SEISMIC REFRACTION MEASUREMENTS OF CRUSTAL STRUCTURE IN WEST ANTARCTICA

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Abstract. Two seismic refraction profiles yield new information about the crustal structure of West Antarctica. One profile on the Ross Ice Shelf grid northwest of Crary Ice Rise shows basement rock with a compressional wave velocity (v_p) of 5.9 ± 0.2 km s^{-1} underlying a layer of presumed sediment about 400 m thick. The irregular basement surface lies about 1.0 km below sea level and has an average apparent dip of 1° to the grid north. The second profile, on the Siple Coast, reveals 1 to 2 km of sediment overlying a basement (v_p = 5.4 ± 0.2 km s^{-1}) that has an apparent dip of 4° to the grid southeast. An abrupt 2-km decrease in depth to basement within the profile is interpreted as being due to faulting. Deep reflections were observed on one record at 50 km, but data are insufficient for identification of their source.

Introduction

Two seismic refraction profiles were obtained during the 1983-1984 and 1984-1985 Antarctic field seasons, one on the Ross Ice Shelf (station CIR, see Figure 1) and the other on the Siple Coast (station UPB). Both profiles give information about crustal structure beneath the ice.

At CIR, shot distances were obtained (to an accuracy of a small fraction of a meter) with an electronic distance measuring device (AGA geodimeter), and absolute positions were determined by satellite positioning equipment (Magnavox geoceiver). Shot distances at station UPB were found by using several methods, including measurement by geodimeter, satellite positioning (good to a few meters), and direct P waves through the ice (accurate to better than 1%). Ice thickness values along the profile lines were determined by electromagnetic sounding (S. Shabtaie, personal communication, 1985). Ten geophone arrays, separated by 60 or 90 m over a total spread length of 690 m, were used at each recording station. Each array comprised six 8-Hz geophones planted in a rectangular pattern. Explosive charges ranging from 90 to 500 kg were used as sources at both CIR and UPB. Data were recorded by a high-speed digital recording system (developed at the Geophysical and Polar Research Center) with a 0.5-ms sampling interval on each channel. Time breaks were recorded for all shots of both profiles.

Ross Ice Shelf Profile

An unreversed profile consisting of five shots spaced roughly 3 km apart was obtained at CIR with shot-to-spread distances ranging from 14 to 27 km. The spread location remained fixed at grid position 6.16°S, 1.45°W (Figure 1). Refracted arrivals through the seafloor were observed on all five records. To analyze these data, travel times were plotted, and arrivals that could be traced across all records were identified. The apparent velocity of each arrival on a single record (the "forward velocity") was measured as well as the apparent velocity of each arrival as recorded on the same channel for all five records (the "reverse velocity"). The forward velocity (v_f) is a function of the dip under the receivers, whereas the reverse velocity (v_r) is a function of dip between the shots (Figure 2). If an assumption of constant dip from the shots to the receivers is made, these two apparent velocities can be used to calculate the true velocity and apparent dip of the refractor.

A reduced-time record section (Figure 3) was made by using the two measured apparent velocities. (Reduced times are travel times adjusted, at some assumed reducing velocity, to some standard distance.) For Figure 3, reducing velocities of v_f = 6.18 km s^{-1} and v_r = 5.67 km s^{-1} were used. Thus a persistent arrival with these apparent velocities should form a straight line across all records. In fact, for shot-to-spread distances greater than 20 km, the first arrivals (at 3.05 s in Figure 3) do line up well. At 17.7 km and 14.3 km, however, the arrivals were delayed by 0.03 s and 0.11 s, respectively. In principle, the delay could be due to changes in water depth, thickness of low-velocity sediments overlying the refractor, or both. In fact, we believe from radar sounding studies that the ice is intermittently grounded in this region [Shabtaie and Bentley, 1986], so we attribute the delay to a thicker sedimentary column under those two stations.

