Geophys. J. R. astr. Soc. (1972) **30,** 199–209

Crustal Low-Velocity Zones Under the Peru-Bolivia Altiplano

Leonidas C. Ocola and Robert P. Meyer

(Received 1972 June 1)*

Summary

In 1968, the Carnegie Institution of Washington together with North and South American collaborators carried out a reconnaissance explosion seismic experiment to investigate the apparently highly anomalous crustal structure under the Peru–Bolivia altiplano. The data of this experiment have been reinterpreted by ray-tracing in a spherical Earth so as to fit as closely as possible arrival times, relative amplitudes, cusps, etc., of seismograms displayed in record section. The resultant model confirms the previous average model consisting of three major refractors: the sedimentary-metamorphic layer 4–9 km thick and 4.5–4.9 $\mathrm{km\,s^{-1}}$ velocity; the 'granitic' layer with 6.0–6.1 $\mathrm{km\,s^{-1}}$ velocity down to 26–30 km depth; and the 'gabbroic' layer reaching depths of 68–70 km below sea level with 6.8–6.9 $\mathrm{km\,s^{-1}}$ velocity. However, in order to account for relatively large amplitudes in the secondary arrivals with apparent velocities close to the first arrivals, two low-velocity zones are postulated within the crust under the Peru–Bolivia altiplano. In Peru, the shallow and thinner low-velocity zone with boundaries at 9 km and 12 km depth is between materials of 6.0 $\mathrm{km\,s^{-1}}$ and 6.1 $\mathrm{km\,s^{-1}}$. The deeper and thicker low-velocity zone with upper and lower bounds at about 30 km and 40 km under Bolivia, and more approximately at 36 km and 46 km under Peru, is embedded in 6.8 and 6.9 $\mathrm{km\,s^{-1}}$ materials.

The shallower low-velocity zone is conceivably related to the parent magma of volcanic and intrusive acidic rocks with the deeper low-velocity zone related to the volcanic and intrusive basic rocks in accord with petrological and geochemical findings of Pichler and Zeil in the Andes of northern Chile. The presence of velocity inversions above the 50 km depth is also in harmony with the postulated existence of a high electrical conductivity zone shallower than 50 km depth under the Andes as postulated recently by Schmucker to explain magnetic 'day-time fluctuation' anomalies.

1. Introduction

The preliminary interpretation of the 1968 Carnegie Institution of Washington seismic experiment in the Peru–Bolivia altiplano (Department of Terrestrial Magnetism Staff and Collaborators 1970; Ocola, Meyer & Aldrich 1971) did not include consideration of large amplitude secondary arrivals having essentially the same apparent velocity as the first arrivals. It was suggested that these arrivals might be related to

* Received in original form 1971 October 8.

low-velocity layers. In this paper, this possibility is examined by ray-tracing in a spherical earth so as better to satisfy the main features of the record sections.

In discussion of the new velocity-depth models and their corresponding travel times, the expression ‘ prograde travel-time branch ’ designates that branch associated with arrivals critically refracted in a layer with small velocity-depth gradient. As the gradient tends to zero, this branch approaches the head wave branch. In record sections to follow, the pro-grade branches are labelled with numerals without stars (Figs 2–5). The expression ‘ retrograde travel-time branch ’ refers to those rays critically refracted in ‘ thin ’ layers with a large velocity gradient. As the thickness of of this layer approaches zero, the velocity-depth gradient tends to infinity and this branch becomes the ‘ specular reflection ’ branch of optics. The retrograde branches are labelled with starred numerals in the record sections.

Finally, in order to have a qualitative index of the energy distribution for each of the branches associated with a particular model, the ray parameter has been incremented by a fixed constant and the resulting time range arising from the ray tracing is marked by an X in the travel-time plots. Thus, the number of X's per unit distance gives an idea of energy flux with range.

