

SEISMIC REFRACTION STUDIES OF THE WESTERN CORDILLERA, COLOMBIA

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ABSTRACT

Two seismic refraction-wide angle reflection profiles made in the Western Cordillera of the Colombian Andes show high, upper crustal (0 to 15 km) velocities: the compressional velocity increases from 4.5 km/sec at the surface to 6.7 km/sec at 6 km depth and to 7.0 km/sec at 11 km depth; the shear velocity increases from 2.5 km/sec at the surface to 4.0 km/sec at 11 km depth. Travel-time and amplitude modeling of first arrivals has resulted in an upper crustal velocity-depth function which is characterized by gradients, and modeling of reflected arrivals has resulted in two alternative lower crustal (15 to 29 km) models, one with and one without velocity inversions. An intra-crustal boundary occurs at 19 to 21 km depth, and the moho at 26.5 to 29 km depth.

These results, which are based on 1976 recordings to both the north and west of a quarry located near 4°N, confirm indications from 1973 reconnaissance data of high-seismic velocities at shallow depths at both ~4°N and ~1°N. A new, laterally inhomogeneous upper-crustal model for the 1973 seismic data at 1°N has been made which indicates 6.7 km/sec material at a depth of 3.0 km in the Cordillera.

The upper crustal velocities from the Cordillera are similar to those from well-controlled determinations for ocean crust. These seismic results, combined with the positive Bouguer gravity anomalies and the geological evidence, suggest that the upper crust of the Western Cordillera consists of igneous oceanic materials of Cretaceous age.

The velocity structure of the lower crust cannot be accurately determined with the present data; the Cordillera may consist entirely of oceanic rocks, or of ~15 km of oceanic rocks overlying continental rocks.

INTRODUCTION

The Andes extend some 9,000 km from the southern tip of South America through Colombia and eastward across Venezuela. Significant advances have been made in understanding mountain building, and the generalized plate tectonic model of mountain building in the Andes (Dewey and Bird, 1970; James, 1971) has withstood nearly a decade of critical review. However, this decade of review has also revealed that considerable geological inhomogeneity exists along the length of this mountain belt, so that the general tectonic model is giving way to specific regional models. Recognizing this, Gansser (1973) suggested a threefold division of the Andes into southern, central, and northern segments. In order to understand the details of this inhomogeneity better, seismic refraction information on subsurface structure is needed; the present study contributes to knowledge of the seismic velocity structure of the Western Cordillera of the northern (or Ecuador-Colombia-Venezuela) segment of the Andes.

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GEOLOGIC AND GEOPHYSICAL SETTING

North of Ecuador, the Andes separate into three distinct ranges, the Western, Central, and Eastern Cordilleras (Figure 1). This study concerns the Western Cordillera, which extends from southern Ecuador to at least 8°N in Colombia. For much of its length, it is characterized by positive Bouguer gravity anomalies (Figure 2) reaching values as high as +60 mgals at 1°N (Case *et al.*, 1971, 1973). Dense (>3.0 gm/cc) basic rocks are found at the surface, in association with marine sediments.

The first detailed geological study of the Western Cordillera in Colombia was

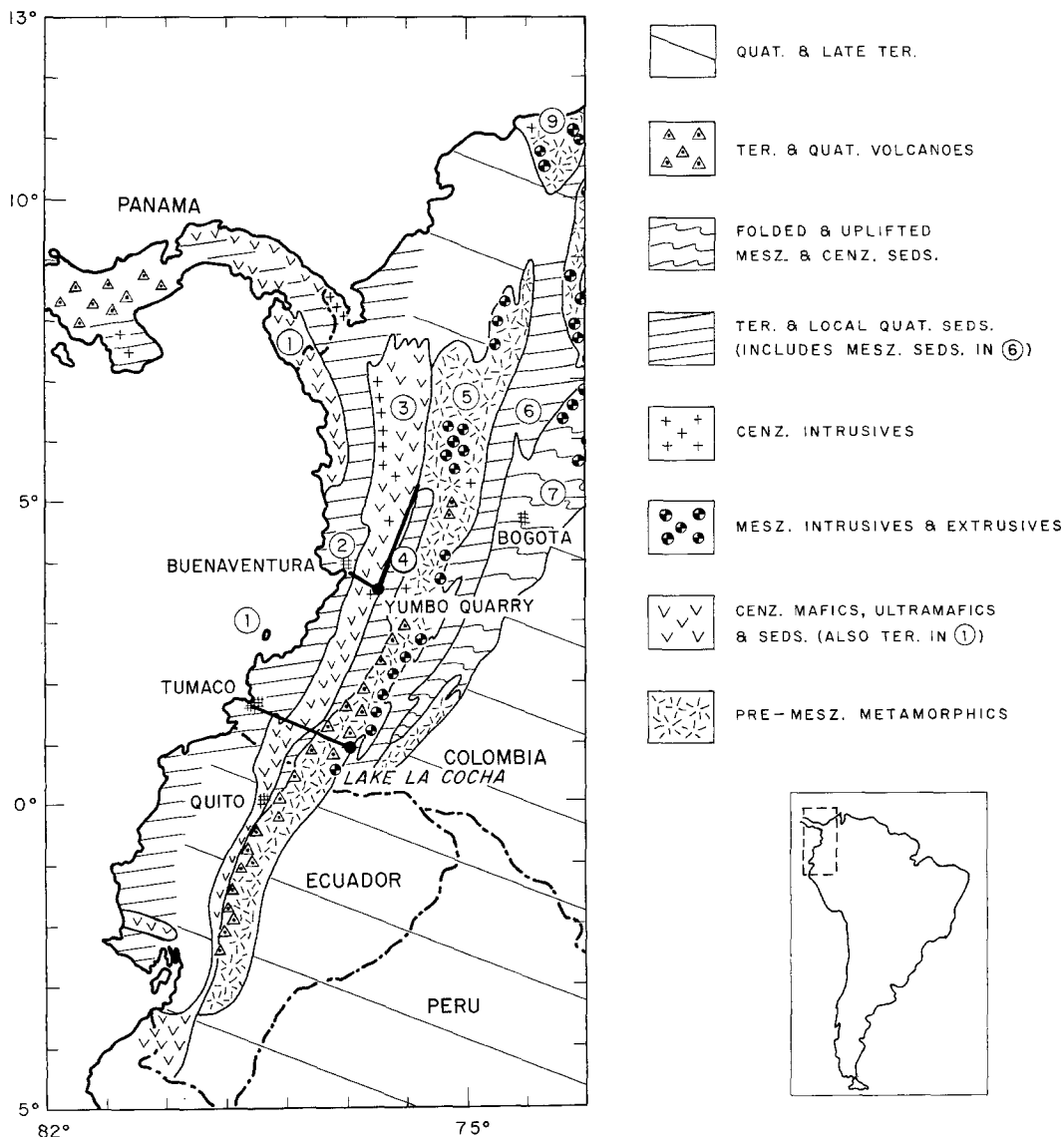


FIG. 1. Generalized geological map of northwestern South America. The region of study, the Western Cordillera, ③, extends from southern Ecuador to 8°N in Colombia. Seismic refraction profiles: Yumbo Quarry-North (1976, this paper), Yumbo Quarry-West [1973 (Meissner *et al.*, 1976; and 1976, this paper)], and Lake La Cocha-West [1973 (Meissner *et al.*, 1976; Hales *et al.*, 1977)]. Solid dots represent shot points, Yumbo Quarry and Lake La Cocha; heavy lines, line of measurements. ① Serranía de Baudo and Gorgona Island, ② Atrato-San Juan Basin, ③ Western Cordillera, ④ Cauca Valley, ⑤ Central Cordillera, ⑥ Magdalena Valley, ⑦ Eastern Cordillera.

made by Nelson (1957), whose work has been continued by Aluja *et al.* (unpublished report) and Barrero (unpublished manuscript). According to these authors, typical stratigraphy of the range at 4°N consists of a lower sedimentary group (Dagua group) overlain by submarine volcanic rocks (diabase group). The diabase group consists mainly of diabase, basalt, and pillowed lavas which occur locally as slivers