Using the travel times and apparent velocities from the more distant shots and assuming a veloci-

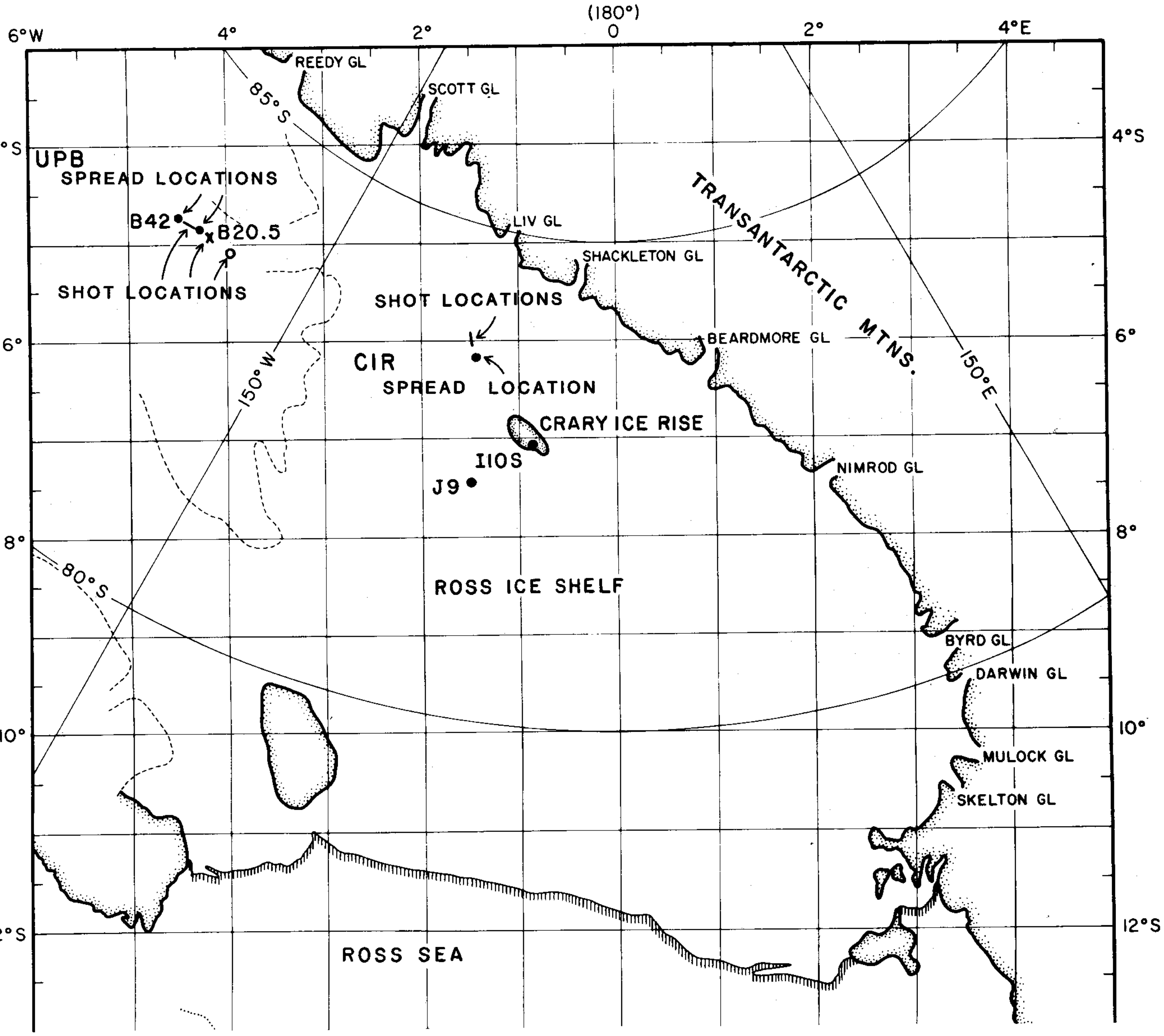

Fig. 1. Map of the Ross Ice Shelf and Siple Coast, West Antarctica, showing the locations of the two seismic refraction profiles described in the text. At CIR shot points were spaced equally along the short line. At UPB shot points were placed along the short line and also at each of the points marked by a cross and a circle. The spreads were at sites B42 and B20.5, both marked with solid circles. In the rectangular grid coordinate system, 0° grid longitude lies along the Greenwich and 180° meridians with grid north toward Greenwich, and the grid equator passes through the geographic South Pole.

ty of 2.4 km s^{-1} in a sedimentary layer (velocities less than that in the ice, 3.8 km s^{-1}, cannot be measured), we find a "true" velocity of 5.9 km s^{-1}, a mean depth to the layer of 1 km below sea level, and a grid northerly dip of 1.1°. The dip beneath the two shots nearest the spread, between which the apparent velocity is 6.5 km s^{-1}, is 2.3° to the grid south. Thus an undulating basement with a relief of a few hundred meters is implied (shown schematically in Figure 4).

