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Indication of a dilatant bed near Downstream B Camp, Ice Stream B, Antarctica

S. R. Atre and C. R. Bentley
Geophysical and Polar Research Center, University of Wisconsin–Madison, Madison, WI 53706, U.S.A.

ABSTRACT. Phases of seismic P-wave reflections from the bed of Ice Stream B at a site on its ice plain have been examined. The survey comprised a 36 km line at a shallow angle (18°) to ice movement and four 3.6 km cross lines. Reversed-phase and unreversed-phase reflections each characterize about half the bed. The corresponding zones can be correlated in stripes quasi-parallel to ice movement. We take this as support for a model previously developed that relates the zones to different types of subglacial sediment dragged along by the ice. There is also evidence for patches of pooled water.

INTRODUCTION

The University of Wisconsin–Madison has conducted seismic experiments during four field seasons on Ice Streams B and C, West Antarctica. The objective of these experiments was to investigate the basal conditions beneath these ice streams and how they might affect their dynamic behavior. We have already reported on the characteristics of the ice/bed interface beneath stations Upstream B (UpB) and Upstream C, centrally located on the two ice streams, as revealed by the phases of seismic P-wave reflections (Atre and Bentley, 1994). Here, we report on a similar investigation at Downstream B station (DnB) on the ice plain of Ice Stream B (Fig. 1).

FIELD WORK

During the 1987–88 field season at DnB, high-resolution P-wave reflection data were collected by S. T. Rooney along a 36 km profile nearly parallel to the direction of ice movement (the Z line) and four 3.6 km transverse profiles (the V, W, X and Y lines) (Fig. 2). For all experiments, the receiving spread was 690 m long with 24 geophones spaced 30 m apart. Sources were 0.15 kg ($\frac{1}{3}$ lb) or 0.45 kg (1 lb) explosive charges detonated in boreholes 14–18 m deep. Amplifiers had a flat frequency response without phase shift within the frequency band employed (50–450 Hz), which extended well beyond the signal frequencies (200–300 Hz). Detailed descriptions of the data collection and reduction can be found in Blankenship and others (1987), Rooney and others (1987), Rooney (1988) and Atre (1990). For this study of phases, we have not carried out any stacking, move-out corrections or any other processing that could conceivably distort the phase information. Instead, we rely on visual inspection of individual seismograms. All the seismograms presented here are displayed with the same gain and all were recorded from 0.45 kg charges.

REFLECTION PHASES

For a detailed discussion of acoustic impedance (the product of density and P-wave speed), the condition for P-wave phase reversal, the process of identifying the phase, and the justification for using real (rather than complex) impedances in both ice and bed, see Atre and

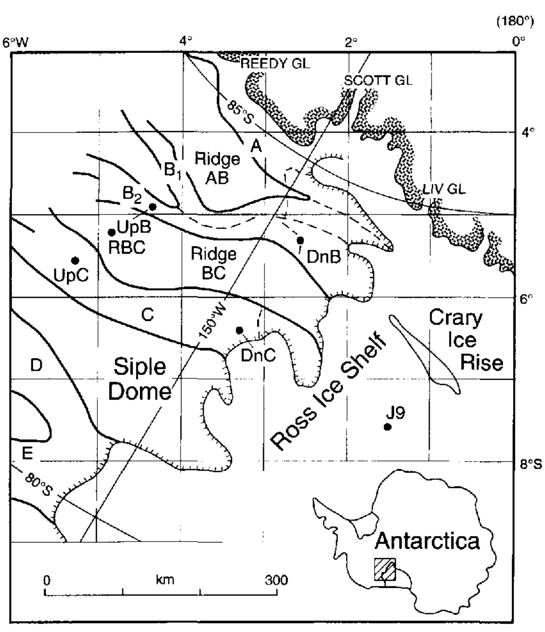

Fig. 1. Map of the Siple Coast ice streams (shaded) showing the location of stations Downstream B (DnB), Upstream B (UpB) and Upstream C (UpC).