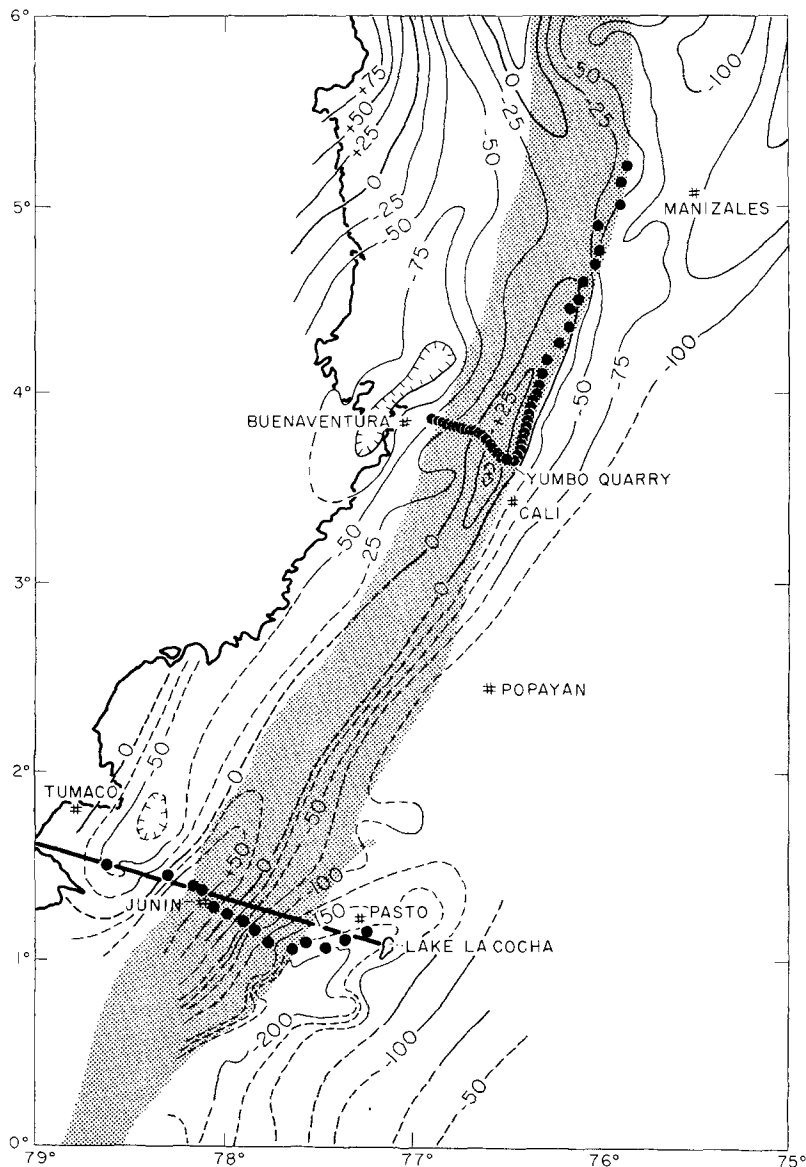


FIG. 2. Bouguer gravity map of western Colombia; the Western Cordillera is shaded. The station locations are for the 1976 profiles Yumbo-North and Yumbo-West, and for the 1973 profile La Cocha-West (Hales *et al.*, 1977). Solid line to the west of Lake La Cocha indicates the azimuth of the upper crustal model of Figure 11.

and slabs separated by the sedimentary rocks of the Dagua group. Scattered ultramafic and acidic plutonic rocks occur along the length of the Western Cordillera. The Dagua group consists mainly of slightly metamorphosed pelagic sediments which were deposited at abyssal and continental slope depths (Barrero, unpublished

manuscript). The lower contact of the sedimentary Dagua group has apparently not been mapped; however, gravity studies (Case *et al.*, 1971, 1973) indicate that the Dagua and diabase groups must be underlain by dense rock, which Case *et al.* suggest is oceanic crustal material. The results of seismic refraction investigations, summarized here, indicating compressional wave velocities >6.7 km/sec (basic rocks) below 7 km depth, support this interpretation.

The Western Cordillera is flanked along much of its length by two sedimentary basins, the Cauca Valley to the east and the Atrato-San Juan Basin to the west (Figure 1). Both are characterized by negative Bouguer gravity anomalies (Figure 2). Based on seismic refraction measurements, the velocity-depth structure in the portion of the Cauca Valley south of 3°N shows velocities no greater than 6.2 km/sec in the first 26 km depth (J. Gettrust, personal communication, 1978). This velocity structure indicates that basic rocks, if present in the southern Cauca Valley, are at much greater depth than in the Western Cordillera. The Atrato-San Juan Basin contains sedimentary fill of more than 10,000 m near Buenaventura, based on geological inference (Nygren, 1950) and gravity modeling estimates (Case *et al.*, 1971). A model combining seismic and gravity measurements also shows more than 10,000 m of sedimentary fill (i.e., 3.5 km/sec material) in the Buenaventura region of this basin (Meyer *et al.*, 1976).

1976 REFRACTION EXPERIMENT

The Western Cordillera was chosen for a detailed seismic refraction experiment in 1976 for several reasons. Four explosions at Yumbo Quarry (Figure 1) recorded in 1973 for reconnaissance purposes by the University of Wisconsin-Madison and the Christian-Albrechts-Universität-Kiel, Germany, proved to be unusually rich in shear-wave energy. In 1973, noise levels at 4 Hz were generally $<2 \text{ \AA}$ (Meyer *et al.*, 1976) throughout the range (~ 200 km) for which seismograms were successfully recorded. These facts suggested that recording closely spaced profiles along and across the geological strike would make possible the determination of the compressional and shear-wave velocity-depth structure underlying the Western Cordillera.

The field seismographs consisted of seven FM tape recording units with programmable turn-on time. Six of the units were three-component stations equipped with Hall-Sears HS-10 seismometers with 1 Hz nominal resonant frequency. In the seventh unit the two horizontal components were replaced with telemetry channels, thus permitting the recording of vertical ground motion at three neighboring sites. The response of these instruments is described in Lewis and Meyer (1968). Timing accuracy of ± 0.01 sec was provided by the internal clocks which were regularly rated to WWVB. True signal amplitude was determined by comparison with the μvolt calibration signals recorded during each instrument deployment.

A. Yumbo-North

The profile Yumbo-North best reveals the seismic velocity structure along the strike of the Western Cordillera. All recording sites were along the eastern flank of the Cordillera; noise levels were again low. Figure 3 gives a composite record section compiled from seven shots; shot numbers and sizes are included. Clear compressional and shear-wave arrivals were observed up to a range of 122 km; beyond 122 km the signal-to-noise ratios of the first arrivals were below 1.

The seismograms in the first 40 km are uncomplicated; first *P*-wave arrivals are high-frequency (8 ± 3 Hz) impulsive, with most of the energy occurring in the first second of the record. Beginning at a range of 40 km, the seismograms are more

complicated, and at 80 km and beyond the highest amplitudes are for secondary arrivals.