This, of course, violates the assumption of constant dip over the entire profile, which was in any case an extreme one, not to be taken literally. However, with apparent velocities that differ only by 0.4 km s^{-1}, it is unlikely that a major error in true velocity will be made. Furthermore, a large dip beneath a layer that averages only about a kilometer in thickness can exist only locally, so that an apparent velocity over a 6-km stretch cannot differ greatly from the true vel-

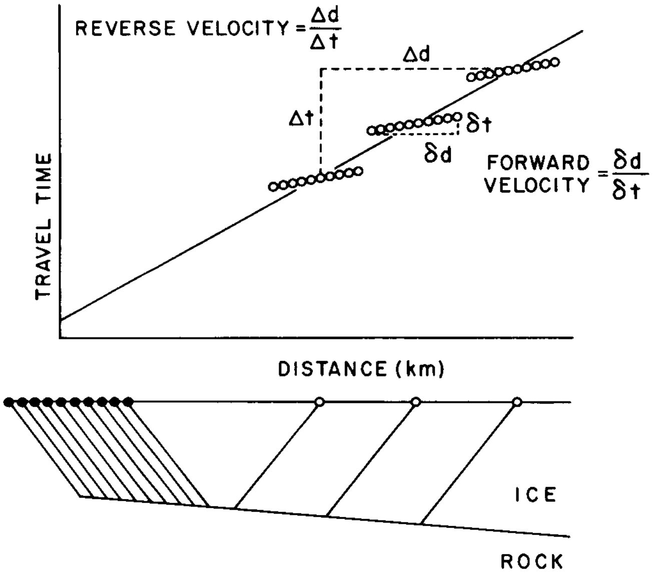

Fig. 2. Diagram showing the arrangement of shots and receivers (not to scale), and the meaning of the forward and reverse velocities.

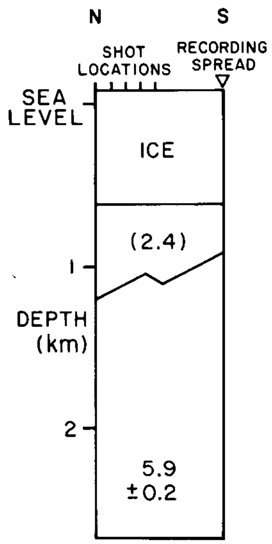

Fig. 4. Upper-crustal structure deduced from the CIR refraction profile. The numbers in the column are P-wave velocities in kilometers per second. Parentheses denote an assumed value. N and S are grid directions (cf. Figure 1).