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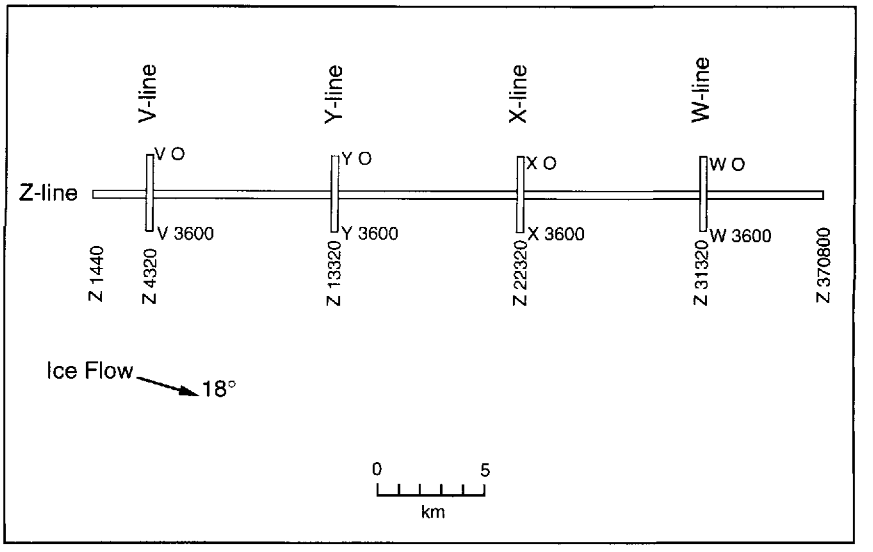

Fig. 2. Diagram of the seismic survey lines at DnB. The arrow shows the direction of ice movement.

Bentley (1993). In brief, it turns out that the acoustic impedances in the ice and the dilated bed are nearly the same. Since the condition for a phase reversal is that the impedance in the bed is less than in the ice, small variations in physical characteristics of the bed can make the difference between a phase reversal and no phase reversal in a reflection.

We show here some seismograms illustrating various characteristics of the reflection. On these seismograms, each horizontal line shows the ground motion detected by one of a linear array of seismometers. Upward deflection of the trace is indicative of upward movement of the ground. Time increases from left to right. The first signal to appear is the direct P wave through the ice; the second strong signal, a few hundred milliseconds later, is the reflection from the bed. The seismogram in Figure 3 provides a typical example of the reversed-phase relationship between direct and reflected P-wave arrivals that is clearly observed, with high signal-to-noise ratio, on most of the records. The reversed phase implies that the acoustic impedance of the bed is less than that of the ice ("low-impedance bed"). Another reflection that can be

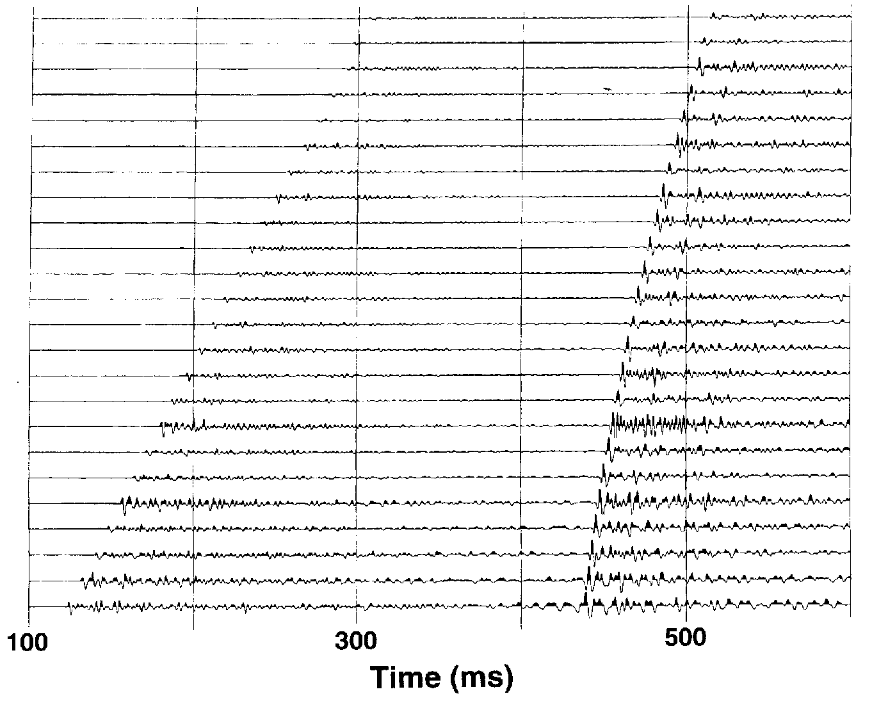

Fig. 3. Seismogram showing reflections at Z20160. Shot-detector offsets: 360–1050 m. On this and succeeding seismograms, each horizontal line shows the ground motion detected by one of a linear array of seismometers. Upward deflection of the trace is indicative of upward movement of the ground. Time increases from left to right. The first signal to appear is the direct P wave through the ice; the second strong signal, a few hundred milliseconds later, is the reflection from the bed. Note in this case that the first motion in the direct P wave is upward, whereas that in the reflection is downward, i.e. reversed in phase.