Upper crust (0 to 15 km). For upper crust analysis, iterative modeling of travel times and amplitudes was used, beginning with first arrivals. Conventional proce-

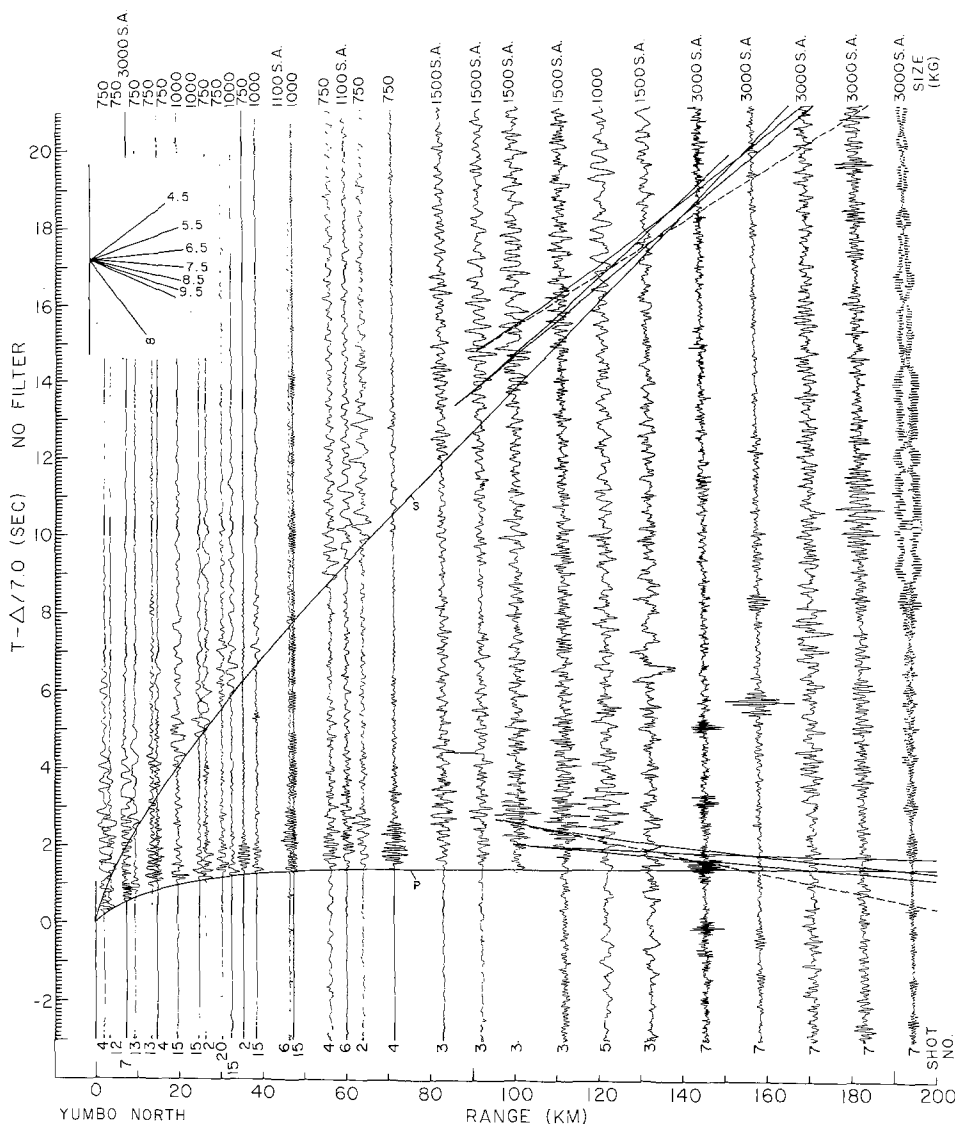


FIG. 3. Record section for the Yumbo-North profile. Records have been plotted to make the first arrival visible. Shot number and size are indicated for each record. Shots were dynamite unless superanfo (S.A.) is indicated. (True amplitude behavior of the first-arrival energy is plotted in Figure 4 for the records for which a calibration was available.) Theoretical travel-time curves are calculated for the velocity-depth function of Figure 5 without low-velocity zones. The signal-to-noise ratio is less than 1 beyond 122 km; all records have been included in the record sections to document the amplitude decrease with range.

dures were used to derive a homogeneous flat-layer velocity-depth model with theoretical times in fair agreement with the observed travel times, but the theoretical amplitudes of this model did not agree with those observed. In order to improve the agreement of theoretical and observed amplitudes, and to achieve a better fit to the

gently curved shape of the first-arrival travel-time curve, the homogeneous layers of the original (upper crustal) model were replaced with velocity gradients, and the first-order seismic discontinuities with transition zones. Ultimately, the iterative modeling produced a velocity-depth model with travel times and amplitudes in good agreement with the observed amplitudes (Figure 4). Theoretical amplitudes were calculated using Kind's (1976) modification of Fuchs and Müller's (1971) synthetic seismogram program.

The compressional-wave velocity (Figure 5) increases from 4.5 km/sec at the surface to 6.15 km/sec at 3 km and reaches 7.0 km/sec at 11 km depth. The velocity is constant below 11 km to a depth of at least 15 km. The upper crustal shear-wave velocity (Figure 5) is also characterized by velocity gradients. The velocity increases from 2.52 at the surface to 3.50 at 3.0 km and reaches 3.97 km/sec at 11 km. The

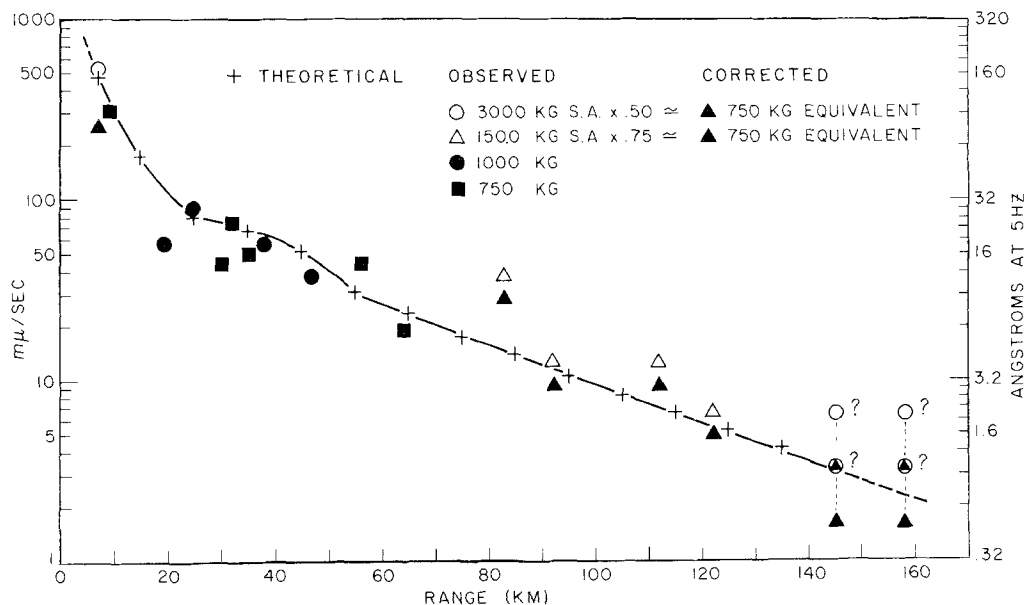


FIG. 4. Observed, corrected, and theoretical maximum displacement in Angstroms at 5 Hz and velocity in millimicrons per second for the first cycle of the first arrivals observed on the profile Yumbo-North. True amplitudes were determined using the field-recorded μ -volt calibration signals; the scaling factors (0.75 and 0.50) applied to the observed amplitude from 1500 Kg and 3000 Kg shots were empirically derived. Shots were dynamite unless superanfo (S.A.) is indicated. The observed amplitudes decrease by more than two orders of magnitude between 7 and 160 km. Amplitudes at 145 and 158 km are estimates based on the observations of a signal-to-noise ratio of less than 1 at these quiet sites (1 to 2 Å noise). Theoretical amplitudes are calculated for the upper crustal model (0 to 15 km) in Figures 6 and 7.

shear-wave velocity is also modeled as remaining constant between 11 and 15 km depth. The travel-time curves for this shear-wave model are in good agreement with the shear-wave first arrivals (Figure 3). The V_P/V_S ratio in the upper crust varies between 1.82 and 1.76, and Poisson's ratio between 0.28 and 0.26.

Lower crust (15 to 29 km). The seismograms from 80 to 132 km range show evidence for secondary arrivals. These are interpreted to be reflected from an intra-crustal seismic discontinuity (P_iP and S_iS) and from the crust-mantle boundary (P_mP and S_mS). The refracted or diving phases (P_i , S_i , P_n , and S_n) are not observed. Two alternative lower crustal models have been derived from the data, one with low-velocity zones (velocity inversions) and one without. These two models give

some sense of the uncertainty in the resolution of the lower crustal velocity structure with the present data.