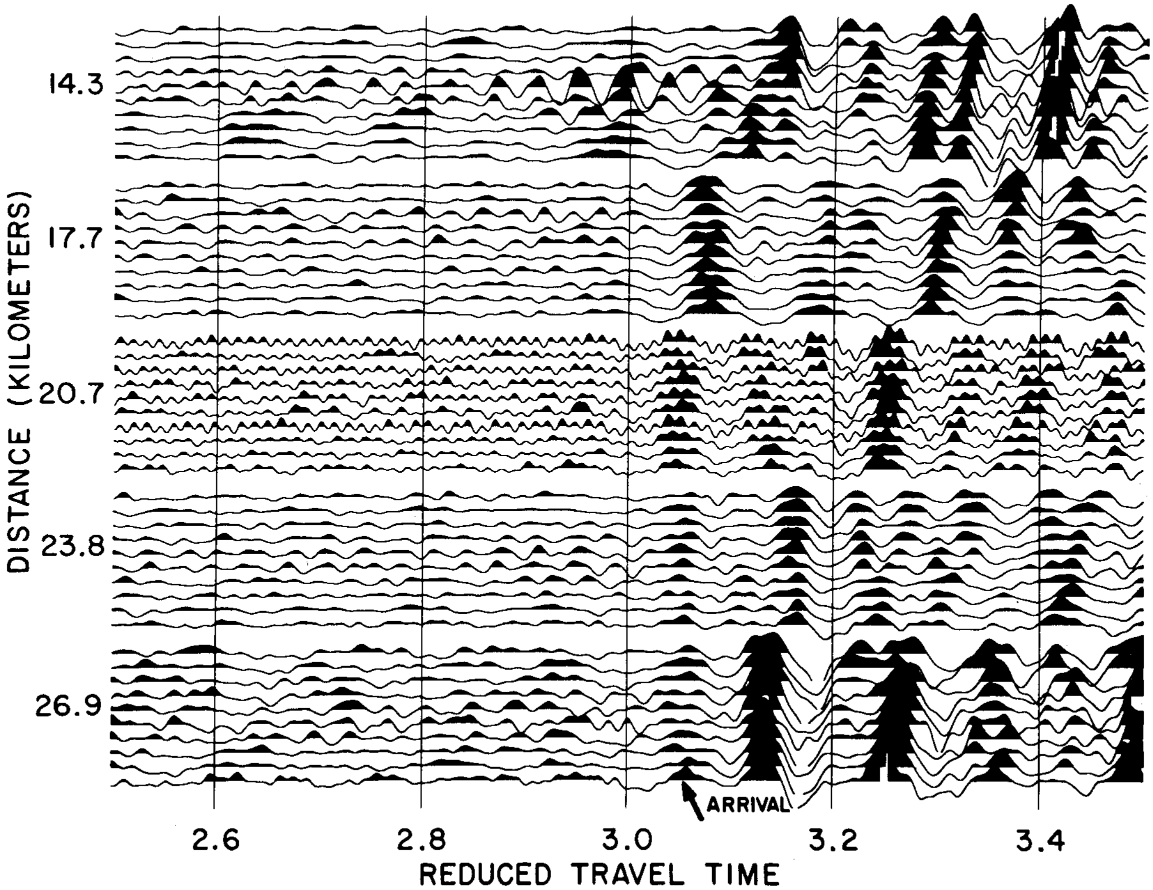

Fig. 3. Reduced-time record section from the CIR profile, on the Ross Ice Shelf. The forward and reverse reducing velocities were 6.18 km s^{-1} and 5.67 km s^{-1}, respectively, and the standard distance used was 14 km. The head wave from the first refractor occurs at a corrected time of 3.05 s.