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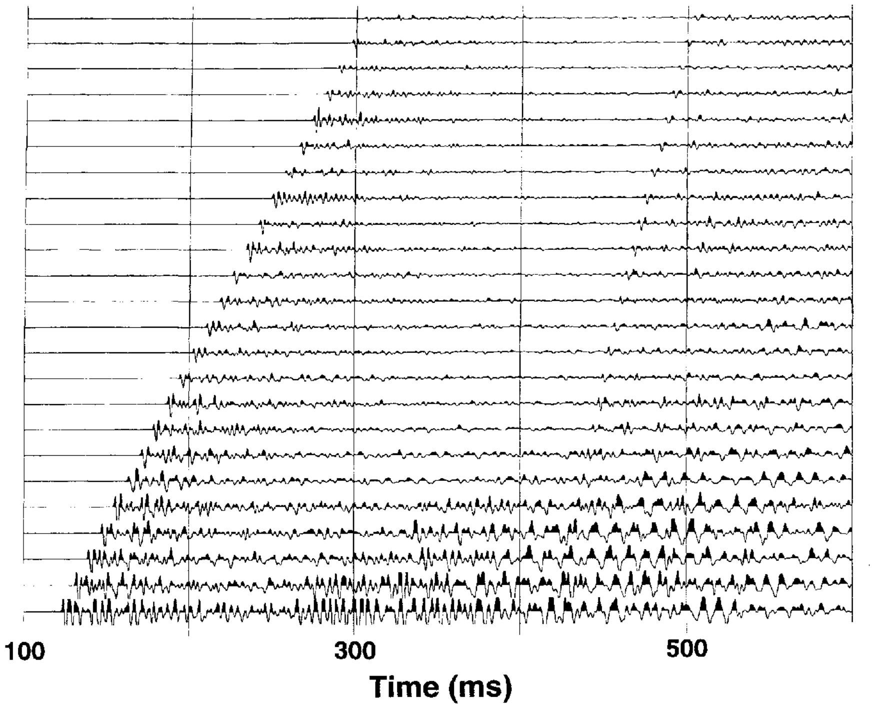

Fig. 4. Seismogram showing reflections at Z33120. Shot-detector offsets: 360–1050 m. Here, the first motion is upward in both the direct wave and the reflection, i.e. the phase is unreversed.

seen in Figure 3, 20 ms after the basal reflection, is the "ghost" of the basal reflection, produced by the wave first reflected off the ice surface above the shot. It is clear on most traces that the ghost, which undergoes a phase reversal at the free surface, is unreversed in phase. This means that it has been reversed twice, which again indicates phase reversal at the bed.

An example of an unreversed-phase basal reflection (with reversed-phase ghost) is shown in Figure 4. This indicates a "high-impedance" bed, which characterizes about half of the area surveyed.

REFLECTION AMPLITUDES

Since we do not have an absolute calibration of reflection amplitudes, we should like to use amplitude ratios relative to the direct P wave. But the direct P wave, unfortunately, is a poor standard to use at DnB, since it is often drastically attenuated by interference from crevasses. This can cause small amplitudes (Fig. 3), a large irregularity from trace to trace (Fig. 3), and/or an abrupt diminution in amplitude beyond a particular distance (Figs 5a and 6). Consequently, amplitude ratios are quantitatively unreliable. However, it is still possible to make some general observations about reflection amplitudes, because they vary so greatly compared with variations that are likely to occur from other causes considering the uniformity of charge size, shot-hole depth and gain.

OBSERVATIONS

There are several observations that we can make about the characteristics of the reflections. We have chosen several sample seismograms to illustrate our points.