Lower crust: P waves. In the first model (without velocity inversions), the reflections are modeled by discontinuities from 7.0 to 7.45 km/sec at 21.5 km depth and 7.45 to 8.2 km/sec at 29.0 km depth. This velocity structure yields theoretical travel times and amplitudes in reasonable agreement with those observed (Figure 6). A drawback to this model is that the model's P_iP and P_mP critical points occur at greater ranges (98 and 94 km, respectively) than in the observed data (~ 92 and ~ 88 km, respectively). As a result, the first arrival, P_g , carries the largest amplitude in the synthetic seismograms at ranges of 83 and 92 km, whereas the secondary arrivals carry the largest amplitudes in the observed data. A second drawback is that the average apparent velocity of the model's P_mP travel-time curve (~ 7.9 km/sec between 92 and 140 km) is somewhat higher than the observed average apparent velocity (~ 7.6 km/sec between 92 and 140 km, as per Figure 6). In the second model (Figure 7) the introduction of low-velocity zones above the intra-crustal and Mohorovičić discontinuities shifts the critical points to shorter range and reduces the apparent velocities of the reflection branches, thus eliminating these drawbacks.

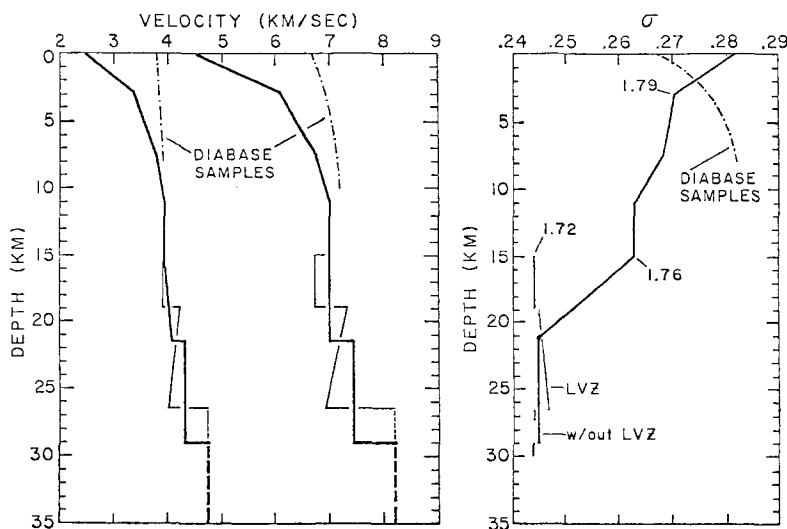


FIG. 5. Compressional wave (V_p), shear wave (V_s), and Poisson's ratio versus depth for the two alternative interpretations of the Yumbo-North profile, and for the average of the laboratory measurements of the diabase samples. Numbers indicated on the curve for Poisson's ratio give the corresponding value of the V_p/V_s ratio at that point.

The velocity structure of the upper 15 km of the second model is identical to that of the first model; however, at 15 km, the velocity drops from 7.0 km/sec to 6.7 km/sec. A discontinuity at 19 km brings the velocity from 6.7 to 7.35 km/sec and is followed in depth by a negative velocity gradient, reaching 6.9 km/sec at 26.5 km depth. The M-discontinuity is at 26.5 km depth, where the velocity increases from 6.9 to 8.2 km/sec.

The theoretical travel times and amplitudes for this low-velocity zone model are in better agreement with the observed data than for the model lacking low-velocity zones. In particular, the amplitudes of both the P_iP and P_mP reflections are larger between 83 and 101 km, and the average apparent velocity of the P_mP curve (7.6 km/sec between 94 and 140 km) matches more closely the observed average apparent velocity (Figure 7).

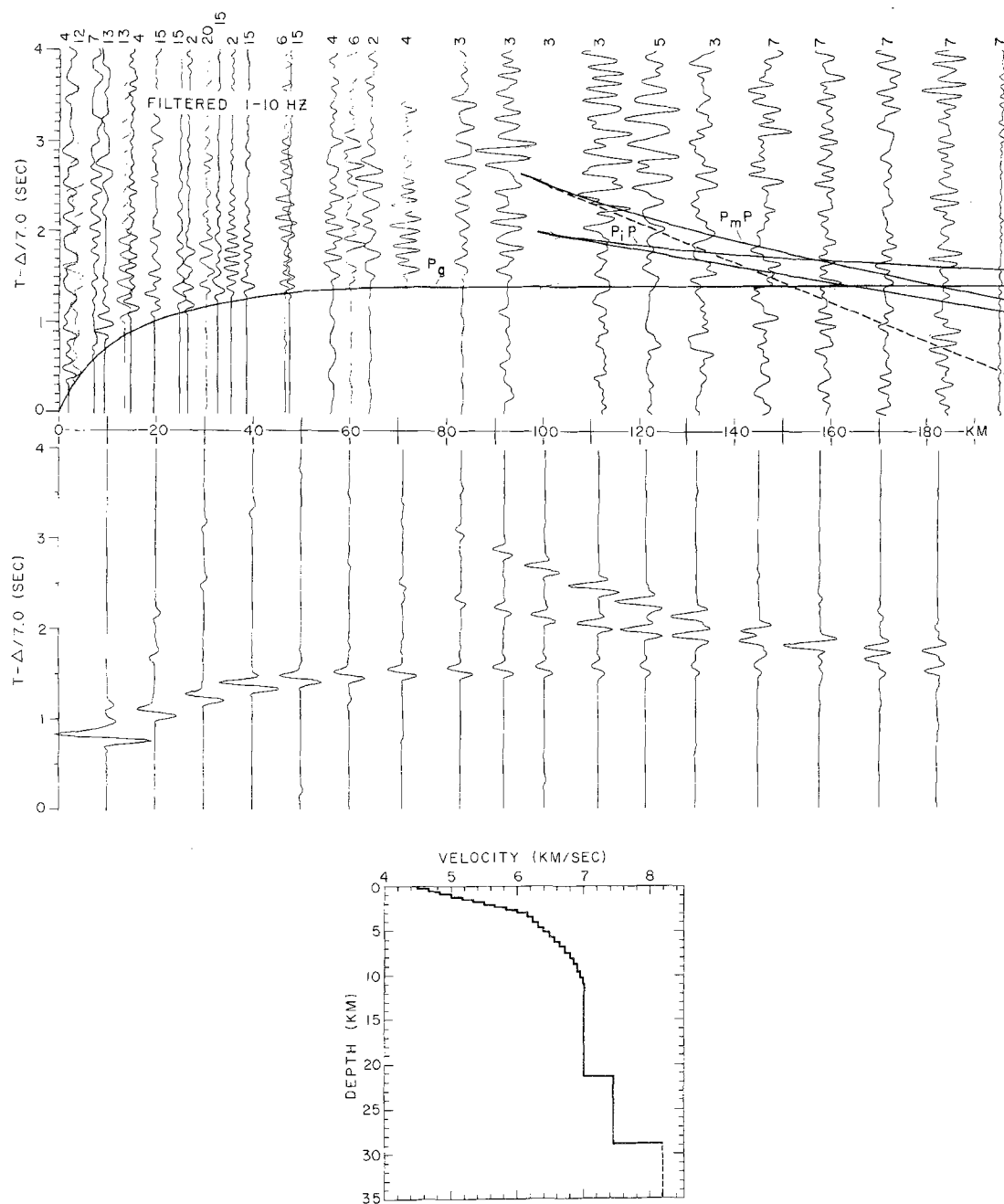


FIG. 6. Yumbo-North: Observed compressional-wave data with theoretical travel times and synthetic seismograms calculated for the velocity-depth function without low-velocity zones. Synthetic seismograms have been multiplied by their range before plotting. This velocity-depth function yields a reasonable fit to the observed travel times and amplitudes; an alternative velocity-depth function is given in Figure 7.