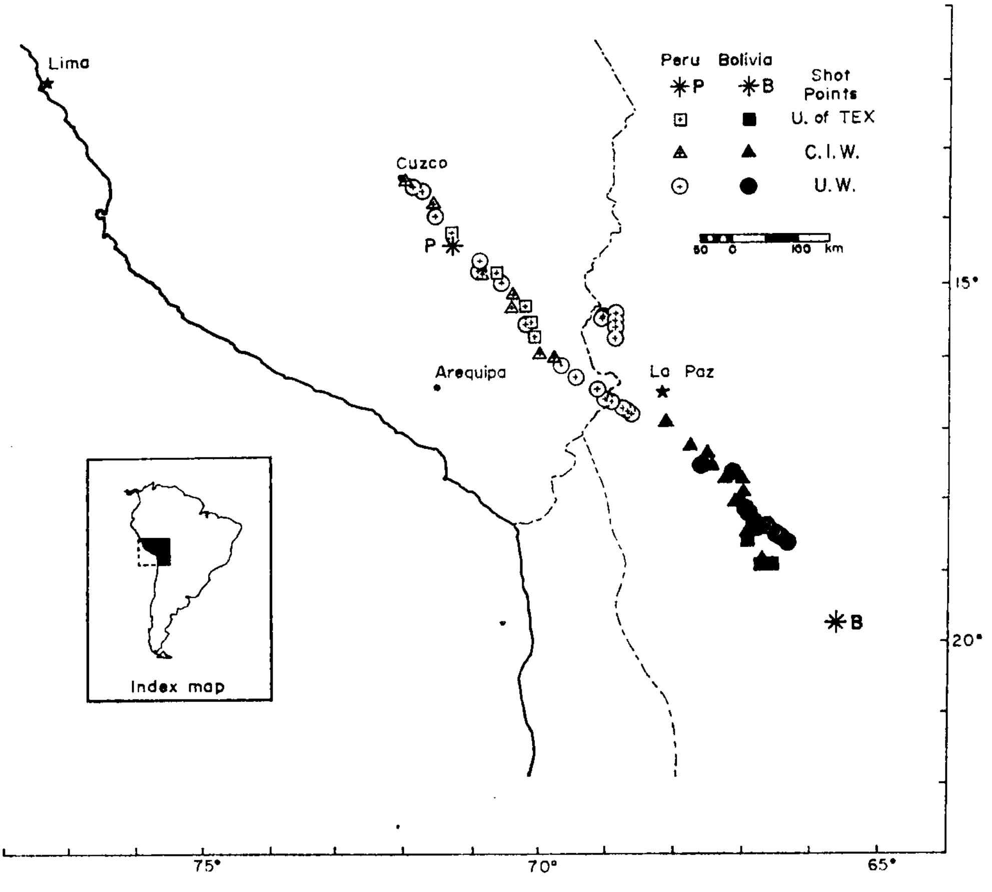

FIG. 1. Shot and recording stations of the 1968 Peru–Bolivia seismic experiment. The shading at the recording locations indicates the shot point for which those locations were used in each record section. (After Ocola *et al.* 1971.)

2. Data

The data for this paper is that presented in Ocola *et al.* (1971). The profile locations are shown in Fig. 1. The record sections for southern Peru and Bolivia with a new interpretation are shown in Figs 2 and 4. In Peru, one-ton shots were placed in Lake Langui-y-Layo (14° 25.79′ S, 71° 16.32′ W, 3900 m a.s.l.). In Bolivia, two-ton shots were fired in Lake Talacocha (19° 44.40′ S, 65° 36.74′ W, 4500 m a.s.l.). The travel times of each seismogram in the record section have not been corrected for the difference in elevation, 1000 m maximum. These corrections are assumed to be small in view of the uncertainties of reconnaissance measurements.

3. Shallow crustal low-velocity zone

The suggestion of a low-velocity zone in the upper crust comes entirely from the southern Peru record section, Fig. 2. Here the apparent velocity of the near surface material is about 4.5 km s^{-1} (prograde branch 1). The retrograde (reflected) branch 2* (whose turning point only is shown in the figure) is associated with the transition between the near surface material and the 6.0 km s^{-1} material, which we suggest is immediately above the low-velocity layer. The arrivals associated with the prograde travel-time branch 2 can be traced as first arrivals to about 120-km range. Because of the small amplitude of branch 2 arrivals, it is difficult to adjudge whether their disappearance beyond the 120-km range is due to geometric spreading, a relatively sudden offset in the travel time, or a low-velocity layer.

