Winnemucca, one through the Copper Canyon Mine and the other near Battle Mountain. First-arrival times give an apparent P_n velocity on the southern part of the lines of 8.4, 8.2, and 8.0 km/sec, much higher than the normal values for the Basin and Range province. Other reversed refraction lines in the area, including one crossing our lines, yield an upper-mantle P velocity of 7.8 to 7.9 km/sec, suggesting that the high velocity found by us may be due to a thinning of the crust northward from central Nevada. Some reversed coverage immediately south of this area of high apparent velocity has been obtained and is consistent with an upper-mantle velocity of 7.8 km/sec.

Assuming an upper-mantle velocity of 7.8 km/sec and attributing the variations in apparent velocities to changes in crustal thickness, a mantle upwarp with a relief of approximately 8 km is present under the Battle Mountain-Winnemucca area in north-central Nevada. Reflection times and amplitudes from quarry blasts at Copper Canyon Mine along the Copper Canyon line and Bouguer gravity profiles are consistent with this interpretation.

On the northern end of the Winnemucca profile evidence was found for a small, low-velocity and high-attentuation zone above a depth of 70 to 90 km in northwest Nevada and southeast Oregon; the amplitudes of P_n first arrivals decrease rapidly, and a large-amplitude, low-frequency phase with an apparent velocity of 7.8 km/sec appears 1.5 sec later. The later phase may be reflected from a velocity increase of 0.2 to 0.3 km/sec at a depth of 70 to 90 km. The lower frequency of the later phase can be explained by an increase in attenuation with depth in the mantle. The decay of P_n amplitudes may indicate a negative velocity gradient in the upper mantle.

If the 2.5 HFU contour of Sass *et al.* (1976) is used to outline the heat flow high, there is not a good correlation with crustal thickness. For example, inside the boundary of the heat flow high the crust ranges in thickness from 22 km in the Winnemucca area to 32 km near Elko. Furthermore, the thin crust found on the Winnemucca profile extends north out of the heat flow high, although it should be noted that the boundary of the heat flow high is not well constrained.

Although there is little correlation between the mapped heat flow anomaly of Sass *et al.* (1976) and absolute values of crustal thickness, a change in crustal thickness of 5 to 8 km in all four profiles in Figure 5 occurs near the southern boundary of the heat flow high. In all the profiles the crust-mantle boundary is 5 to 8 km higher inside than to the south of the heat flow high boundary. The heat flow boundary from Figure 1 is located on the crustal sections of Figure 5 by arrows, and is roughly coincident with the change in crustal thickness. The mismatch in positions on Figure 5 c, and d is within the uncertainties in the location of the heat flow boundary.

In the Battle Mountain-Winnemucca area, where the heat flow measurements are dense enough to reliably show a mean flow of 3.0 HFU, the occurrence of thin crust has implications for the occurrence of crustal melting. Lachenbruch and Sass (1978, Figure 13) present geotherms for the Battle Mountain heat flow high for a variety of conductive and convective heat transfer models. A convective model with dike intrusion through the lithosphere results in the lowest temperatures for a given depth and the purely conductive case gives the highest. The dry basalt solidus is reached at approximately 60 km (1230°C) in the intrusive case and 26 km (1130°C) in the conductive case. The wet gabbro solidus from Wyllie (1971) is reached at depths of 20.5 km (725°C) and 16 km (760°C), respectively. Total crustal thickness of 21 to 24 km in the Battle Mountain-Winnemucca area is less than the depth to the dry basalt solidus, and is greater than the depth to the wet gabbro solidus for the limiting cases of both the conductive and convective geotherms. No melting of basaltic material is required if the lower crust is dry, while basaltic partial melting is expected near the base of the crust if it is water saturated.

Acknowledgments

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