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THE RELATIONSHIP OF ULTRASONIC VELOCITIES TO *c*-AXIS FABRICS AND RELAXATION CHARACTERISTICS OF ICE CORES FROM BYRD STATION, ANTARCTICA

By A. J. Gow

(U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755, U.S.A.)

and H. Kohnen

(Institut für Geophysik, Gievenbecker Weg 61, 44 Münster/Westf., West Germany)

Abstract. Deep cores from Byrd Station were used to calibrate an ultrasonic technique of evaluating crystal anisotropy in the Antarctic ice sheet. Velocities measured parallel ($V_p\downarrow$) and perpendicular ($V_p\rightarrow$) to the vertical axis of the cores yielded data in excellent agreement with the observed *c*-axis fabric profile and with the *in-situ* P-wave velocity profile measured parallel to the bore-hole axis by Bentley. Velocity differences ΔV ($\Delta V = V_p\downarrow - V_p\rightarrow$) in excess of 140 m s^{-1} for cores from below 1 300 m attest to the tight clustering of *c*-axes of crystals about the vertical, especially in the zone 1 300–1 800 m. A small but significant decline in $V_p\downarrow$ with ageing of the core, as deduced from Bentley's down-hole data, is attributed to the formation of oriented cracks that occur in the ice cores as they relax from environmental stresses. This investigation of cores from the 2 164 m thick ice sheet at Byrd Station establishes the ultrasonic technique as a viable method of monitoring relaxation characteristics of drilled cores and for determining the gross trends of *c*-axis orientation in ice sheets. The Byrd Station data, in conjunction with Barkov's investigation of deep cores from Vostok, East Antarctica, also indicate that crystal anisotropy in the Antarctic ice sheet is dominated by a clustering of *c*-axes about a vertical symmetry axis.

Résumé. *Relation entre les vitesses des ultra-sons avec la disposition cristalline des axes-c et les caractéristiques de la relaxation des carottes de glace issues de la station Byrd, Antarctique.* On a utilisé des carottes de glace profonde issues de la station Byrd pour essayer une technique ultra-sonique d'estimation de l'anisotropie des cristaux dans la calotte glaciaire antarctique. Les vitesses mesurées parallèles ($V_p\downarrow$) et perpendiculaires ($V_p\rightarrow$) à l'axe vertical des carottes ont donné des résultats en excellent accord avec les profils de disposition cristalline des axes-*c* et avec le profil de vitesse *in situ* des ondes P mesuré parallèlement à l'axe du trou de forage par Bentley. Des différences de vitesses ΔV ($\Delta V = V_p\downarrow - V_p\rightarrow$) dépassant 140 m s^{-1} pour des échantillons provenant d'en dessous de 1 300 m confirment le groupement serré des axes-*c* des cristaux autour de la verticale, spécialement dans la zone des 1 300–1 800 m. Une légère mais significative diminution de $V_p\downarrow$ avec l'âge de l'échantillon, déduite des résultats de forages de Bentley est attribuée à la formation de fissures orientées dans les échantillons de glace lorsqu'elles échappent aux contraintes de leur milieu d'origine. Cette exploration de carottes provenant d'une calotte de 2 164 m d'épaisseur à la station Byrd montre que la technique des ultra-sons est une méthode convenable pour repérer les caractéristiques de la relaxation des carottes de forage et pour déterminer les tendances principales de l'orientation des axes-*c* dans les calottes glaciaires. Les résultats obtenus à la station Byrd, comparés avec les recherches de Barkov sur des carottes profondes provenant de Vostok, Est Antarctique, indiquent également que l'anisotropie dans la structure de la glace de la calotte antarctique est diminuée par un regroupement des axes-*c* autour d'un axe de symétrie vertical.

Zusammenfassung. *Die Beziehung von Ultraschallgeschwindigkeiten zum c-Achsen-Gefüge und Relaxationscharakteristiken von Eiskernen der Byrd-Station, Antarktis.* Für die Kalibrierung einer Ultraschalltechnik zur Feststellung der Kristall-Anisotropie im antarktischen Eisschild wurden tiefreichende Bohrkerne von der Byrd-Station herangezogen. Geschwindigkeitsmessungen parallel ($V_p\downarrow$) und senkrecht ($V_p\rightarrow$) zur Längsachse der Kerne lieferten Daten, die ausgezeichnet mit dem beobachteten Profil des *c*-Achsen-Gefüges und mit dem Profil der Geschwindigkeit der P-Welle, *in situ* parallel zur Bohrlochachse gemessen von Bentley, übereinstimmen. Geschwindigkeitsunterschiede ΔV ($\Delta V = V_p\downarrow - V_p\rightarrow$) von mehr als 140 m s^{-1} für Kerne aus einer Tiefe über 1 300 m bestätigen die dichte Häufung der *c*-Achsen der Kristalle um das Lot, besonders in der Zone von 1 300 m bis 1 800 m. Eine kleine aber signifikante Abnahme von $V_p\downarrow$ mit der Alterung des Kerns, wie sie gegenüber Bentley's Bohrlochdaten festzustellen ist, wird der Bildung orientierter Risse zugeschrieben, die in den Eiskernen bei der Entspannung vom Umgebungsdruck auftreten. Diese Untersuchung von Kernen aus dem 2 164 m dicken Eisschild an der Byrd-Station erweist die Ultraschalltechnik als gangbare Methode zur Ermittlung der Relaxationscharakteristiken von Bohrkernen und zur Bestimmung der überschlägigen Tendenz der *c*-Achsen-Orientierung in Eisschilden. Die Daten an der Byrd-Station zeigen, zusammen mit Barkov's Untersuchung tiefreichender Bohrkerne von Vostok, Ost-Antarktis, ausserdem, dass Kristall-Anisotropie im antarktischen Eisschild in erster Linie auf eine Häufung der *c*-Achsen um eine vertikale Symmetrieachse zurückzuführen ist.