1. The entire survey is characterized by frequent spatial switches between a low-impedance bed and a high-impedance bed (Fig. 7). Each bed type covers about half of the region.
2. There is agreement in phase on records on the Z line and the transverse lines near their crossing points (Fig. 5).
3. Reflectivity varies more rapidly across flow than parallel to flow. Half the records from the transverse profiles show marked changes in amplitude across the spread, compared with only one-tenth of those on the Z line. This is true of both reversed-phase and unreversed-phase reflections.
4. The reversed-phase and unreversed-phase zones can be correlated between the Z line and the transverse lines. Two different correlations are possible; one of those, which we prefer, yields stripes of reversed and unreversed phase that are quasi-parallel to flow (Fig. 7). (The other correlation would yield stripes at about 60° to flow; such an orientation would be difficult to explain.)
5. The unreversed-phase reflections are fairly weak, with reflection-to-direct-P-wave ratios of 1 or less (Fig. 4). By contrast, the reversed-phase echoes vary widely in strength, from undetectable (Fig. 6) to several times as large as direct P wave (Fig. 5). In several cases, a large change takes place within a single record (Fig. 6), although we have not found a clear switch between reversed and unreversed in a single record.

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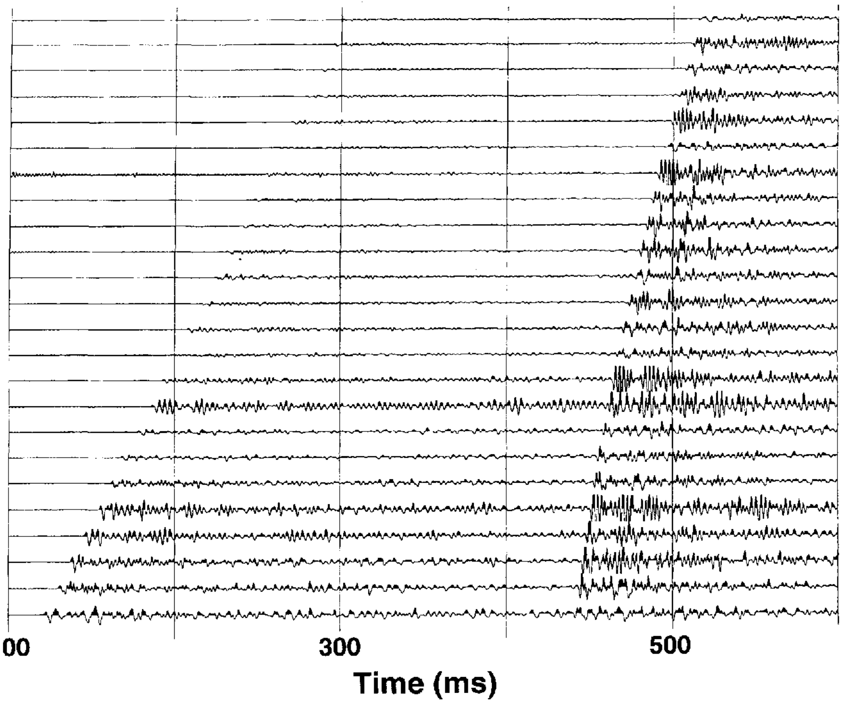

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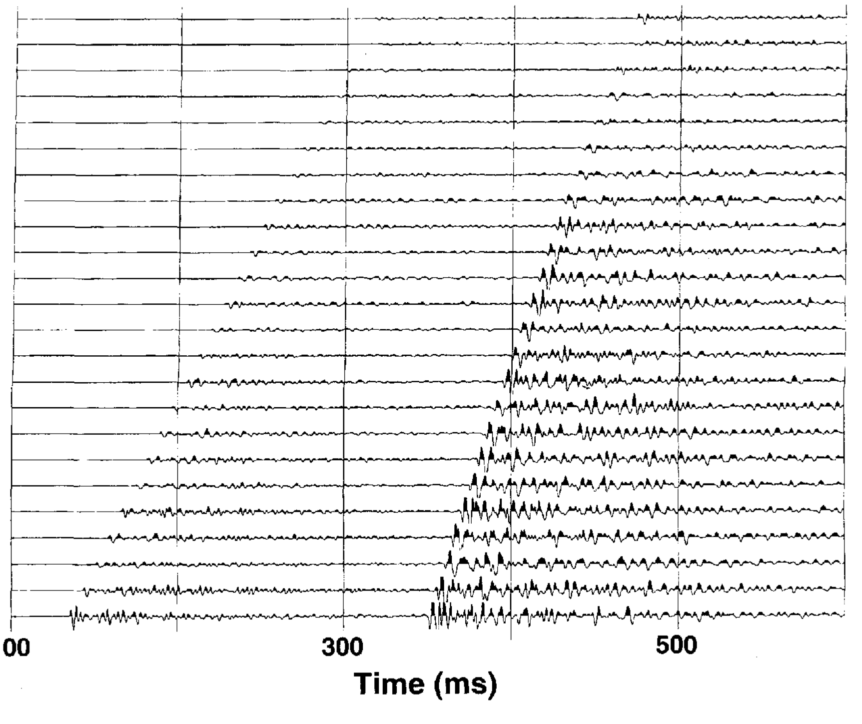

