UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 22
CRUSTAL STRUCTURE BETWEEN LAKE MEAD, NEVADA, AND MONO LAKE, CALIFORNIA*

by

Lane R. Johnson**

DENVER, COLORADO

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Technical Letter
Crustal Studies-22
July 15, 1964

Dr. Charles C. Bates
Chief, VELA UNIFORM Branch
Advanced Research Projects Agency
Department of Defence
Pentagon
Washington 25, D. C.

Dear Dr. Bates:

Transmitted herewith are 10 copies of:

TECHNICAL LETTER NUMBER 22

CRUSTAL STRUCTURE

BETWEEN LAKE MEAD, NEVADA,

AND MONO LAKE, CALIFORNIA*

by

Lane R. Johnson**

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-64

** U. S. Geological Survey, Denver, Colorado; present address: California Institute of Technology, Pasadena, California.

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Abstract. Interpretation of a reversed seismic-refraction profile between Lake Mead, Nevada, and Mono Lake, California, indicates velocities of 6.15 km/sec for the upper layer of the crust, 7.10 km/sec for an intermediate layer, and 7.80 km/sec for the uppermost mantle. Phases interpreted to be reflections from the top of the intermediate layer and the Mohorovicic discontinuity were used with the refraction data to calculate depths. The depth to the Moho increases from about 30 km near Lake Mead to about 40 km near Mono Lake. Variations in arrival times provide evidence for fairly sharp flexures in the Moho. Offsets in the Moho of 4 km at one point and 2 1/2 km at another correspond to large faults at the surface, and it is suggested that fracture zones in the upper crust may displace the Moho and extend into the upper mantle. The phase $\overline{P}$ appears to be an extension of the reflection from the top of the intermediate layer beyond the critical angle. Bouguer gravity, computed for the seismic model of the crust, is in good agreement with the measured Bouguer gravity. Thus a model of the crustal structure is presented which is consistent with three semi-independent sources of geophysical data: seismic-refraction, seismic-reflection, and gravity.

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Introduction. During the summer of 1962 the United States Geological Survey, with the assistance of United ElectroDynamics, Inc., made seismic-refraction measurements in a broad area of the western United States. A reversed profile between Lake Mead, Nevada, and Mono Lake, California, was included in this work (Figure 1). This report is concerned with the presentation and interpretation of the data from that profile.

The profile crosses the predominantly north trending structures of the Basin and Range province at an oblique angle, and the results of this study should be considered with this fact in mind. The profile terminates on the northwest at Mono Lake, which is just at the eastern edge of the Sierra Nevada.

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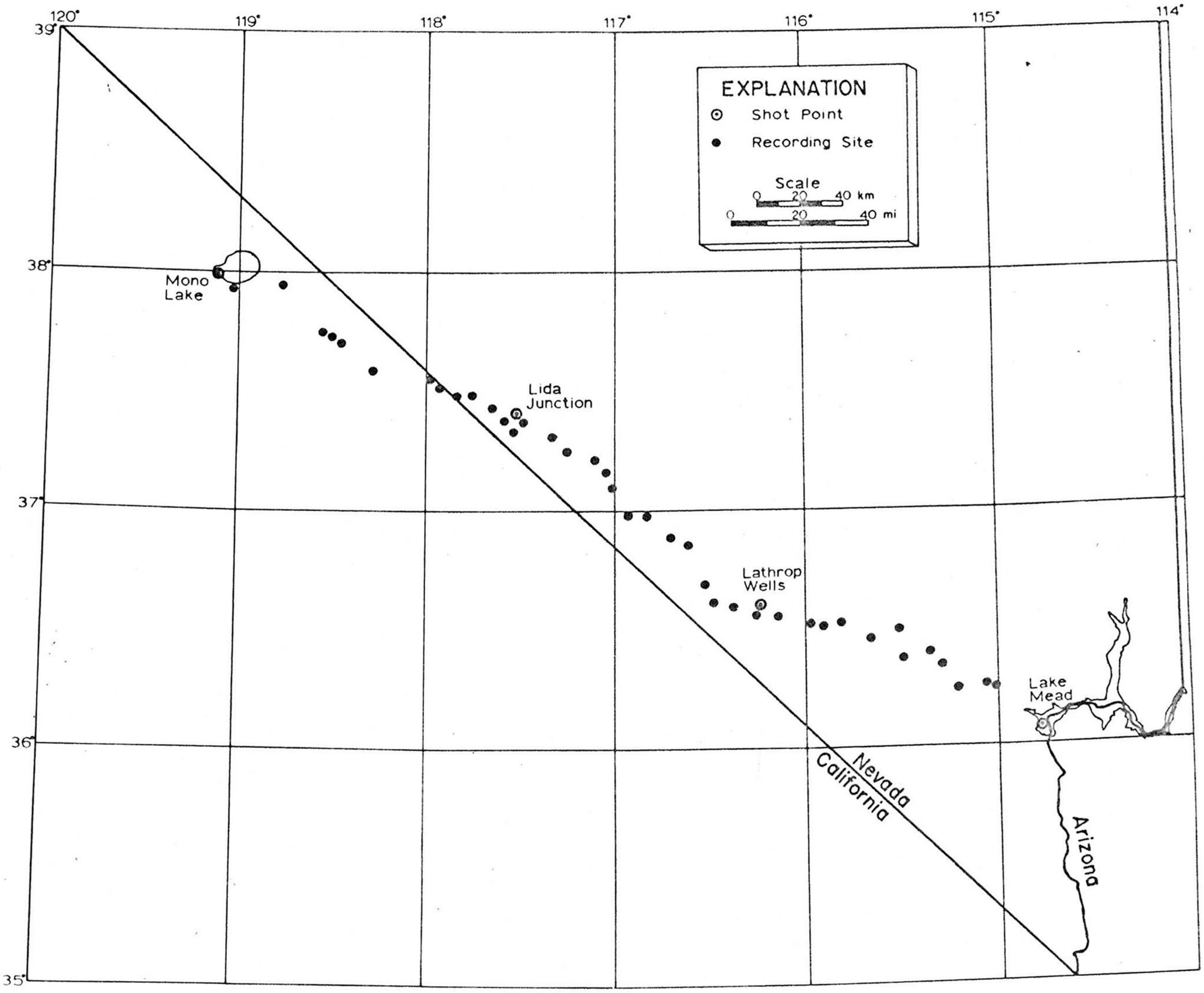