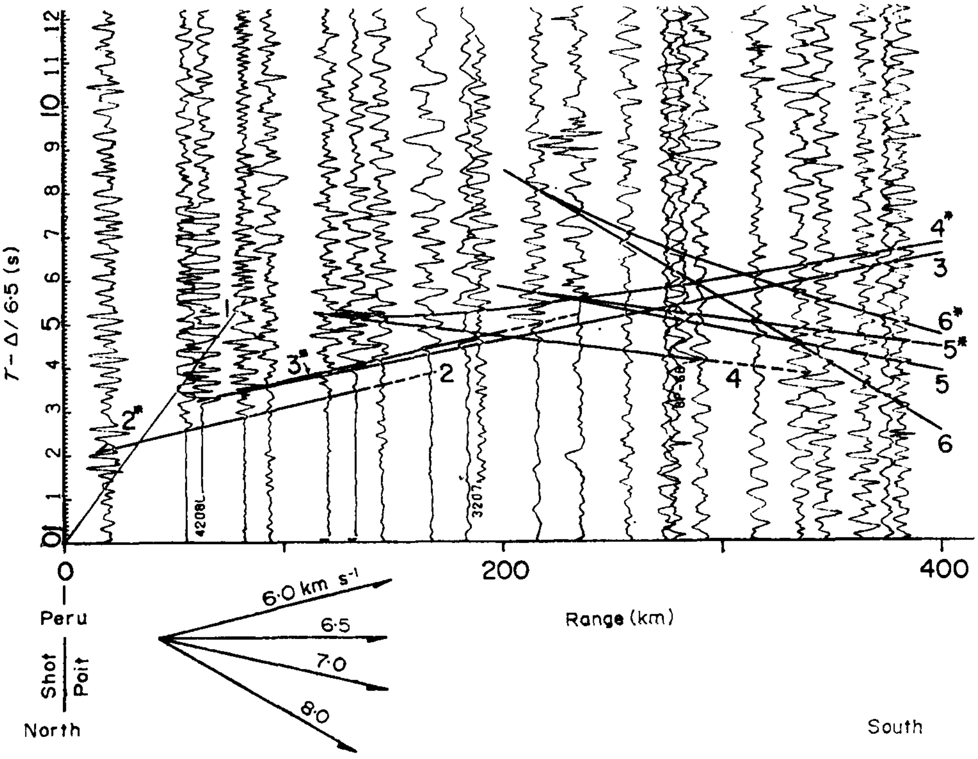

Fig. 2. Record section from Ocola *et al.* (1971) and superimposed interpretation (Fig. 3, Table 1) for the Peru profile.