The average velocity of the crust is 6.84 km/sec for the first model and is 6.70 km/sec for the second model. These values compare well with the calculated maximum possible average crustal velocity which is obtained from the $P_m P$ reflection curve alone using the relationship (Giese, 1976, page 148)

$$\bar{V} \leq V_{\max} = [(V_{\text{app}} \cdot X)/t]^{\frac{1}{2}}$$

where $V_{\max}$ is the maximum possible average crustal velocity and V_{app} is the apparent velocity at a reflection point at range X and with travel-time t . Using the reflection at 92 km where $V_{\text{app}} = 8.1 \pm 0.2$ km/sec and $t = 15.8 \pm 0.3$ km/sec yields $\bar{V} \leq V_{\max} = 6.87 \pm 0.15$ km/sec.

Lower crust: shear waves. Shear-wave first arrivals are clear to a range of 112

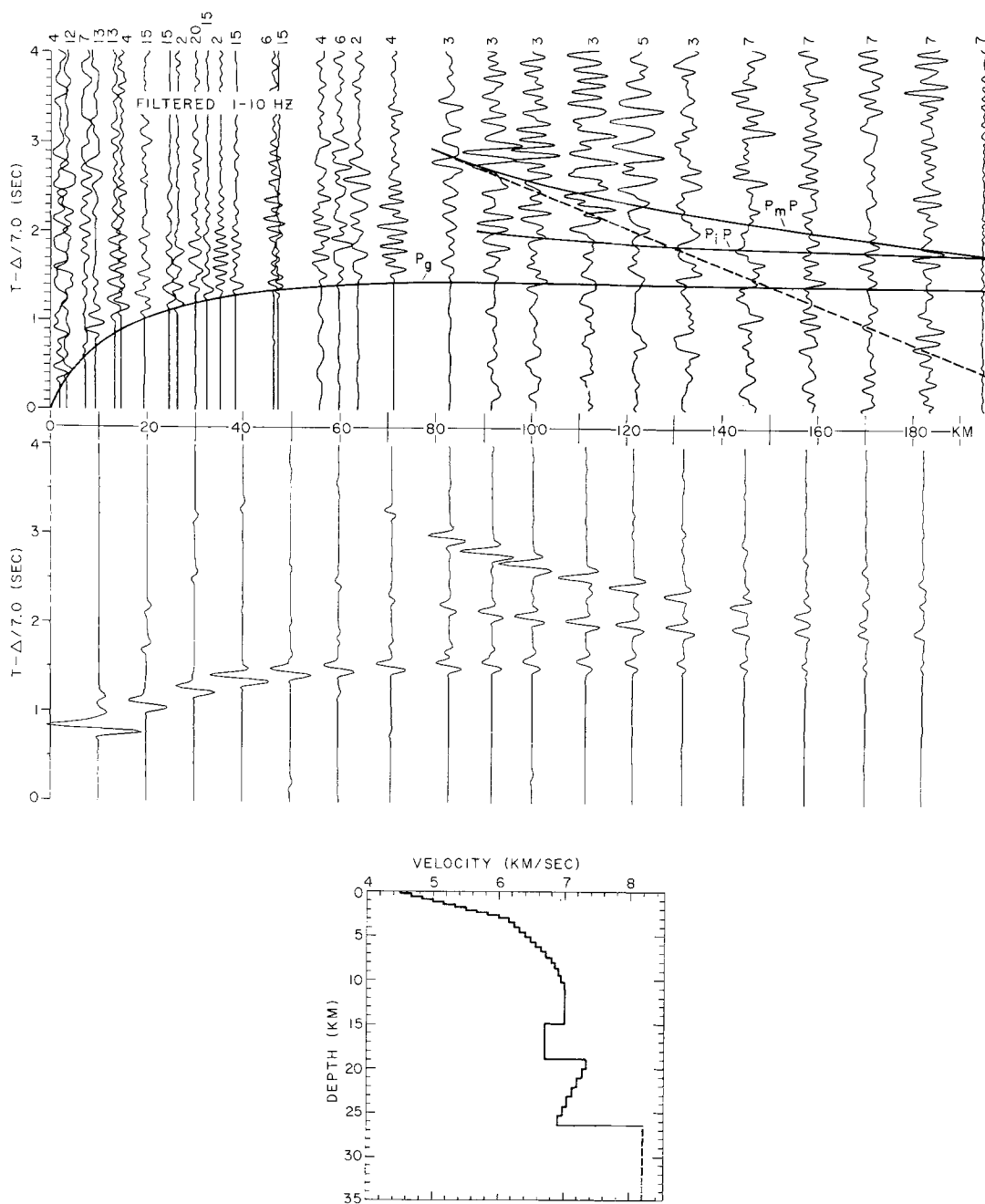


FIG. 7. Yumbo-North: Observed compressional-wave data with theoretical travel times and synthetic seismograms calculated for the velocity-depth function with low-velocity zones. Synthetic seismograms have been multiplied by their range before plotting. Compared with the model without low-velocity zones (Figure 6), this model produces a lower average apparent velocity for the reflection phases P_1P and P_mP , and higher amplitudes for these phases between 80 and 100 km range.

km; beyond that range, the signal-to-noise ratio for first arrivals is less than 1. Secondary arrivals are visible in the seismograms only between 92 and 112 km; these include arrivals with travel times and apparent velocities appropriate for the intra-crustal and Mohorovičić discontinuities modeled from the compressional-wave data.

Following the analysis of the compressional-wave data and under the assumption that the shear-wave boundaries occur at the same depth as the compressional-wave boundaries, two alternative velocity-depth functions are presented for the shear-wave data. These models are based only on travel-time analysis; amplitude modeling was not attempted because of the poor data quality beyond 90 km range. The first model does not include low-velocity zones while the second model does, at the same depths as in the compressional-wave velocity-depth function. The first 15 km of the two velocity-depth functions are identical: the shear velocity increases from 2.48 km/sec at the surface to 3.97 km/sec at 11 km depth and remains constant at 3.97 from 11 to 15 km. In the first model (Figure 8), the velocity increases gradually from 3.97 at 15 km to 4.07 at 21.5 km depth where, at the intra-crustal boundary, the velocity increases discontinuously to 4.33 km/sec. Below 21.5 km the velocity remains constant at 4.33 km/sec, until at 29.0 km it increases at the M-discontinuity to 4.77 km/sec. This velocity structure yields travel times in reasonable agreement with the observed data (Figure 8).

The second shear-wave velocity-depth model (Figure 8) corresponds to the compressional-wave model with low-velocity zones (Figure 7). The velocity of the upper 15 km is identical to the other shear-wave model. However, at 15 km the velocity drops from 3.97 to 3.92 km/sec. The velocity rises to 4.27 km/sec at 19.0 km depth and then gradually decreases with depth, reaching 4.00 km/sec by the moho, where it rises to 4.77 km/sec. Compared to the velocity-depth model without low-velocity zones, this velocity-depth structure yields S_iS and S_mS critical points at shorter ranges, and lower apparent velocities on these reflected phases (Figure 8). Unfortunately, because of the data quality neither model clearly recommends itself over the other.

B. Yumbo-West

The 1976 Yumbo-West profile was taken along straight, unimproved roads from Yumbo Quarry to Loboguerrero and along the Buga-Buenaventura highway from Loboguerrero toward Buenaventura (Figure 1); records from six shots have been compiled to produce the composite record section (Figure 9). The signal-to-noise ratio was generally good to a range of 50 km, beyond which the noise level increased, presumably due to the alluvium marking the start of the Atrato-San Juan Basin. The profile began in a region of slightly positive Bouguer gravity values at Yumbo Quarry, crossed a high of +25 mgals, and ended at -50 mgals (Figure 2).

Some records between a range of 3 and 9 km are emergent; the P waves are more impulsive beyond 10 km, and from 25 to 50 km the records (all recorded on bedrock) are very similar in character to those recorded along the Yumbo-North profile (cf. Figure 3). As is the case for the Yumbo-North profile, many records show strong S -wave arrivals.