Figure 1.--Shot point and recording locations.

Field operations. Seismic energy was generated by detonation of chemical explosives at four different shot points. The terminal shot points at Lake Mead and Mono Lake were in 210 and 50 feet of water respectively. Two intermediate shot points--one near Lathrop Wells, Nevada, and the other near Lida Junction, Nevada--were in drilled holes. Seventeen shots were detonated at the four shot points, and the charge sizes ranged from 2,000 to 10,000 pounds.

First arrivals from the water shots in Lake Mead and Mono Lake were identifiable to distances of 325 and 350 km respectively. Lake Mead and Mono Lake are 438 km apart, so about 240 km was covered by reversed data at the surface. No usable data were obtained beyond distances of 90 km from the shots in drilled holes at Lathrop Wells and Lida Junction.

The field procedures are only briefly outlined here; more detailed descriptions are given by Jackson and others (1963) and Healy (1963). Each spread consisted of six vertical seismometers equally spaced along a line 2 1/2 km long and two horizontal seismometers at the position of either the third or fourth vertical seismometer. The horizontal seismometers were placed to record radial and transverse motions from the shot points. The spreads were as straight as topographic and road conditions permitted, and in most places they were approximately parallel to a radial line from the shot point. Seismometers of resonant frequency 2 cps were used.

The instrumentation was described by Warrick and others (1961). The traces of the six vertical and two horizontal seismometers were recorded on photographic paper at two different gain levels, 0 db and -15 db. The traces of the six vertical seismometers were also recorded on magnetic tape at gain levels of 0 db and -30 db. The frequency response of the complete system, excluding the seismometers, is down 3 db at 1 and 200 cps and approximately flat in between.

The data of the present study consist of 84 seismic records which were obtained at 39 different recording sites (Figure 1).

Seismic data. The picking of "phases" or "events" on the seismograms is probably the most subjective part of the entire seismic-refraction process. In the crustal-studies recording system the seismic signal is recorded at three different gain levels, and in addition the magnetic tape can be played back at any desired gain level and filter setting. Thus it is possible to select a copy of the seismogram which best displays any particular part of the signal. This is an advantage because the various phases recorded on a single seismogram may have dynamic ranges as large as 100.

The method by which the phases on a seismogram are picked varies with both the individual and the data. I used the following method on this profile: Initially the phases were picked and tentatively identified on each seismogram on the basis of amplitude, arrival time, apparent velocity, frequency, and "character." The arrival time of a phase at the first and last seismometer on the spread was measured and recorded on a travel-time graph (Figure 2). Then the seismograms were mounted on a time-distance section and the phases were correlated between adjacent seismograms. It was generally possible to make a direct correlation between phases on two seismograms from recording sites not more than 10 km apart. When the distance exceeded 10 km the direct correlation of phases became difficult, and the correlation was assisted by projecting apparent velocities on the travel-time graph. The various phases were judged to be either strong or weak and distinguished on the travel-time