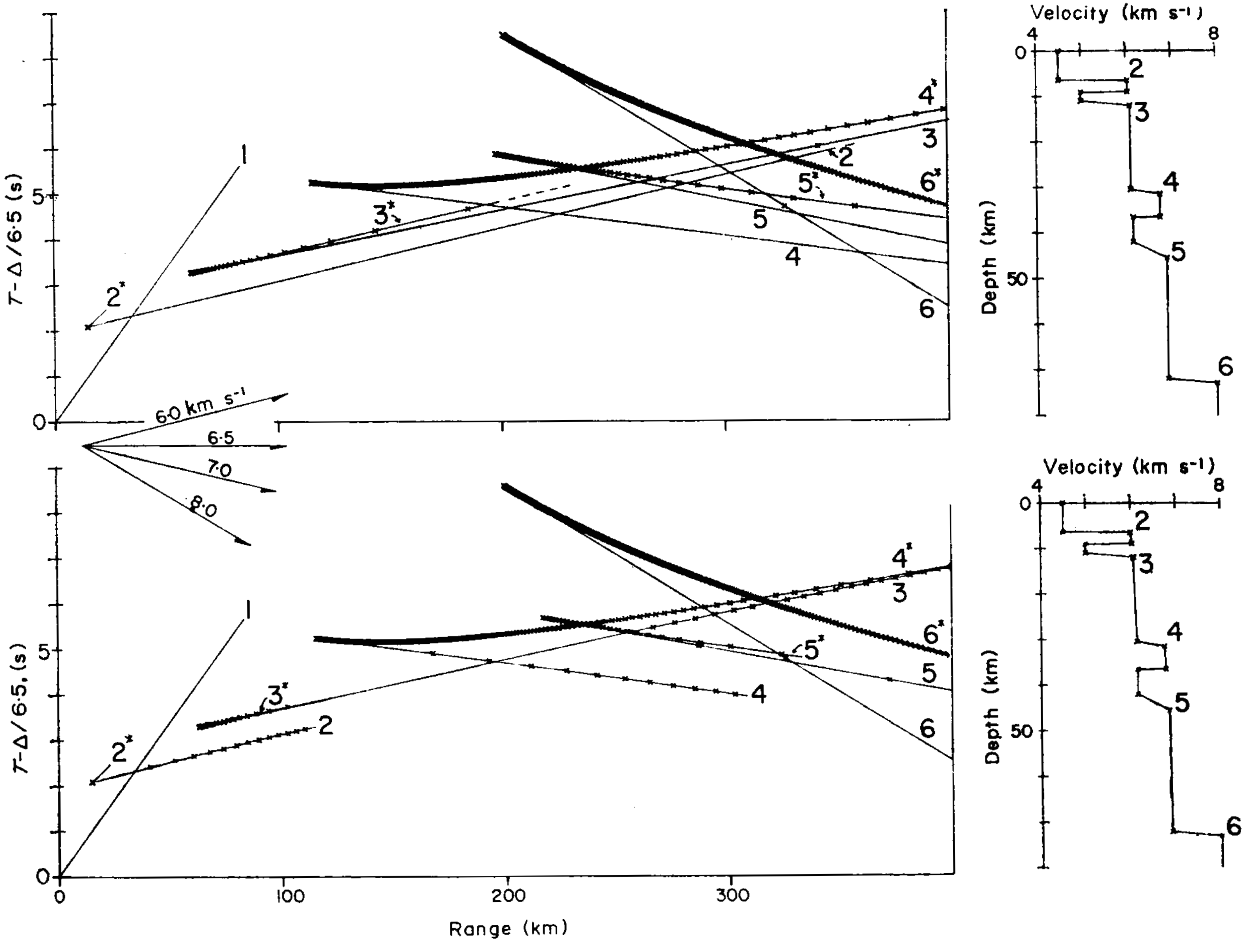

FIG. 3. Theoretical travel times and velocity depth function that satisfy reasonably well the Peru record section travel times. The upper travel-time plot and velocity depth function is for model A, Table 1. The lower travel-time plot and velocity depth function is for model B, Table 1. Each X represents one ray.

Travel-time times and corresponding velocity-depth functions for the two models considered are shown in Fig. 3(A) and 3(B). Fig. 3(A) for the model with no gradient, rays corresponding to prograde branch 2 continue to beyond 400 km range, although with little apparent energy. Fig. 3(B) for the model with small gradient, velocity-depth functions (about $+1.2\times10^{-2}$ (km s^{-1})/km), satisfy not only the travel times well but also the apparent jump in the travel time through the decrease of the velocity at the top of the low-velocity layer. The relatively large amplitude of arrivals associated with travel-time branch 3 and 3* between 60 and 220 km range and the apparent cuspy look of the arrivals relatively close to the shot point are taken as indicative of a large velocity contrast and small velocity-depth gradient material immediately below the low-velocity layer. Because the apparent velocities of branch 3 and 2 are very close in value, the average velocity below the low-velocity layer ought to be very near the corresponding value in the material above the low-velocity zone. In both models (Fig. 3(A) and (B), and Table 1), the transition zone from the low-velocity zone is about 1 km thick. It is worthwhile mentioning that the retrograde branch 3* associated with low velocity transition in the model of small velocity gradient 'layers', model 3B, is not, for practical purposes, a distinct branch. It falls almost on 'top' of the prograde branch.

Evidence for a similar low-velocity zone has been found in other parts of the world (see Landisman, Mueller & Mitchell 1971, for a review). This low-velocity zone, according to Landisman *et al.*, consists of a channel with the lower boundary at 8–15 km depth, and with about 5.5 km s^{-1} compressional velocity.

Table 1

Depth (km)	Velocity (km s^{-1})	
	A	B
0·0	4·50	4·50
6·4	4·50	4·50
6·5	6·04	6·01
9·0	6·04	6·04
9·1	5·00	5·00
11·0	5·00	5·00
12·0	6·10	6·08
30·5	6·10	6·12
31·5	6·75	6·75
36·5	6·75	6·78
36·6	6·15	6·15
42·0	6·15	6·15
45·5	6·90	6·85
72·0	6·90	6·90
73·0	8·00	8·00
90·0	8·00	8·00

4. Deep crustal low-velocity zone

The best evidence for a low-velocity zone in the lower crust comes from the Bolivia record section, Fig. 4. The shallow structure of models that satisfy the travel times beyond the 130-km range is taken to be that of the Peru models, since there are no observations for lesser ranges from the Bolivia shot point and because both the Peru and Bolivia profiles are in the same tectonic province (see for example Sonnenberg 1963).