b

Fig. 5. Seismograms from shots at the intersection of the V and Z lines (V1800 and Z4320). a. Recording along the Z line. Shot-detector offsets: 360–1050 m. b. Recording along the V line. Shot-detector offsets: 1080–1770 m.

DISCUSSION

At UpB and UpC, the principal profile lines were transverse to the direction of ice movement ("flow"). We concluded that changes from "low impedance" to "high impedance" probably arose from changes in the nature of the sedimentary component of the subglacial dilated till (Atre and Bentley, 1993). That would imply that the reflection phase should be more consistent from record to record along the ice stream than across it, because sediments of the same type should be dragged into stripes parallel to flow by the ice-induced deformation of the till. Evidence from the secondary lines at UpB and UpC, which ran parallel to flow, supported this idea but the lines were too short to produce a convincing test. Here, the long line is at a small angle (18°) to flow and the observations do indeed support the model (observations 1–4).

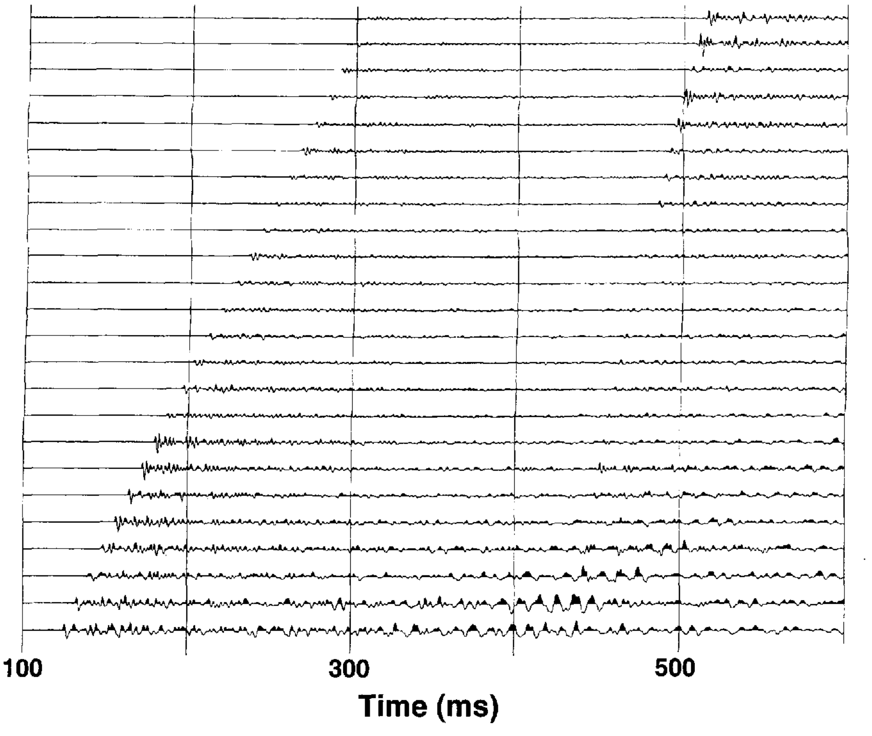

Fig. 6. Seismogram showing reflections at Z23400. Shot-detector offsets: 360 1050 m. Note that the reflection virtually disappears on some traces.