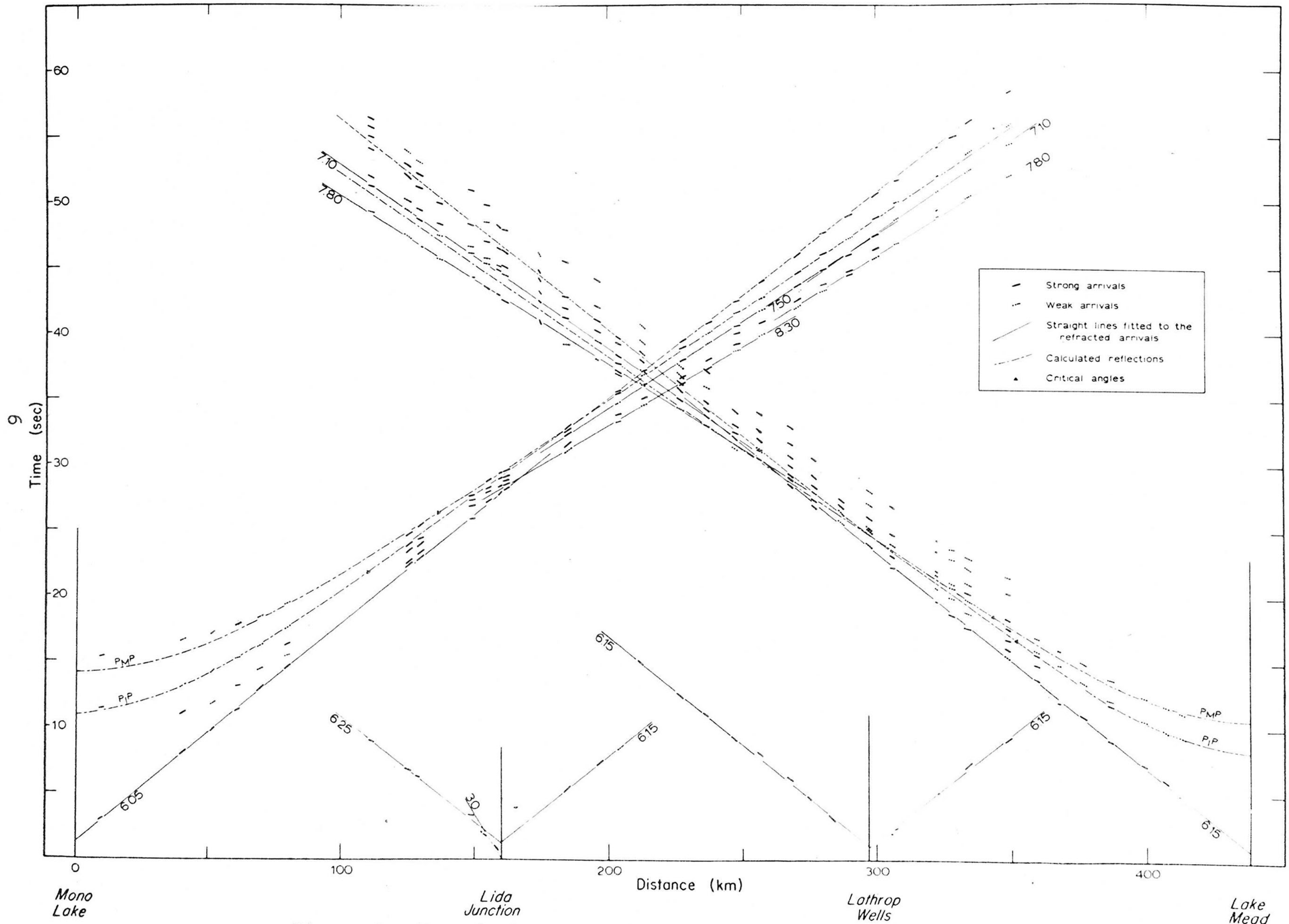

Figure 2.--Travel-time graph for Mono Lake-Lake Mead profile.

graph by representing them as solid or broken-line segments respectively. The refracted phases on the travel-time graph were then fitted with straight-line segments (Figure 2) and the calculations of the underlying structure were based on the slopes and intercepts of these segments.

Of the various phases that were picked, five proved to be the most prominent on the seismograms and the most persistent in their correlation between seismograms. Following the notation discussed by Pakiser (1963) these five phases were interpreted to be:

P_g, the direct arrival through the upper layer of the crust,

P*, the refracted arrival from an intermediate layer,

P_n, the refracted arrival from below the Mohorovicic discontinuity,

$P_I P$, the reflected arrival from the top of the intermediate layer,

$P_M P$, the reflected arrival from the Moho.

These phases are displayed in Figure 3, in which single traces have been selected from various seismograms and assembled to form a composite seismogram for the Mono Lake profile.

The amplitudes of the various phases were also measured, but the results showed a high degree of scatter and are not included in this report. The scatter in the amplitudes probably reflects to some extent the large variation in "ground factor" (Gutenberg, 1957) between the basement ridges and alluvium-filled basins of the Basin and Range province.