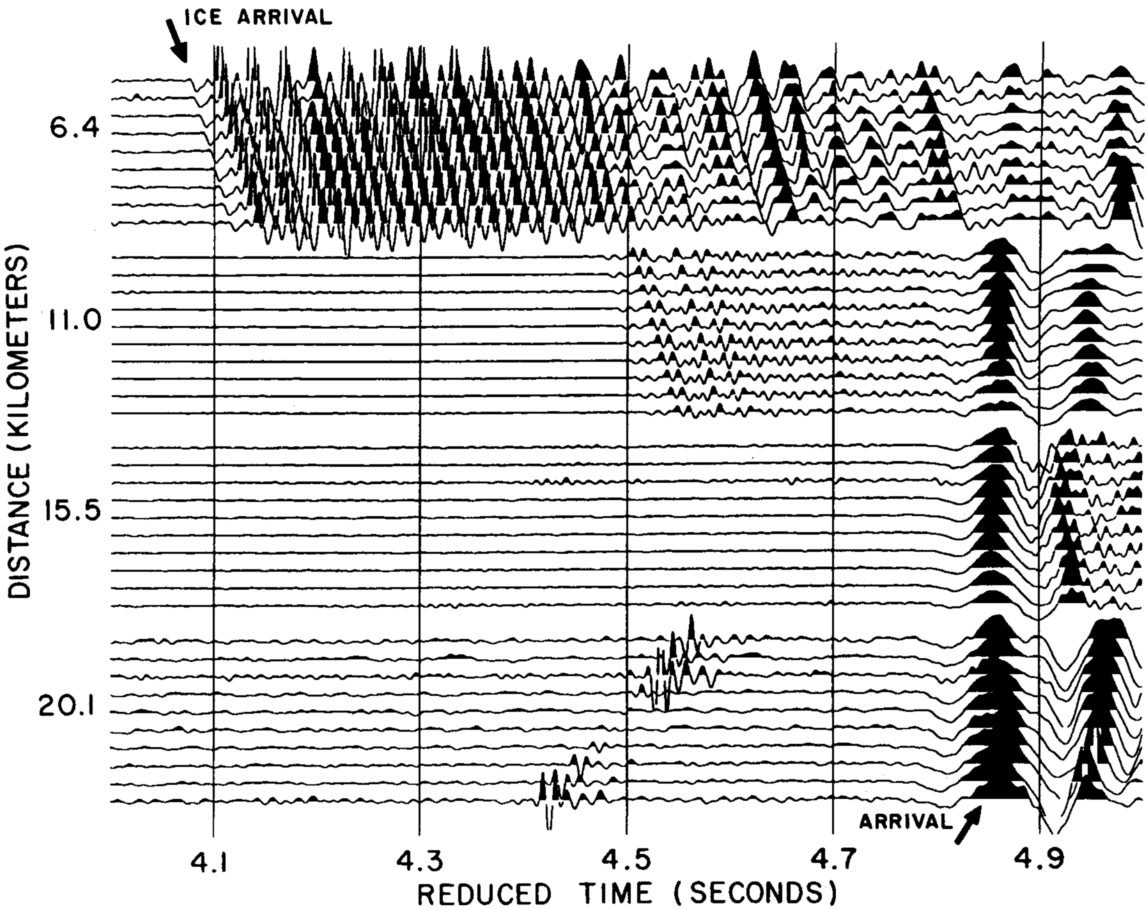

Fig. 5. Reduced-time record section from the UPB profile, recorded at B20.5. The forward and reverse reducing velocities were 5.05 km s^{-1} and 5.80 km s^{-1}, respectively, and the standard distance used was 20.2 km. The head wave from the first refractor occurs at a corrected time of 4.8 s. The high-frequency arrivals at 4.1 s, 4.5 s, and 4.95 s on the first three records, respectively, are the direct wave through the ice. The event around 4.5 s on the 20.1-km record is noise.

ocity. We thus arbitrarily say that the actual velocity probably lies between the apparent velocities, i.e., v = 5.9 ± 0.2 km s^{-1}.

Strong energy arrivals with v_f = 6.7 km s^{-1} occur on all our records (at reduced time of 3.1-3.4 s in Figure 3). We cannot correlate these arrivals with any consistent V_r, and our attempts to interpret them quantitatively have led to serious inconsistencies. We therefore cannot say whether they represent refraction energy from a deeper, higher velocity layer.

The basement velocity of 5.9 ± 0.2 km s^{-1} is not significantly different from that (5.7 km s^{-1}) found at about the same depth beneath station I10S on Crary Ice Rise (Figure 1), 130 km to the grid southeast [Robertson et al., 1982]. As Robertson et al. [1982] point out, that velocity is typical of crystalline basement in all the surrounding geological provinces, so it is difficult to make any specific association. However, since both their profiles and ours were located on the same ridge of the ridge-and-trough sea-bottom topography under the ice shelf [Robertson et al., 1982], we believe that this additional occurrence of basement rock at a depth that is shallow compared to those found on other profiles on the Ross Ice Shelf (e.g., 2 km at the Ross Ice Shelf Geophysical and Glaciological Survey, station J9 (Figure 1) in the adjacent trough [Robertson et al., 1982]) is further evidence for structural control of the linear sea-bottom topographic features [Robertson et al., 1982].

Siple Coast Profile

At station UPB, the coverage, more or less along the axis of the ice stream, comprised a 20-km-long reversed profile between recording points called B42 and B20.5 (solid circles in Figure 1), plus two extended shots, one recorded at B42 and set off 28 km to the grid southeast (cross in Figure 1), and the other recorded at