The large first arrivals between 140- and 250-km range are taken to be associated with prograde travel-time branch 4, and it is modelled as related to rays propagated in the material immediately above the deep low-velocity zone (see Fig. 5, Table 2). Arrivals associated with this branch may extend to at least 280-km range, although amplitudes are small. The corresponding retrograde branch 4* seems also substantiated across the entire record section by secondary arrivals. The distinct secondary arrivals between 180- and 340-km range, branch 5, with apparent velocity very close in value to the first arrivals branch (prograde branch 4) are interpreted as associated with rays emerging from material immediately below the low-velocity zone with an average bulk velocity practically the same as the material above the low-velocity zone. The corresponding retrograde branch 5* seems to be associated with the large amplitude arrivals.

Table 2

Depth (km)	Velocity ($km\ s^{-1}$)	
	A	B
0·0	4·50	4·50
6·4	4·50	4·50
6·5	6·04	6·01
9·0	6·04	6·04
9·1	5·00	5·00
11·0	5·00	5·00
12·0	6·10	6·08
26·0	6·10	6·12
28·0	6·80	6·75
31·0	6·80	6·77
31·1	6·15	6·15
35·0	6·15	6·15
39·0	6·90	6·85
71·0	6·90	6·90
72·0	8·00	8·00
90·0	8·00	8·00

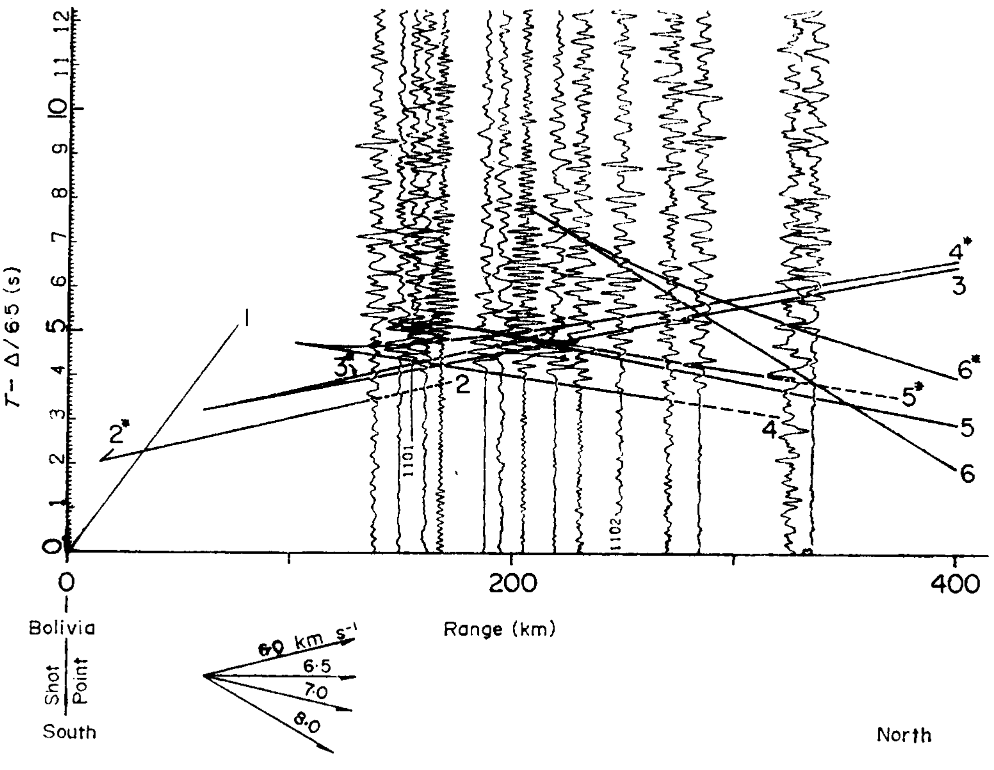

Fig. 4. Record section from Ocola *et al.* (1971) and superimposed interpretation (Fig. 5, Table 2) for the Bolivia profile.