Since the profile extends to a range of only 62 km, the data give information only about the uppermost crust. The upper-crustal compressional and shear-wave velocity-depth function derived from the Yumbo-North data was found to predict travel times in excellent agreement with the Yumbo-West arrivals, indicating homogeneity of material within the central Western Cordillera. Refinement of the Yumbo-West velocity-depth function through amplitude modeling did not prove feasible because

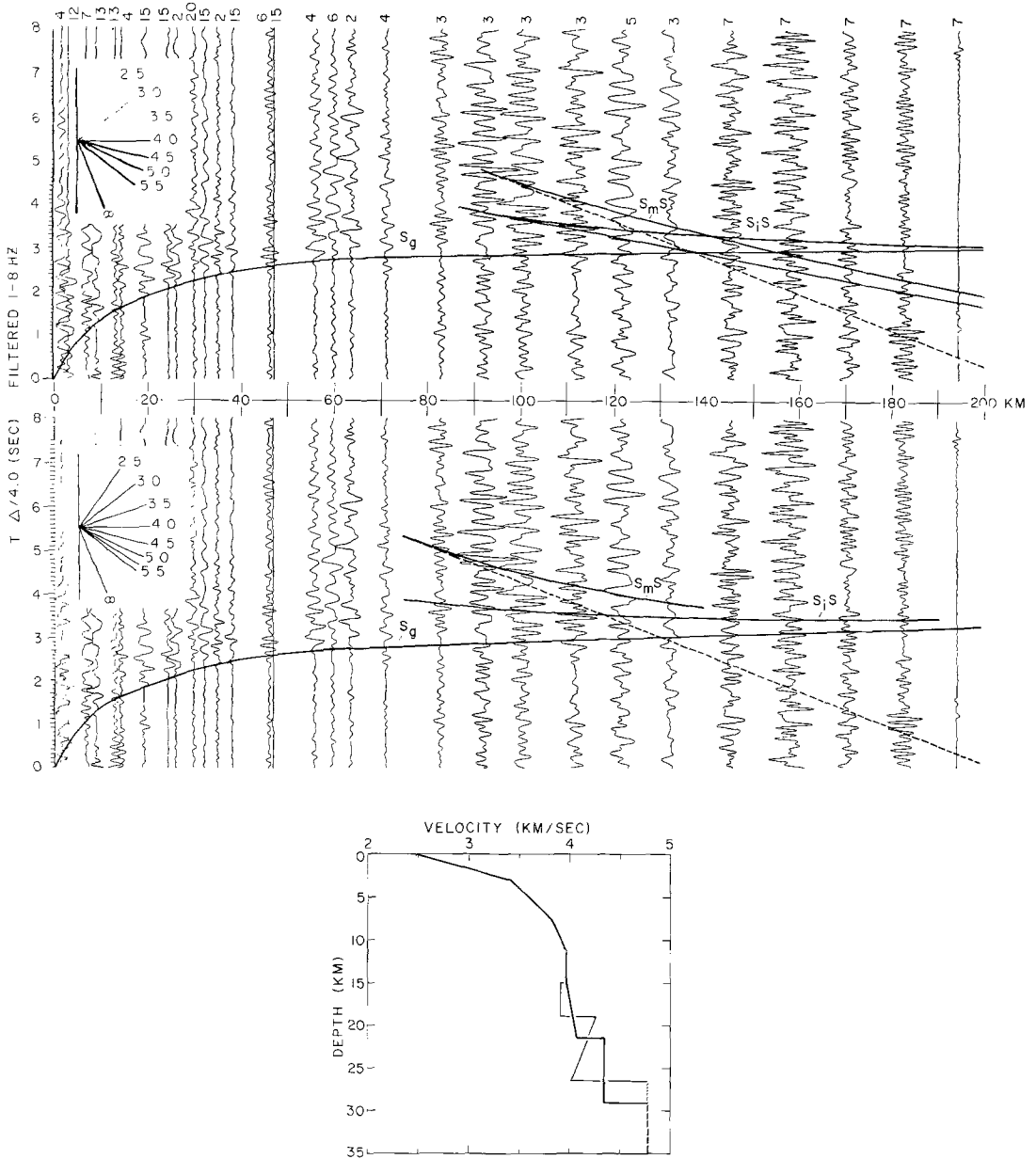


FIG. 8. Shear-wave data and two alternative velocity-depth functions for the Yumbo-North profile. The direct arrival (S_0) can be identified only to a range of 112 km; secondary arrivals (S_1S and S_2S) are clear only for the seismograms between 92 and 112 km. *Upper* record section: travel times for the interpretation without low-velocity zones (corresponding to the velocity-depth function of Figure 6); *lower* record section: travel times for the interpretation with two crustal low-velocity zones (corresponding to the P -wave velocity-depth function of Figure 7). Neither interpretation is clearly superior to the other.

of the short length of the profile and the large scatter in first-arrival amplitudes, probably due to the great local variation at recording sites along this cross-strike profile.

First arrivals extending beyond a range of 43 km are increasingly delayed relative to the theoretical Yumbo-North profile arrival time; the first arrival for the record at a range of 56 km is delayed by 0.9 sec. This delay is in accord with an estimate of 7.5 km of sediments in the Atrato-San Juan Basin under that site, assuming that

the upgoing ray travels through sediments with a velocity of 3.5 km/sec rather than crustal materials with an average velocity of 6.0 km/sec.

LABORATORY VELOCITY MEASUREMENTS: DIABASE CORE SAMPLES

In order to compare the seismic velocities determined for rocks at depth in the Western Cordillera with the intrinsic velocity of the dense surficial rocks, laboratory