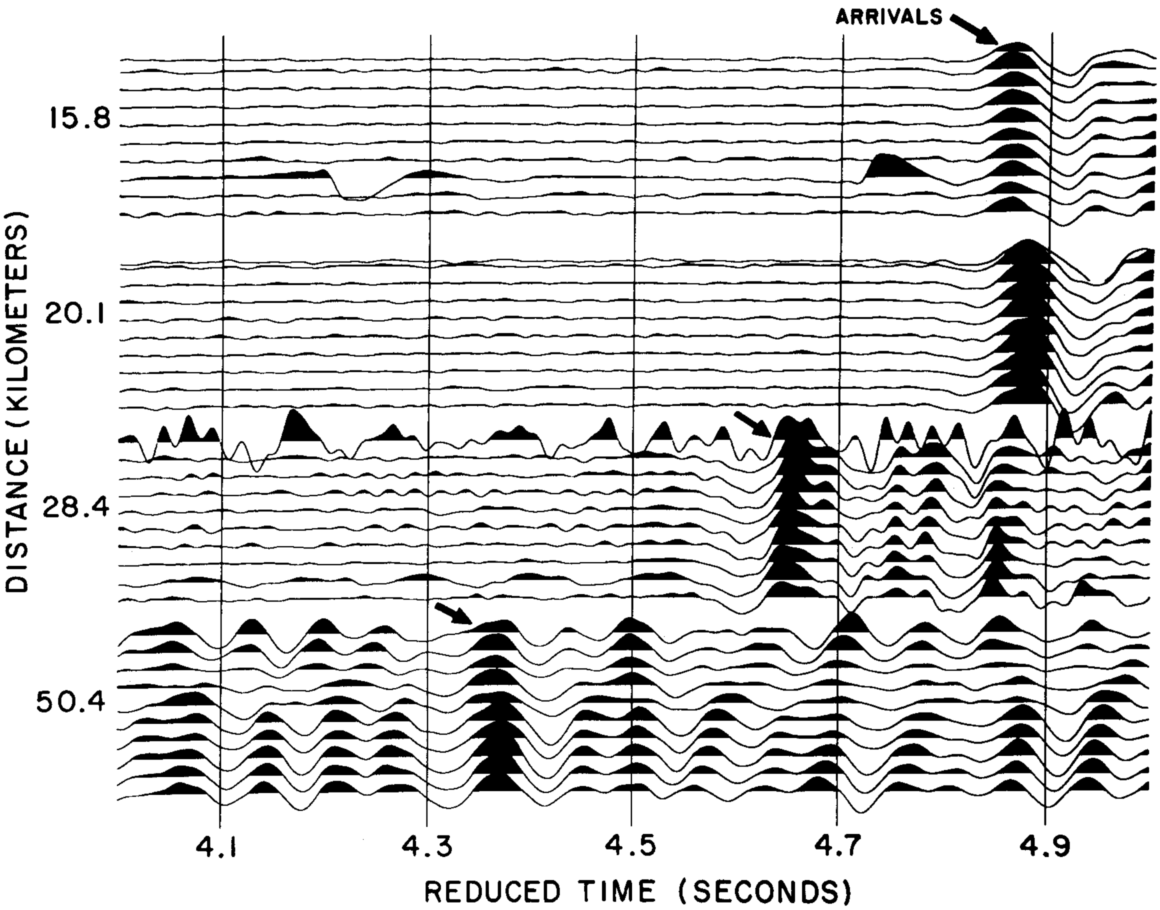

Fig. 6. Reduced-time record section from the UPB profile. The 16-km, 20-km, and 28-km records were recorded at B42; the 50-km record was recorded at B20.5. The forward and reverse reducing velocities were 5.80 km s^{-1} and 5.05 km s^{-1}, respectively, and the standard distance used was 20.2 km. The head wave from the first refractor occurs at corrected times of 4.85, 4.85, 4.65, and 4.35 s.

B20.5 and fired 50 km to the grid southeast (open circle in Figure 1). The records from these two shots are both included in Figure 6, the other records from shots being set off grid southeast of the recording point.

Two reduced-time record sections (Figures 5 and 6) were prepared by using the same pair of reducing velocities (v_f on one leg equals v_r on the other). The reversed profile included shots at 6, 11, 16, and 20 km recorded at B20.5 (Figure 5) and at 16 and 20 km recorded at B42 (top two records in Figure 6). Five of the six records of the reversed profile show a strong coherent arrival with excellent alignment, which indicates that the dip of the refractor is steady across the profile; the calculated true velocity is 5.4 ± 0.2 km s^{-1}.

To calculate depths, we assume that the layer between the ice and the refractor is composed of lithified sediments, and that the corresponding wave velocity is 4 km s^{-1}, as is commonly indicated elsewhere in West Antarctica [Bentley and Clough, 1972]. Then the depth of the 5.4 km s^{-1} layer under B42 is 2.4 km and the dip is 4° to the grid southeast (Figure 7).

The shot 50 km southeast of the spread (B20.5) yielded a first arrival at 10.2 s (Figure 8) that has an apparent velocity of 4.6 km s^{-1}, which is lower than the apparent velocity of the first arrivals on all the closer shots. (Note that the total travel time constrains the average speed along the ray path beneath the ice to greater than 5 km s^{-1}). The strong arrival with an apparent velocity of 5.8 km s^{-1} at around 11 s in Figure 8 can also be seen at a reduced time of 4.35 s in Figure 6. Its apparent velocity is close to that for the head wave from the 5.4 km s^{-1} layer, but it arrives 0.5 s earlier than predicted by extension of the single-planar-layer model derived from the reversed profile described above to the southeast. The first arrival on the 28-km shot recorded at B42 also arrives earlier (at reduced time of 4.65 s on Figure 6) than expected for a head wave from the 5.4 km s^{-1} layer. We interpret all these occurrences as being due to a decrease in basement