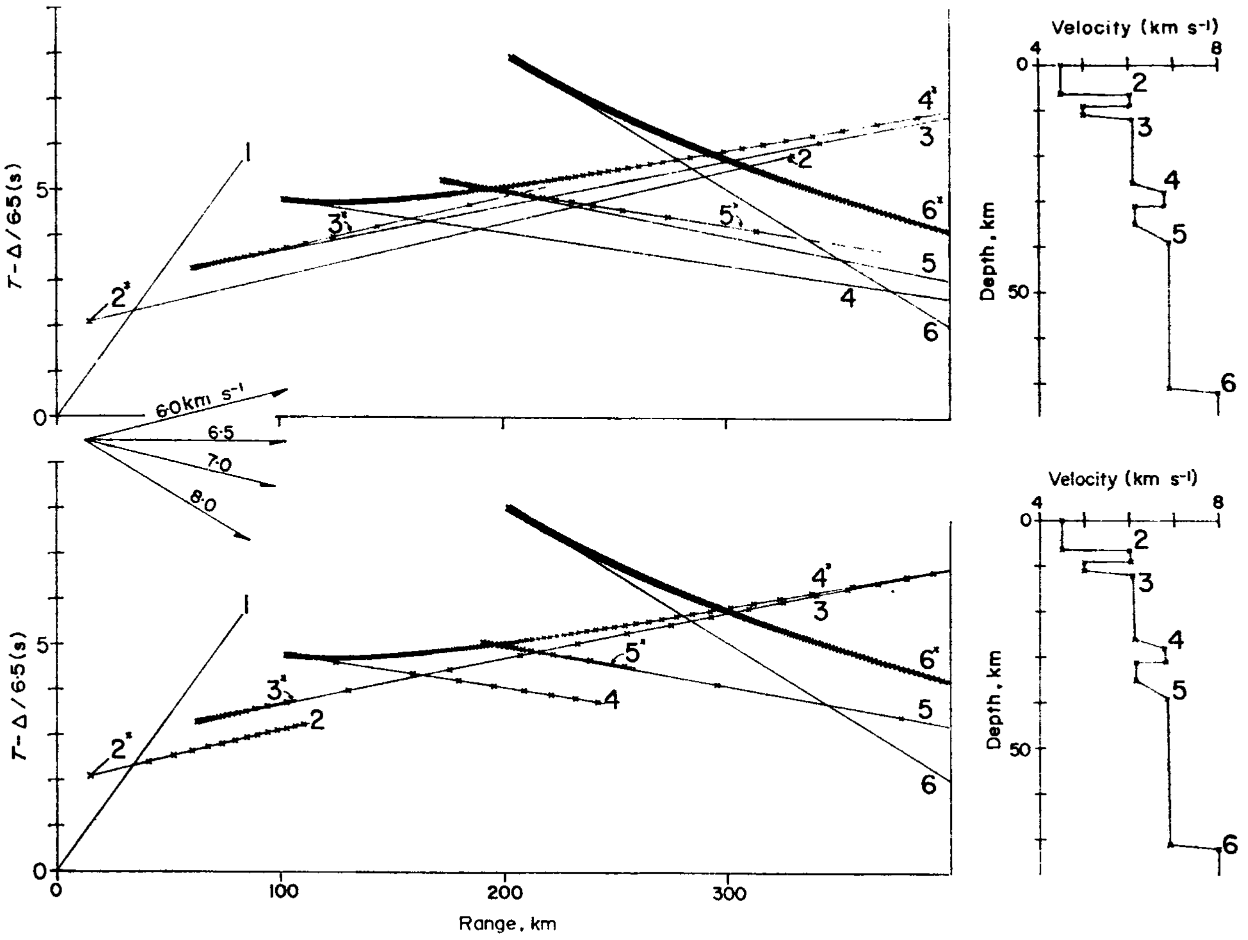

Fig. 5. Theoretical travel times that satisfy the near shot range arrivals in the Peru record section and the data of the Bolivia record section. The top travel-time plot and velocity depth function corresponds to the velocity model A, of Table 2. The bottom travel-time plot and velocity depth function corresponds to the velocity model B, Table 2.

These relatively large amplitudes are interpreted as indicative of a large velocity contrast between the low-velocity material and the imbedding material. However, the actual value of the low-velocity cannot be estimated from the travel times alone. It requires at least quantitative estimation of amplitudes through calculation of the dynamic response of the model of a match of the record section with theoretical seismograms.