Mono Lake profile. From the Mono Lake shot point P_g is a first arrival out to a distance of 170 km; it was not possible to pick P_g as a secondary arrival at larger distances. The P_g arrivals were fitted

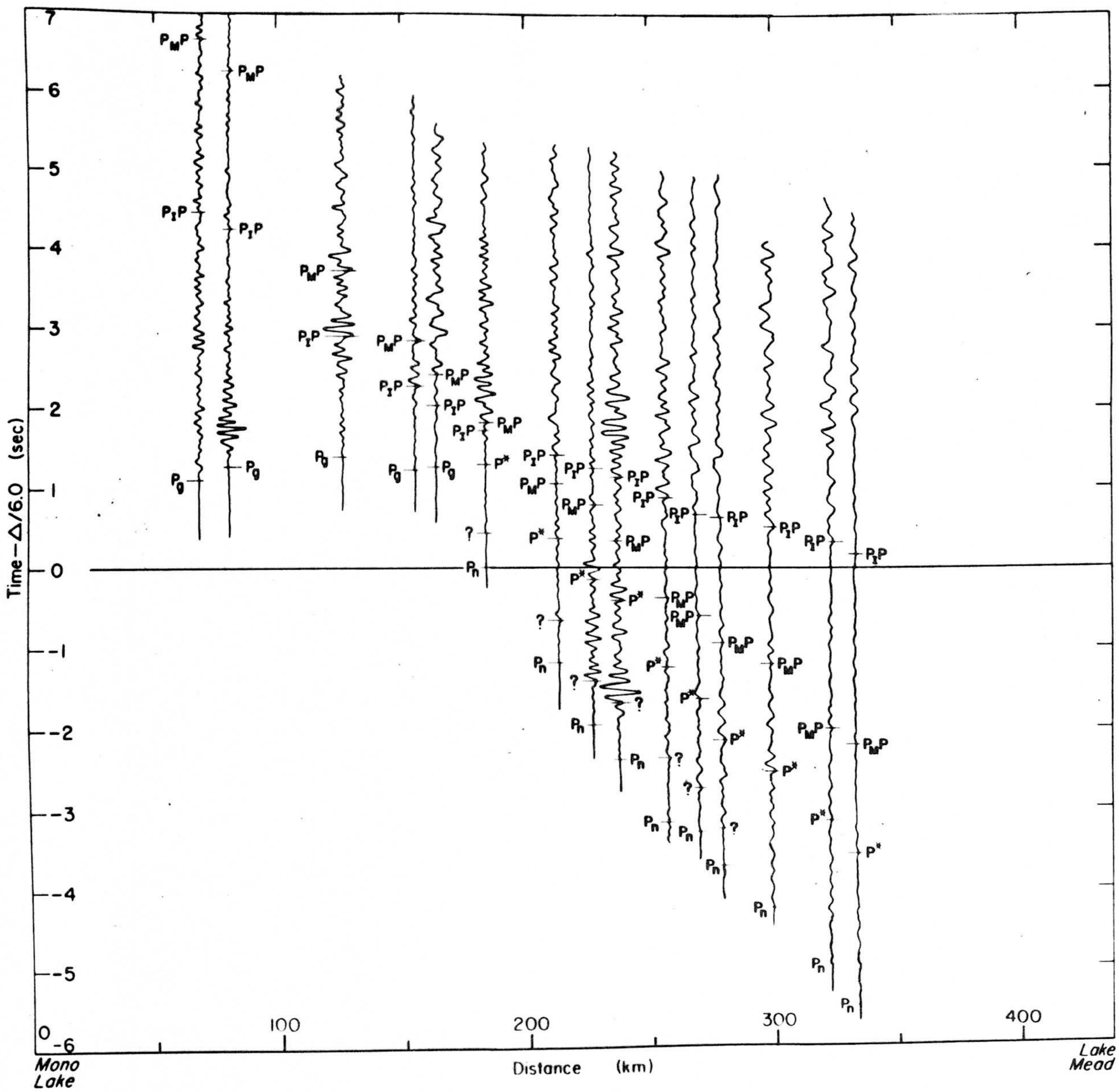

Figure 3.--Composite seismogram for recordings of seismic waves generated in Mono Lake showing the various seismic phases.