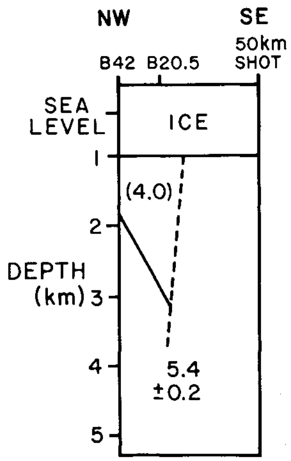

Fig. 7. Upper-crustal structure deduced from the UPB refraction profile. The numbers in the column are P-wave velocities in kilometers per second. Parentheses denote an assumed value. The dashed line is a possible fault discussed in the text; see also Figure 9. NW and SE are grid directions (cf. Figure 1).

depth southeast of the UPB camp, perhaps caused by faulting. The 4.6 km s^{-1} arrival was successfully modeled by ray tracing as a refraction through an interface with an apparent dip of 7° (Figure 9). This suggests that there is a fault located somewhere between B20.5 and the shot point for the record at 28 km. A fault throw of about 2.2 km is required to match observed travel times with travel times obtained from ray tracing. The model of Figure 9 is also consistent with the observed early arrivals from the 5.4 km s^{-1} layer (apparent velocity 5.8 km s^{-1}) recorded from the 50-km shot.

Since the profile was shot nearly parallel to the axis of the ice stream, the 7° dip represents the component of dip normal to that axis. Because the subglacial topography [Albert and Bentley, 1986; map reproduced in Bentley and Ježek, 1981] shows a grain continuing inland from the Ross Ice Shelf that is almost parallel to the ice stream, we might expect basement structures to trend in the same direction. The 7° apparent dip could, therefore, result from a steep fault striking nearly parallel to the seismic profile. (The limiting case would be a vertical fault with a strike 7° off parallel with the profile). The facts that the low-apparent-velocity arrival does