Evidence for this deeper low-velocity zone in the Peru record section, Fig. 2, is not as good as in the Bolivia record section, possibly because the Peru shots' size was about one-half of that of the Bolivia shots. Nevertheless, there is energy associated with predicted arrivals along the prograde branch 4 between 110- and 220-km range, and between 110 km and at least 260 km for the retrograde branch 4*. The position of an apparent cusp at about 120 km from the shot point corresponding to the convergence of the branch 4 and the branch 4* agrees reasonably well with travel times computed for models of Fig. 3(A) and (B). Evidence for branches 4 and 4* is meager, i.e. evidence for rays emerging from the material immediately below the low-velocity zone. However, the relatively large amplitude arrivals at about 180- and 220-km range are in the right place for a cusp between branch 5 and 5*.

Although two models have been presented here that reasonably well satisfy the travel times, it is clear that other models are also possible. However, the general form of the velocity-depth model for both Peru and Bolivia profiles is not expected to change significantly. The preferred models are those with relatively sharp velocity transitions and with refractors having small velocity-depth gradient. These models provide an explanation of the relative amplitudes of the arrivals observed as well as the apparent offset in the travel time.

5. Discussion

The exceptional attenuation of body waves under the Andes in southern Peru and northern Chile (Tatel & Tuve 1958; Aldrich *et al.* 1958) led the Department of Terrestrial Magnetism, Carnegie Institution of Washington, Instituto Geofisico del Peru, and Instituto Geofisico Boliviano investigators to search for high temperature material under the Andes through the study of the electrical conductivity.

The conductivity structure under the Andes has been inferred from the analysis of induced fields produced by night-time magnetic variations: magnetic bays; and day-time magnetic variations: equatorial electroject. Observations were made at many widely separated areas in Peru and Bolivia during the period 1963–1966 (Schmucker *et al.* 1966). They found that a 'large-scale induced subterranean jet current is guided into a high conductivity channel under the crust of the Andes' (Schmucker *et al.* 1966, pp. 15–16). Further, they unexpectedly found a negative anomalous *Z* (vertical component)-amplitude along the Peruvian coast when *H* (horizontal component)-amplitude is positive. From these results together with the magnitude of the *Z* component, it was concluded that 'the absence of such a (normal positive-coastal) anomaly in Peru implies . . . that a highly conductive sub-stratum comes close to the surface, thereby damping the oceanic induction currents and likewise reducing the coastal anomaly' (Schmucker *et al.* 1966, p. 361). Finally, Schmucker concluded that the depth of the high-conductivity zone 'has to be small in comparison to the half-width of the jet (equatorial electrojet) field, *i.e.* of the order of 50 km or less' (Schmucker 1969, p. 136).

These important results about the conductivity structure of the crust under the Andes together with the low-velocity zones postulated here seem to support the hypothesis that the high attenuation of body waves observed in the Andes is related to high temperature materials within the Earth's crust.

The existence of shallow low-velocity zones under the Peru–Bolivia altiplano are also supported by the findings of Pichler & Zeil (1970) concerning the petrochemical distinction between acidic and basic lavas in northern Chile and southern Bolivia.

Table 3

Depth (km)	Velocity (kms^{-1}) A	B
0·0	4·5	4·5
6·41	6·04	5·91
31·8	6·75	6·78
72·9	8·0	8·0

Table 4

Depth (km)	Velocity (kms^{-1}) A	B
0·0	4·7	4·94
9·1	6·0	6·10
25·9	6·8	6·79
76·0	8·0	8·0

According to Pichler & Zeil, the two lavas evolved from different parent magmas and at different depths. Ocola *et al.* (1971), in agreement with many investigators, have shown that material with velocity about 6·0–6·1 km s^{-1} is of the granite type, while material with velocity 6·8–6·9 km s^{-1} is of the basaltic type. Hence, if each low-velocity zone is of the same composition as the imbedding material but at a significantly different temperature, then the shallower low-velocity zone would seem to be a logical source for the acidic lavas, and the deeper low-velocity zone should be related to the basic lavas. Furthermore, the source of two types of mineralization (porphiritic and lode) in the western coast of South America is very likely related to these velocity anomalies and their tectonic evolution across the continent-ocean transition.