by the line

$$T = 1.30 + \Delta/6.05$$

where T is the travel time in seconds and Δ is the distance from the shot point in kilometers. Beyond 170 km the first arrivals were interpreted to be P_n, although it was necessary to fit them with two different line segments. From 170 to 260 km the first arrivals were fitted by

$$T = 8.84 + \Delta/8.30$$

and from 260 to 350 km by

$$T = 7.44 + \Delta/7.80$$

At about 260 km, where the segment with the velocity of 8.30 km/sec appears to terminate, the segment with a velocity of 7.80 km/sec is delayed by about 0.7 sec (Figure 2). The refraction from the intermediate layer, P*, is never a first arrival on this profile, and a secondary phase was picked as P* between 190 and 350 km. This was also fitted by two different line segments,

$$T = 7.51 + \Delta/7.50$$

and

$$T = 5.30 + \Delta/7.10$$

Phases interpreted to be the reflections P_IP and P_MP were picked on the entire Mono Lake profile. At distances less than about 100 km the amplitudes of these phases are only slightly above the background level. However, beyond about 125 km they are larger in amplitude and more oscillatory and prolonged (Figure 3). On the basis of the model of the crustal structure which is presented later in this report, the distances corresponding to the critical angles for P_IP and P_MP near Mono Lake are about 110 and 136 km respectively. P_IP is more prominent than P_MP at large distances and exhibits the characteristics which are usually associated with the phase $\overline{P}$ (Roller and Healy, 1963; Ryall and Stuart, 1963). Very clear arrivals follow P_n by about 1/2 sec between 180 and 300 km (Figure 3). The nature of these arrivals has not been explained.

Lake Mead profile. From the Lake Mead shot point P_g is a first arrival out to a distance of 175 km and the arrivals fit the line

$$T = 0.86 + \Delta/6.15$$

Beyond 175 km the first arrivals were taken to be P_n and fitted by the line

$$T = 7.12 + \Delta/7.80$$

However, between 230 and 260 km the arrivals, although weak, fall as much as 0.5 sec earlier than this line. Between 200 and 325 km an event was picked and interpreted to be P*, although for the most part it is a very weak event. It was fitted by the line

$$T = 5.35 + \Delta/7.10$$

Following the P* refraction is another phase which also has a velocity of about 7.10 km/sec. One cannot interpret this phase as P* because its reversed travel time is not consistent with the reversed travel time of the P* phase observed from the Mono Lake shot point. So this phase is unexplained.

Phases interpreted to be the reflections P_IP and P_MP were also picked on the Lake Mead profile, but the quality of these events is not as good as those on the Mono Lake profile. Again the phases exhibit a much different character at distances less than the critical angle than at greater distances, and at large distances P_IP appears to be the phase $\overline{P}$.

Profiles from the intermediate shot points. Only the first arrivals could be picked on the records from the intermediate shot points at Lathrop Wells and Lida Junction, and these only at distances less than 90 km. At Lathrop Wells the first arrivals were fitted with the line segments

$$T = 1.10 + \Delta/6.15$$

for the profile toward Mono Lake, and

$$T = 1.00 + \Delta/6.15$$

for the profile toward Lake Mead. At Lida Junction the results were

$$T = 1.25 + \Delta/6.25$$

for the profile toward Mono Lake, and

$$T = 1.35 + \Delta/6.15$$

for the profile toward Lake Mead. All of these arrivals were interpreted to be P_g , and they were used to calculate the thicknesses of the low-velocity near-surface layers at the shot points.

Seismic interpretation. United ElectroDynamics recorded and interpreted short-range refraction seismograms near the Mono Lake and Lake Mead shot points. These results were used with the long-range recordings to calculate models of the near-surface structures underlying the four shot points (Figure 4). The velocity of the near-surface layer underlying Lathrop Wells and Lida Junction was assumed to be 3.0 km/sec.

After making corrections for the low-velocity near-surface layers, the refraction arrivals in Figure 2 were used to compute the crustal structure underlying the profile. This was facilitated by dividing the travel-