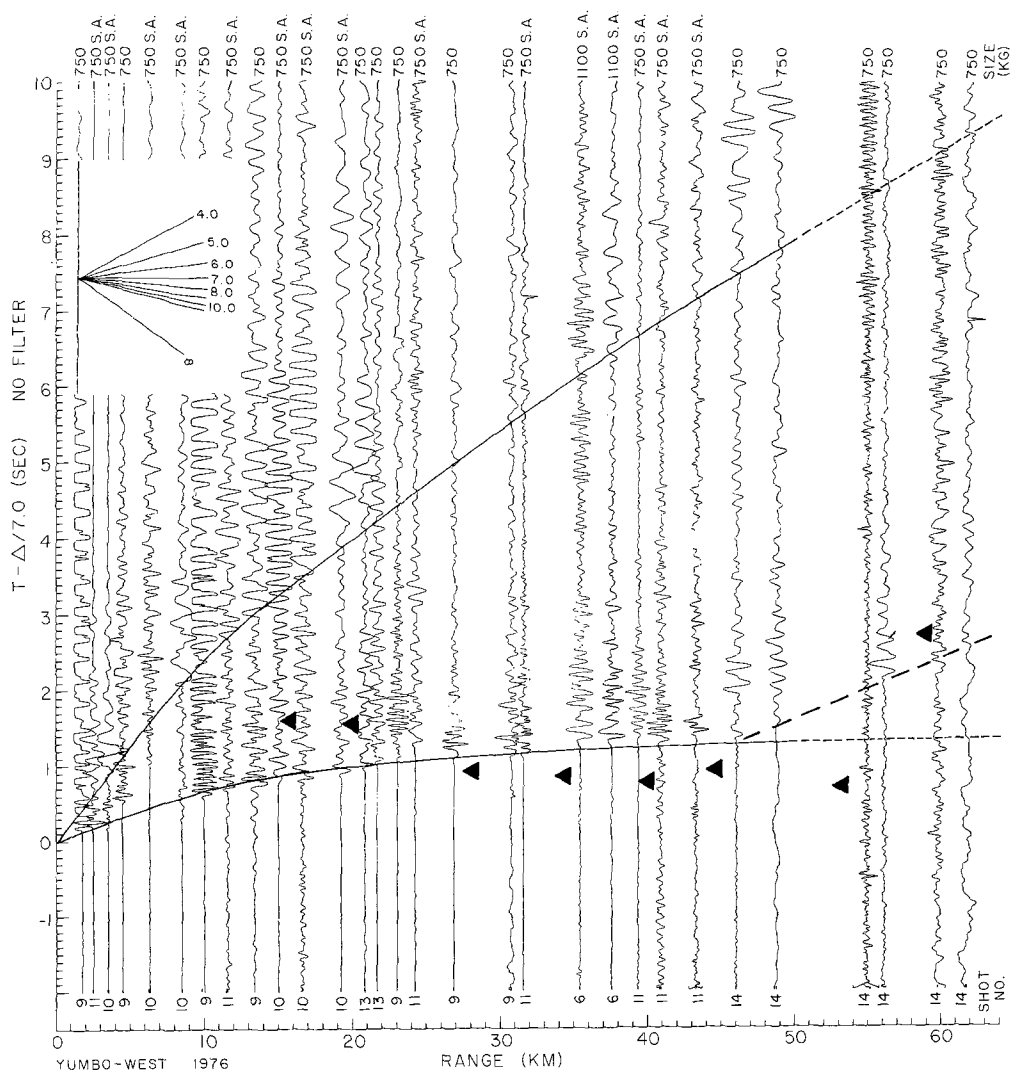


FIG. 9. Record section for the Yumbo-West profile. Theoretical travel-time curves are calculated from the upper crustal (0 to 15 km) velocity-depth functions determined for the Yumbo-North profile (Figure 5). The agreement between the Yumbo-North and Yumbo-West travel times demonstrates the degree of geological homogeneity within the upper crust of the Cordillera. Shot information as in Figure 3. Line with long dashes beyond 46 km range shows travel-time delay due to the sediments of the Atrato-San Juan Basin. Triangles are arrival times for the 1973 Yumbo-West profile (Meissner *et al.*, 1976).

measurements were made on samples taken from the diabase group of the Cordillera, using several 2½ in cores taken from a drill hole at kilometer post 65 of the Buga-Buenaventura Highway (near the town of Cisneros).

Analysis of a thin section indicated that the cores were diabase; the rock was of ophitic texture, composed mainly of thoroughly altered plagioclase and relatively

unaltered calcic pyroxene. Alteration of the plagioclase and the presence of chlorite, sericite, calcite, and epidote in veins indicate a greenschist facies metamorphism for these rocks (C. Guidotti, personal communication, 1978). This identification agrees with other descriptions of diabase from the Western Cordillera (Nelson, 1957; Barrero, unpublished manuscript).

The compressional-wave seismic velocity of five 1-in diameter cylinders of air-dried diabase (cut from the original core samples) was measured to a hydrostatic confining pressure of 3 kbar. To test for consistent results, three of the samples were oriented in the same direction; the other two were drilled out in mutually perpendicular directions to test for anisotropy. Birch's (1960) pulse transmission technique

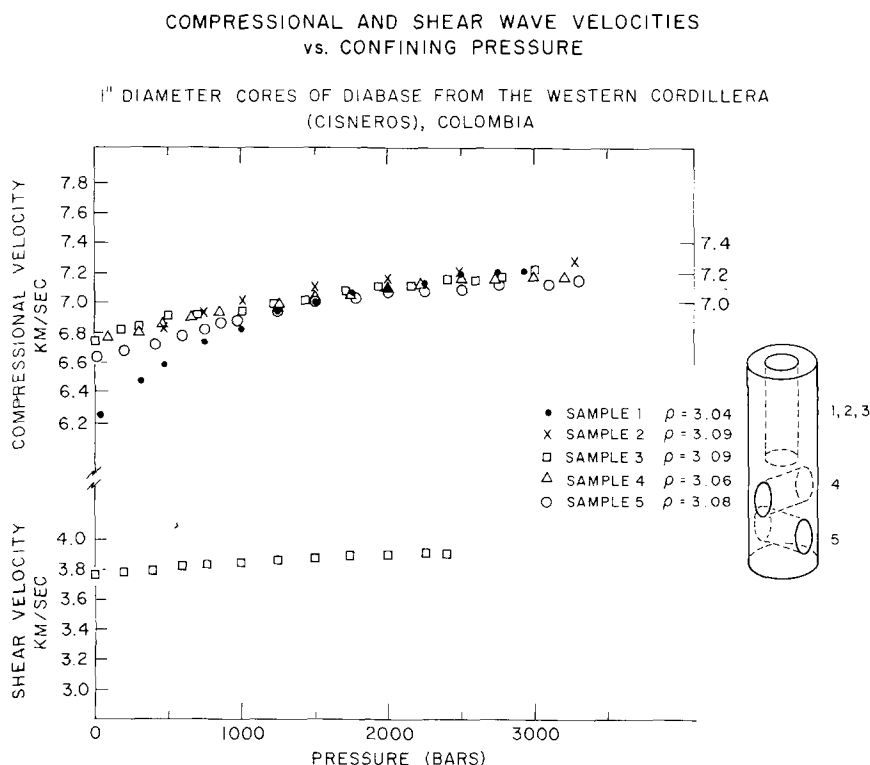


FIG. 10. Compressional-wave velocity versus confining pressure for five diabase samples, and shear-wave velocity versus confining pressure for one sample. Values are for the increasing pressure measurements. Velocities are accurate to ± 0.04 km/sec, pressures to 10 bars. Orientation and density of samples (calculated from their weights and dimensions) are indicated at right. Sample 1, which has the lowest density and velocity at pressures less than 1 kb, is cut by a thin (1 mm) calcite vein.

was employed, except that a calibrated delay pulse generator was used for timing. In one sample, the shear-wave velocity was measured. Velocities were recorded for both increasing and decreasing pressure. Under decreasing pressure, hysteresis, primarily due to the adjustment of cracks to the change in pressure, was noticeable below 1 kbar.

The velocity versus confining pressure curves from these measurements (Figure 10) show a remarkably small velocity increase from 1 to 1000 bars (the pressure range within which most cracks or pore spaces close). The diabase is fine-grained and apparently has little space to close under this initial increase in pressure. The slower increases at higher pressures result from intrinsic effects of pressure on the mineral components (Birch, 1960). The average velocity of the samples at 1 kbar

pressure is 6.9 ± 0.1 km/sec; the 3 kbar average is 7.2 ± 0.05 km/sec. The samples show no evidence of seismic anisotropy (Figure 10).

In order to compare the laboratory data with the field refraction results, the velocity-pressure behavior of the diabase samples was converted to a velocity-depth relationship by the approximation that 1 kbar = 3 km depth (assuming an average density of 3.0 gm/cc in the Cordillera).

The diabase velocities are consistently higher than those of the rocks of the Western Cordillera (Figure 5), the difference decreasing with depth. The difference is particularly large for the first 5 km, which implies that diabase-like rocks, while present, are not the exclusive nor predominant rock type in the uppermost crust (0 to 5 km) of the Cordillera; this is consistent with the mapped geology of the area which indicates significant amounts of surficial marine sediments (Barrero, unpublished manuscript). A mixture at the surface of 50 per cent sediments with a 3.5 km/sec velocity and 50 per cent diabase with a 6.7 km/sec velocity (i.e., laboratory velocity at 1 bar) would yield a net average velocity of 4.6 km/sec, in agreement with the observed velocity at the surface. At 10 km depth, the compressional velocities differ by only 0.2 km/sec and, extrapolating the laboratory shear velocity measurements, the shear velocities are in close agreement. Poisson's ratio differs at most by 0.02. It is concluded from these comparisons that diabase-like rocks predominate in the depth range 10 to 15 km of the upper crust of the Western Cordillera.

RELATION TO 1973 REFRACTION EXPERIMENT

The two 1976 profiles can be used to clarify the results of the 1973 reconnaissance refraction experiment in the same general area (1973 Yumbo-West) and to the south (1973 La Cocha-West).

A. 1973 Yumbo-West

A 1973 Yumbo-West profile (Meissner *et al.*, 1976) consisted of eight recordings made at distances from Yumbo Quarry ranging from 15 to 60 km, along a different road (the Dagua-Buenaventura Highway) from that used for the 1976 Yumbo-West profile (unimproved roads and the Buga-Buenaventura Highway). The arrival times for the 1973 profile (solid triangles in Figure 9) between a range of 28 and 54 km are an average of 0.4 sec early relative to the 1976 data, but show similar apparent velocity (~ 7.0 km/sec); however, the first two 1973 arrivals have an unexplained 0.8 sec delay, and the arrival at 60 km has an 0.4 sec delay. Because the arrival times for the 1976 Yumbo-North and Yumbo-West data generally differ by <0.1 sec, it is considered unlikely that the differences between the 1973 and 1976 Yumbo-West data are due to real lateral variations in velocity structure. Range errors are a more likely source of these differences; the 1973 data were collected before accurate maps for the area of investigation were available, while the receiver locations for the 1976 investigation were determined using both newly-issued maps and air photos.