It is instructive to compare the interpretation of record sections of Figs 2 and 4 by Ocola *et al.* (1971) based on head waves and horizontally-layered media with our new ‘diving wave’ interpretation in a spherical Earth. As Ocola *et al.* stated, their interpretation represents a gross average structure of the crust under the Peru–Bolivia altiplano. Thus in order to make both models comparable, the interpretation based on ray-trace in the spherical earth has been smoothed by calculating a mean weighted average velocity for layers between the major discontinuities. The results are shown in Table 3 and 4 for southern Peru and Bolivia profiles, respectively. The velocity values differ at the most by about 0·1 km s^{-1} and the corresponding major discontinuities depth by less than 0·5 km for the southern Peru profile. The velocity values for the Bolivia profile agree better than 0·15 km s^{-1} with the greatest difference in the near surface. The corresponding depths of the intra-crustal discontinuities agree better than 3 km and the depths for the *M*-discontinuity differ by about 4 km (i.e. about 5 per cent).

The total crustal thickness under the Peru–Bolivia altiplano is around 70 km. This value is in reasonable agreement with thicknesses estimated by Fernandez & Careaga (1968), 64·5 ~ 7·8 km; Anzoleaga (1964), 48 to 84 km. James (1971) estimates a crustal thickness of 50 km along La Paz (Bolivia) and Cuzco (Peru) wave-path from Rayleigh-wave dispersion. This thickness is also in reasonable agreement with our determination considering the frequencies used by James in the inversion.

6. Summary and conclusions

1. From the interpretation of apparent offsets in the travel times, the amplitude variations with range of first and secondary arrivals, and the close values of the apparent velocities of the first and secondary arrivals associated with the travel-time offsets, it is suggested that: (a) There may exist a shallow low-velocity layer in Peru

imbedded in the granite crustal layer. Its presence in Bolivia is postulated on geologic grounds because of the similarity of known lithology, tectonic history, and elevation. (b) There may exist a deep and thick low-velocity zone imbedded in the crustal gabbroic layer within the Bolivia and Peru altiplano.

2. The existence of low-velocity zones in the Andean crust is in harmony with a shallow electric conductivity anomaly postulated by Schmucker and others from areal studies of induced-magnetic-field variations produced by the equatorial electrojet and magnetic bays.

3. The shallower low-velocity zone is conceivably related to the parent magma of acidic (intrusive and volcanic) rocks with the deeper low-velocity zone related to basic (intrusive and volcanic) rocks in accord with the petrological and geochemical findings of Pichler and Zeil in the Andes of northern Chile.

4. The crustal low-velocity zones are plausibly produced by overheated material. This provides a reasonable explanation for the high attenuation of body waves in the Andean crust and it also furnishes plausible explanation for the difficulty of recording arrivals from the *M*-discontinuity under the altiplano.

Acknowledgments

As the number of people who contributed significantly to the success of this experiment is large, acknowledging the specific contributions of each would make an extensive list. Hence, we wish instead to list the institutions in South America and North America which provided participants.

South American collaborators included: Instituto Geofisico Boliviano; Universidad de San Calixto; Peru: Instituto Geofisico del Peru; Universidad Nacional de San Agustin de Arequipa (Instituto Geofisico).

North American collaborators: Department of Terrestrial Magnetism, Carnegie Institution of Washington; University of St Louis, St Louis, Missouri; University of Texas, Dallas; and University of Wisconsin, Madison.

We gratefully acknowledge financial support by the Carnegie Institution of Washington, H. O. Wood Fund, and the Air Force Office of Scientific Research.

Leonidas C. Ocola:
Instituto Geofisico del Peru
Lima, Peru

Robert P. Meyer:
Geophysical and Polar Research Center
University of Wisconsin,
Madison, Wisconsin

References

Aldrich, L. T., Tatel, H. E., Tuve, M. A. & Wetherill, G. W., 1958. The Earth's crust, *Carnegie Institution of Washington: Yearbook* **57**, 104–111.

Anzoleaga, R., 1964. *Algunas consideraciones sobre la Corteza Terrestre debajo de los Andes*, Licentia Thesis, Universidad Mayor de San Andres, La Paz, Bolivia.

Department of Terrestrial Magnetism Staff and Collaborators, 1970. Explosion studies in the altiplano, *Carnegie Institution of Washington: Yearbook* **68**, 459–462.

Fernandez, L. M. & Careaga, J , 1968 The thickness of the crust in central United States and La Paz, Bolivia, from the spectrum of longitudinal seismic waves, *Bull. seism. Soc. Am.*, **58** (2), 711–741.

James, D. E., 1971, Andean crustal and upper mantle structure, *J. geophys. Res.*, **76** (14), 3246–3271.