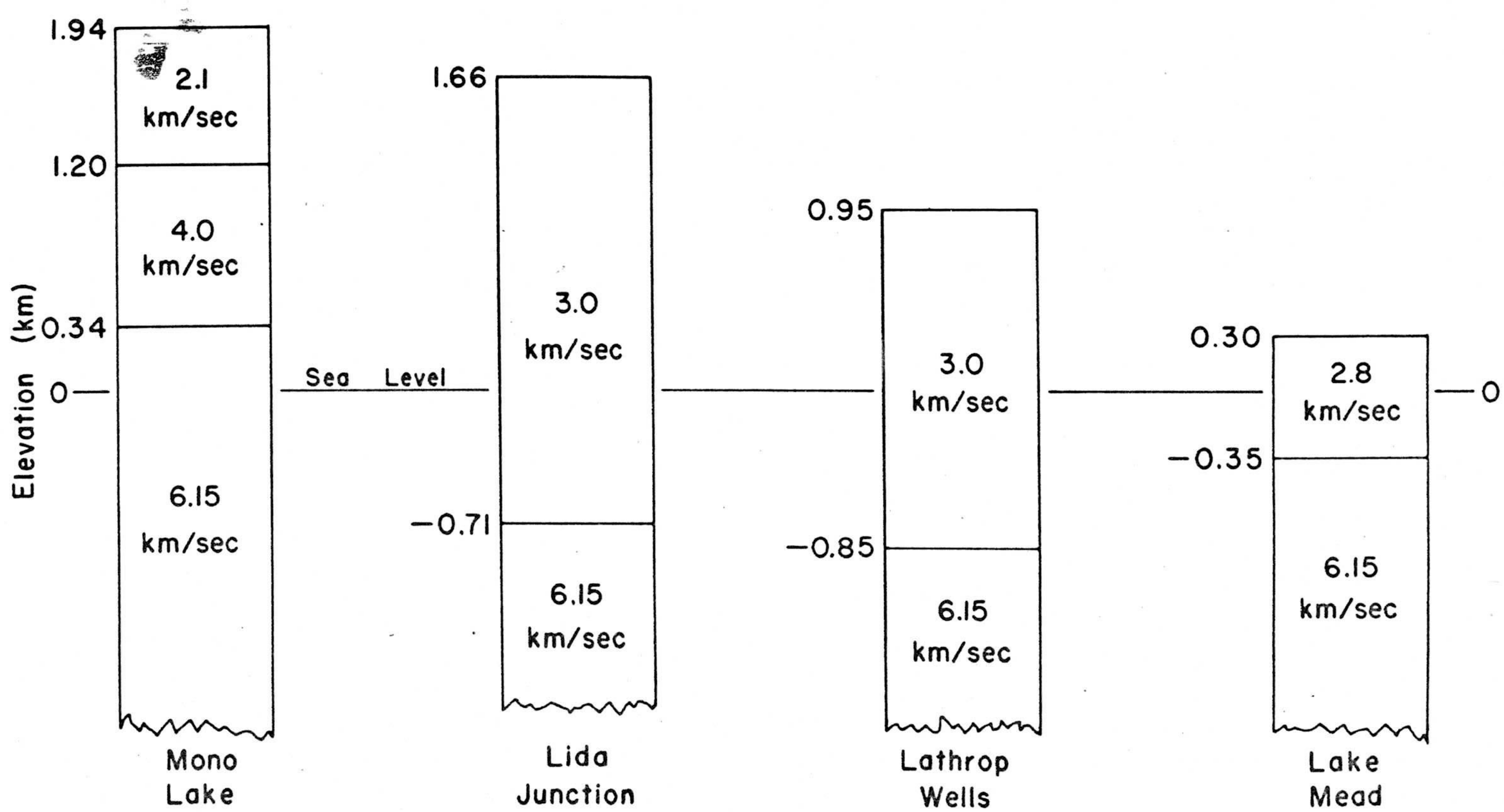

Figure 4.--Thicknesses and velocities of near-surface deposits beneath shot points. The velocity of 3.0 km/sec at Lida Junction and Lathrop Wells was assumed.

time graph into three sections with respect to distance. The sections within 160 km of Mono Lake and within 175 km of Lake Mead are very similar in terms of the velocities and intercept times of the various phases. However, the central section, which is about 100 km wide, is characterized by higher velocities on the Mono Lake profile and the suggestion of lower velocities on the Lake Mead profile. The results of the two exterior sections were interpreted in terms of three horizontal layers to yield the following average structures:

Layer	Velocity	Thickness
1	6.15 km/sec	26.2 km
2	7.10 km/sec	8.8 km
3	7.80 km/sec	

This gives an average depth to the Moho of 35 km. If the data had been interpreted in terms of a two-layer structure, disregarding the evidence for an intermediate layer, the results would have been:

Layer	Velocity	Thickness
1	6.15 km/sec	31.3 km
2	7.80 km/sec	

If the velocities of the above three-layer model are taken to be the true velocities, the higher velocities on the Mono Lake profile in the central section of the travel-time graph, 8.30 km/sec for P_n and 7.50 km/sec for P*, suggest dipping interfaces. With these assumptions, dips of 5° for the intermediate layer and 4° for the Moho were calculated.

The P_n arrival from Mono Lake is offset at a distance of about

260 km. If one makes the simple assumption that both segments are true P_n arrivals and that the true velocity below the Moho is 7.80 km/sec, this feature indicates a rather sharp flexure or fault in the Moho. Such an interpretation is included in the crustal model shown in Figure 5. In this model the intermediate layer is pictured as parallel to the Moho in the area of this flexure, but this is an assumption. This flexure is midway between Mono Lake and Lake Mead. At the surface it corresponds to the region of Sarcobatus Flat, which is northwest of Death Valley and the Grapevine Mountains and just north of the Bullfrog Hills.

In an attempt to fit the observed reflections, the following models were assumed as a first guess, and theoretical arrival times for the reflections P_IP and P_MP were calculated and compared to the observed times (Figure 2).