Our previously developed model for unreversed phases at UpB also implied that they would necessarily be fairly weak, because the high porosity of the bed, ~0.40 (Blankenship and others, 1987; Kamb and Engelhardt, 1991), was inconsistent with an acoustic impedance in the bed much larger than that in the ice (Fig. 8). That implication is borne out here (observation 5). On the other hand, there would be no such limitation for reversed-phase reflections, because there is no necessary limit on the proportion of water present at the bed. In fact, we believe it likely the stronger reflections (observation 5) arise from pooled water under the ice. As the acoustic impedance of water is only about 1.4×10^6 ($kg\,m^{-2}\,s^{-1}$), less than half that of ice, water at the bed could easily produce an acoustic-impedance contrast with the ice that is an order of magnitude larger than the contrast between ice and till. (The acoustic impedance would depend upon the thickness of the water layer.) The occurrence of free water beneath the ice on the ice plain would not be surprising (Alley and others, 1987).

CONCLUSION

Seismic reflection profiling on the ice plain of Ice Stream B reveals an ice–bed interface that varies laterally in

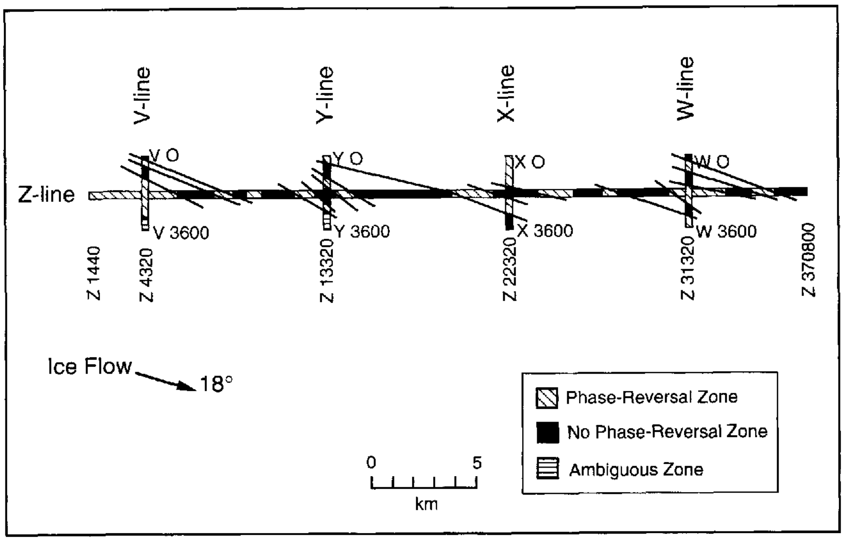

Fig. 7. Diagram of the seismic survey lines at DnB showing the reversed-phase and unreversed-phase zones. Short straight-line segments are drawn to show our preferred correlations between zones. The arrow shows the direction of ice movement.

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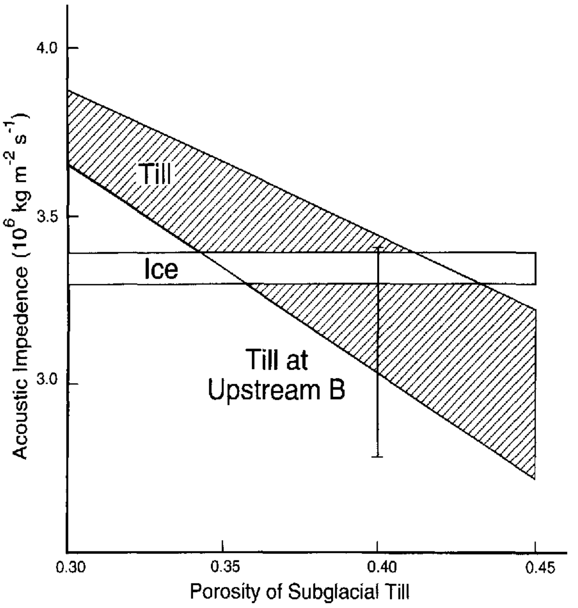

Fig. 8. Acoustic impedance versus porosity for ice and till. The vertical line shows the range of possible values at UpB. (From Atre and Bentley, 1993.)

acoustic ratio between greater than 1 and less than 1, just as found before beneath the trunks of Ice Streams B and C. A previously developed model that explains the variability in terms of lateral changes in the nature of the subglacial deforming till is supported by the observations at Downstream B. In addition, there is good evidence of pooled water beneath the ice in this boundary region between the ice stream and the ice shelf.

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