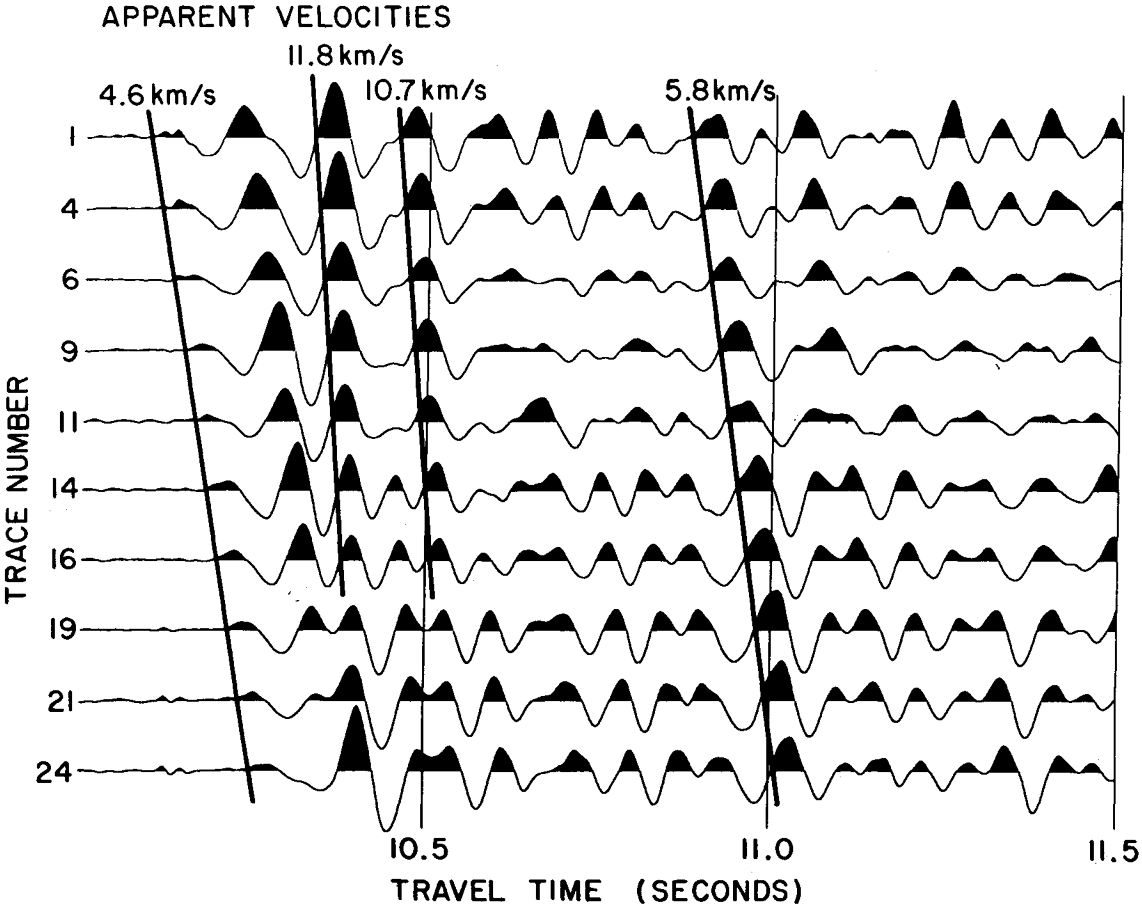

Fig. 8. Seismogram from the 50-km shot at UPB. Note the compressed time scale. Lines denote refracted arrivals with apparent velocities of 4.6 km s^{-1} and 5.8 km s^{-1}, and reflections with apparent velocities of 10.7 km s^{-1} and 11.8 km s^{-1}.

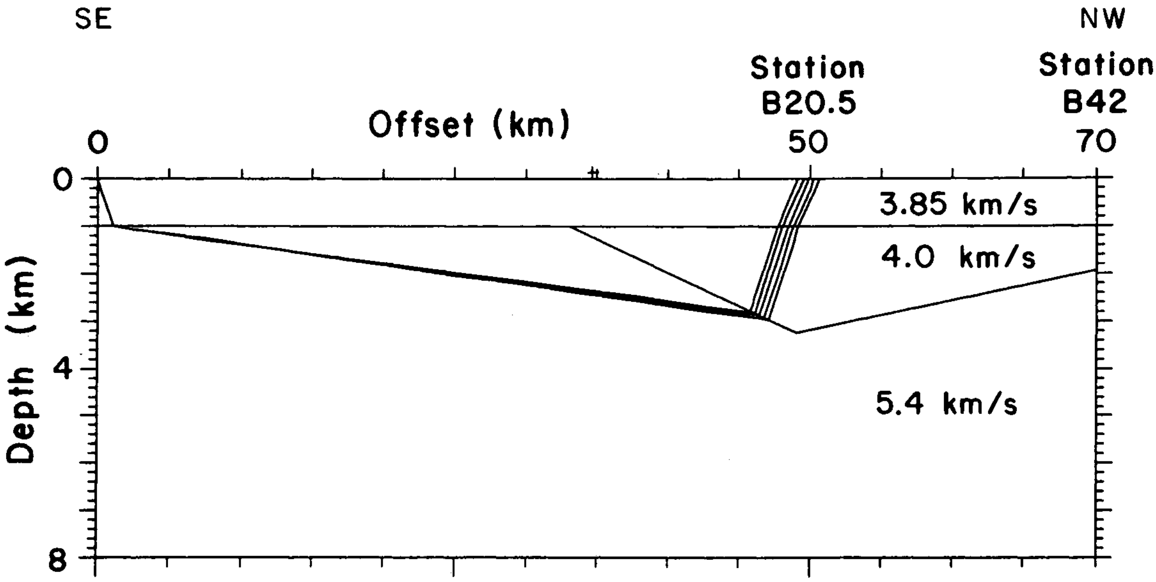

Fig. 9. Crustal model derived to produce an arrival with an apparent velocity of 4.6 km s^{-1} at 10.1 s from the 50-km shot, recorded at B20.5. Refraction through a fault face with an apparent dip of 7° is indicated. SE and NW are grid directions.

not occur on the 28-km shot, which is laterally offset by about 1.9 km, and that the first arrival (from the 5.4 km s^{-1} layer) occurs earlier than expected, are consistent with such a model.

The two arrivals recorded on the 50-km shot at 10.4 and 10.5 s (Figure 8) have apparent velocities, 11.8 km s^{-1} and 10.7 km s^{-1}, respectively, characteristic of reflection events. These reflections cannot be from irregularities in the ice rock boundary because the travel time is less than the travel time of the direct wave in the ice. In fact, when the velocity model derived from the reversed profile is used and a velocity of 6.5 km s^{-1} at depths greater than 6 km is assumed, the reflection travel times indicate that the reflector must be at least 8 km, but not more than 20 km, deep and must lie within 10 km laterally. The reflector must be quite large (the radius of the first Fresnel zone is ~2 km) in order to result in the large reflection amplitude. The arrival could be a reflection from Moho at 20 km, but the large dip (>18°) indicated by the apparent velocities makes this identification questionable. Because we observe these reflections clearly on only one record, it is impossible for us to delineate their source any more precisely.

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