Layer	Velocity	Thickness Mono Lake	Thickness Lake Mead
1	6.20 km/sec	30.0 km	23.5 km
2	7.10 km/sec	11.1 km	8.4 km
3	7.80 km/sec		

At large distances the observed reflections P_IP approach the velocity 6.30 km/sec. This suggests that the velocity in the upper layer of the crust increases from 6.15 km/sec near the surface to 6.30 km/sec near the boundary with the intermediate layer. For this reason an average velocity of 6.20 km/sec was assigned to the upper layer for computing reflections.

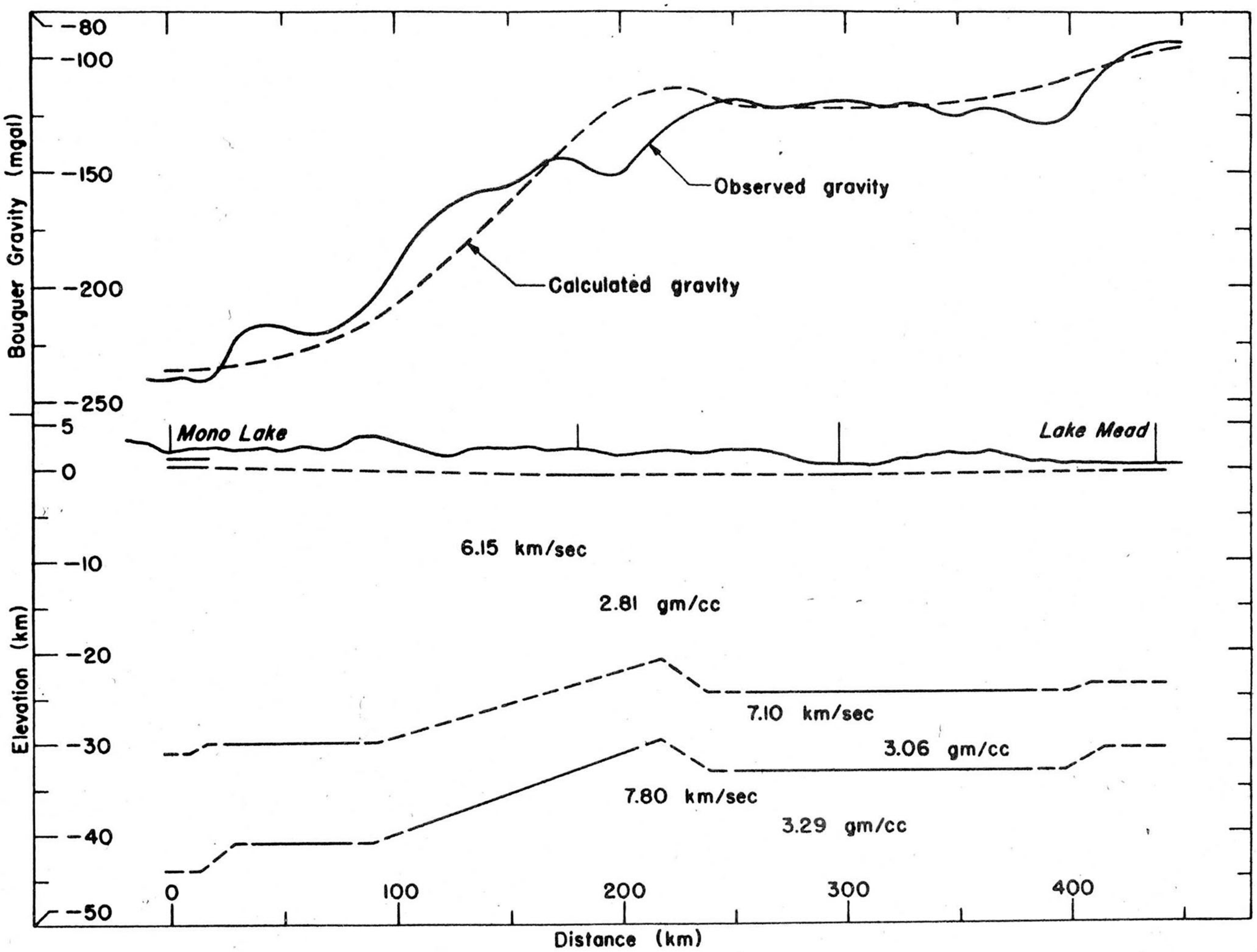

Figure 5.--Crustal structure between Mono Lake and Lake Mead from seismic and gravity observations.

The agreement between observed and calculated times for the reflections is in general good, which confirms the basic structure obtained from the refraction interpretation. Note that the model calculated from the reflection data yields average depths to the intermediate layer (26.8 km) and the Moho (36.5 km) which are only slightly greater than those calculated from the refraction data (26.2 km and 35.0 km respectively). A small discrepancy is to be expected because the refracted phases are usually first arrivals and one is much more likely to pick the beginning of the phase, whereas the reflected phases are always secondary events and the probability of picking a later cycle of the phase is high.