If the five 1973 records between 38 and 54 km are each moved 2.5 km closer to the shot point, the 1973 and 1976 arrival times for these data differ by an average of less than 0.1 sec. The two arrivals between 16 and 21 km would agree with the 1976 data if moved 4 km further from the shot.

B. 1973 La Cocha-West

Two profiles were made in 1973 at 1°N , recording west from Lake La Cocha (Meissner *et al.*, 1976; Hales *et al.*, 1977) (Figure 1).

These profiles crossed three geological provinces: the first 60 km are within the Colombia-Ecuador Altiplano (the elevated southern extension of the Cauca Valley) the next 70 km are in the Western Cordillera, and the remaining records are in the Coastal Plain (Figure 1). The profiles are perpendicular to the strike of the geological structure and cross from a region of strongly negative Bouguer gravity values (-180 mgals just west of the shot point) to the positive values of the Western Cordillera (a high of $+60$ mgals near Junin, 115 km from the shot point), and end in the negative Bouguer gravity values (-50 mgals) of the Coastal Plain.

The apparent velocities determined from the two profiles are similar and indicate three distinct seismic velocity regions (corresponding to the three geological provinces noted above). The Hales *et al.* (1977) profile shows a 5.65 km/sec apparent velocity in the Altiplano and 6.65 km/sec crossing the Western Cordillera; for these regions the Meissner *et al.* (1976) profile shows 5.9 km/sec and 7.0 km/sec, respectively. The large travel-time delay for the record near Tumaco indicates the thick sediments of the Coastal Plain.

Because these single-ended profiles cross three geological provinces, it is not possible to determine the true depth, dip, or velocity of the materials responsible for

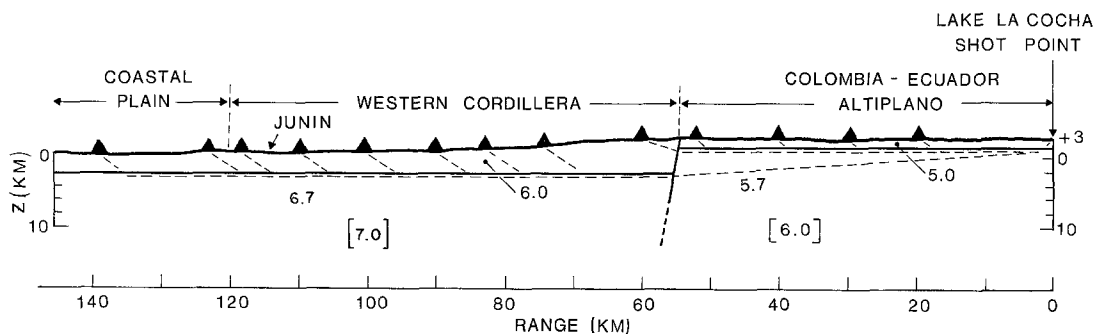


FIG. 11. Seismic velocity model at $\sim 1^\circ\text{N}$. Azimuth of the cross section is indicated in Figure 2. The model satisfies the first arrival times of the La Cocha-West profile of Hales *et al.* (1977) to ± 0.05 sec in the Altiplano and the Western Cordillera; model times are < 0.20 sec early for the two stations in the coastal plain. The 13 receiver stations are indicated by triangles. The velocity in brackets beneath the Altiplano is the velocity at 10 km depth as determined by the profile La Cocha-North (J. Gettrust, personal communication, 1978). The velocity in brackets beneath the Western Cordillera is the velocity at 10 km depth in the cordillera at $\sim 4.5^\circ\text{N}$ as determined by the profile Yumbo-North (this paper).

the apparent velocities. However, in order to compare the 1976 Yumbo Quarry results with those from 1973 La Cocha-West, a laterally-inhomogeneous flat-layer model (Figure 11) was made that satisfies the Hales *et al.* (1977) seismic observations. This model shows 6.7 km/sec material under the southern Western Cordillera at 3.0 km below the surface, 3.5 km less deep than had been determined for this velocity in the central Western Cordillera from the 1976 profile Yumbo-North. The shallower depth to 6.7 km/sec material is consistent with the Bouguer gravity, which reaches higher values (maximum $+60$ mgals) along the La Cocha-West profile than along the Yumbo-North profile (maximum $+20$ mgals) (Case *et al.*, 1973) (Figure 2). The model's 5.7 km/sec velocity in the Altiplano is in close agreement with the 5.8 km/sec uppermost crustal velocity determined for the profile La Cocha-Yumbo (J. Gettrust, personal communication, 1978.)

DISCUSSION

The positive Bouguer gravity (Case *et al.*, 1971, 1973) and high velocities observed in reconnaissance seismic measurements (Meissner *et al.*, 1976) led those authors to

suggest that the upper crust of the Western Cordillera contains significant amounts of mafic oceanic rocks (ocean crust). The most important result of the 1976 seismic investigation is the confirmation of high compressional and shear-wave velocities. The compressional velocity of 6.8 to 7.0 km/sec and shear velocity of 3.8 to 4.0 km/sec found between 7 and 15 km are atypical of continental velocity structure (cf. Steinhart and Meyer, 1961, p. 347) but agree well with the 6.7 to 7.0 km/sec compressional velocities and 3.7 to 3.9 km/sec shear velocities that are most common for oceanic layer 3A (Christensen and Salisbury, 1975, Table 1 and Figure 1). In addition, Poisson's ratio for the upper crust of the Cordillera is in agreement with the 0.25 to 0.29 values that are typical for the ocean crust (Christensen and Salisbury, 1975, Table 1; Spudich *et al.*, 1978).

The major difference between the Cordillera and ocean crust is the greater crustal thickness of the Cordillera. Both the Cordillera's oceanic upper crust (0 to 15 km) and its total crustal thickness (26.5 to 29.0 km) far exceed the 5 to 7 km thickness of normal ocean crust. Complete understanding of the nature and origin of the Cordillera is hampered by the imprecise knowledge of the lower crustal velocity structure. No refracted arrivals from the lower crust can be identified in the present data; the two alternative lower crustal velocity models (Figures 6 and 7) are based on reflected arrivals. These models permit an interpretation of the lower crust as consisting of either continental or oceanic materials: the model without low velocity zones (Figure 6) may be interpreted to indicate a lower crust consisting of materials similar to those normally associated with oceanic layer 3B (typical velocities of 7.2 to 7.5 km/sec; Christensen and Salisbury, 1975, Table 1 and Figure 1); the low velocity zone model (Figure 7) may be interpreted as indicating 15 km of ocean crust accreted to or overthrust on continental crustal material.

The decrease in Poisson's ratio with depth (Figure 5) is an interesting feature of both velocity models; Poisson's ratio appears to reach 0.24 to 0.25 in the lowermost crust. Relatively few seismic refraction determinations of Poisson's ratio have been made for the lower crust in other continental or oceanic areas; values span 0.23 to 0.27 for continental regions (Assumpção and Bamford, 1978) and 0.25 to 0.29 for oceanic layer 3B (Christensen and Salisbury, 1975; Spudich *et al.*, 1978). Thus, it is not possible to determine the nature of the Cordillera's lower crustal material on the basis of the observed Poisson's ratio. Improved data in the distance range 80 to 200 km are needed to resolve this important question.

The oceanic materials of the Cordillera may have been emplaced at the continental margin of western Colombia and Ecuador by a gradual accretionary process during subduction in Mesozoic time, or the Cordillera may be an anomalous piece of ocean crust [i.e., an aseismic ridge or other buoyant feature (Vogt *et al.*, 1976)] which resisted subduction and clogged the subduction zone, causing it to step westward (seaward), most likely to the present-day site of the Atrato-San Juan Basin. An important aspect of this study is the use of seismic refraction data to verify the tectonic origin of a geological structure, in this case the upper crust of the Western Cordillera of the Colombian Andes.

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