At places where the observed and calculated reflections differed, the model was altered accordingly. Near Mono Lake the observed reflections, especially P_MP, are later than the calculated reflections, so the depth to the intermediate layer and the Moho were increased by 0.6 km and 4.0 km respecitvely. In a more detailed geophysical investigation of Mono Basin, Pakiser and others (1960) interpreted gravity data to indicate that the block underlying Mono Basin had subsided about 18,000 ft. along near-vertical faults. The area of the deep subsidence is east of the shot point in the western part of Mono Lake. The results of this study suggest that structures of this type may extend as deep as the Moho.

To improve the fit between the observed and calculated reflections near Lake Mead, it was necessary to include a rather sharp change in the depth to the Moho at a distance of about 30 km northwest of Lake Mead. The fact that this offset in the Moho occurs near the point where the profile crosses the Las Vegas Valley shear zone (Longwell, 1960) suggests that the shear zone may extend to the Moho. Roller (1964) arrived at a similar conclusion from seismic-refraction and gravity data.

At distances beyond the critical angle the calculated reflections P_IP agree quite well with the observed data for both profiles. As was noted earlier, the phases that were picked as P_IP at these distances were identical to the phase that is normally picked as $\overline{P}$. Thus these results support the conclusion of Roller and Healy (1963) and Ryall and Stuart (1963) that $\overline{P}$ is the extension of P_IP beyond the critical angle. Beyond the critical angle it may be more instructive to consider this phase as a normal mode phase rather than a single ray. This helps to explain the oscillatory nature of $\overline{P}$. On the Mono Lake profile the calculated reflection P_MP agrees with the observed reflection at large distances. However, no phase corresponding to P_MP was observed beyond about 150 km on the Lake Mead profile.

A crustal model which is consistent with both the refraction data and the reflection data is shown in Figure 5. The velocities and the average depths of the various layers and the evidence for a sharp flexure in the Moho near the center of the profile were derived from the refraction data. However, since the refraction data yield only average depths, the reflection data were necessary to fix the depths in the vicinity of Lake Mead and Mono Lake. The reflection data also provide evidence for two offsets in the Moho, one near Lake Mead and the other near Mono Lake.

Gravity data. Values of the measured Bouguer gravity along a line from Lake Mead to Mono Lake were taken from a map compiled by Shawn Biehler (unpublished, 1964) from the data of Woollard and Rose (1963). These data were compared to the Bouguer gravity that was computed for the crustal model derived from the seismic data. In computing the gravity a two-dimensional structure was assumed, and the densities were derived from the seismic velocities using the empirical relations of Nafe and Drake (Talwani and others, 1959). For a profile such as this the end conditions have a significant effect. The structure under Lake Mead was assumed to continue to infinity unchanged, but at the Mono Lake end of the profile the root of the Sierra Nevada had to be taken into account. A model similar to that of Eaton (1963) was assumed, in which the depth to the intermediate layer and Moho remained at 31 and 44 km respectively for a distance of 20 km west of Mono Lake and then decreased linearly to 20 and 25 km respectively at a distance of 200 km west of Mono Lake.

The gravity data substantiate the gross features of the seismic model (Figure 5). If the effects of near-surface structures were removed from the measured Bouguer gravity, the agreement between the actual and computed anomalies would improve.

<u>Conclusions</u>. A model of the crustal structure between Mono Lake and Lake Mead that is consistent with three semi-independent sources of geophysical data--seismic-refraction, seismic-reflection, and gravity--has been proposed. Among the basic features of the model are an upper layer with a velocity of 6.15 km/sec in its upper part, an intermediate

layer with a velocity of 7.10 km/sec, and a sub-Moho velocity of 7.80 km/sec. The depth to Moho increases from about 30 km near Lake Mead to about 40 km near Mono Lake.

Evidence for fairly sharp flexures in the Moho suggests that an offset in the Moho of about 4 km near Mono Lake corresponds to large faults at the surface. Near Lake Mead the Moho is offset by about 2 1/2 km where the profile crosses the Las Vegas Valley shear zone. These two features suggest that major fracture zones in the upper crust may penetrate through the Moho and into the upper mantle. There is also evidence of a flexure in the Moho about midway between Mono Lake and Lake Mead, but no surface expression of this feature is known.

The phase which is customarily called $\overline{P}$ appears to be an extension of the P_1P reflection beyond the critical angle. Subject to the condition that this interpretation of $\overline{P}$ is correct, the velocity in the upper layer of the crust appears to increase from 6.15 km/sec in the upper part to 6.30 km/sec near the bottom.

Acknowledgments. I gratefully acknowledge the assistance that I received from personnel of the U. S. Geological Survey while preparing this study. The discussions with Drs. J. H. Healy and J. P. Eaton were especially rewarding. Thanks are also extended to Dr. Shawn Biehler of the California Institute of Technology for the use of his unpublished gravity map and his computer programs for gravity data analysis.

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