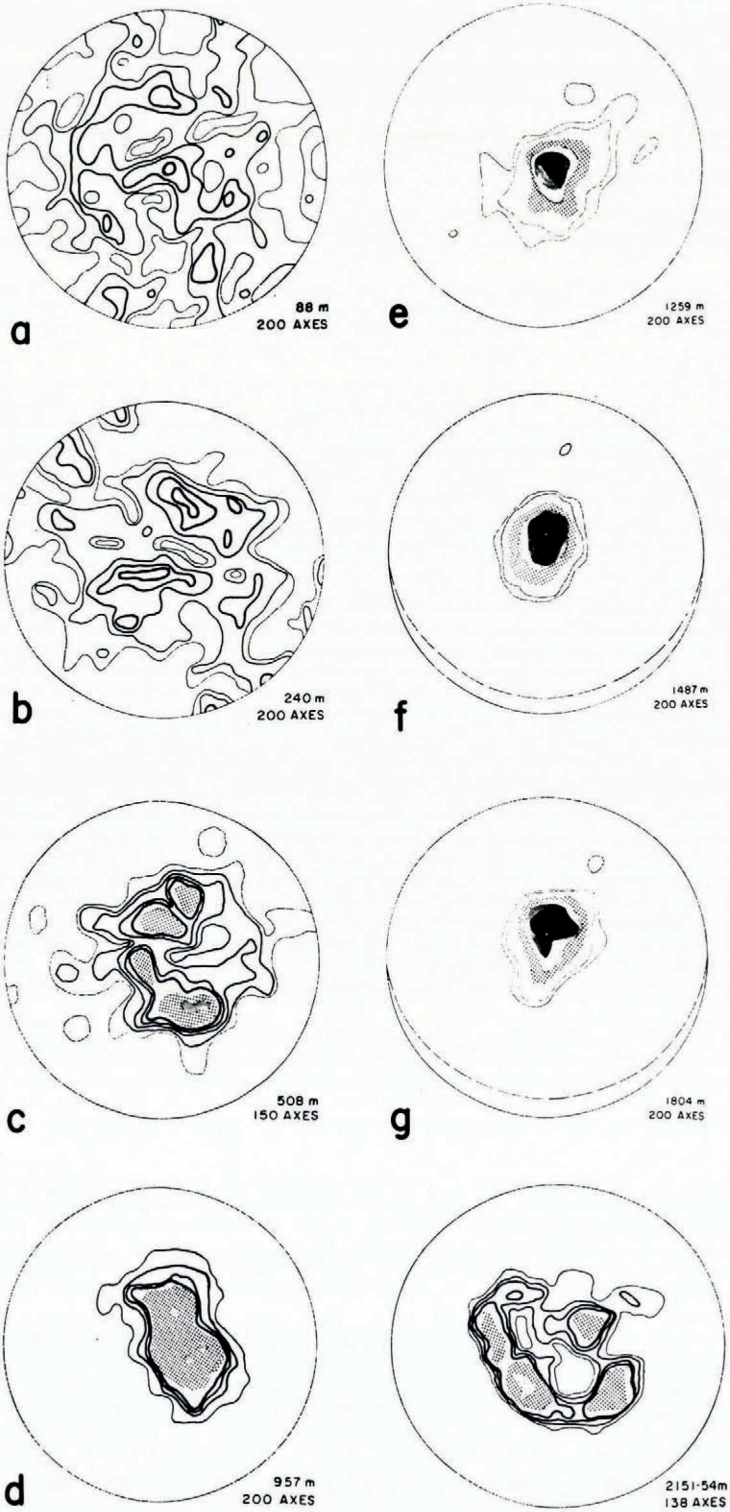

Fig. 1.

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Introduction

The importance of crystal anisotropy (oriented crystal structure) in determining the rheological behavior of polar ice sheets can no longer be ignored, especially in the light of recent observations of widespread crystal anisotropy in West Antarctica. This anisotropic state of the ice has been established both on the basis of direct examination of *c*-axis fabrics in ice cores from the 2 164 m deep drill hole at Byrd Station and from seismic records. Fabric investigations of the Byrd Station cores by Gow and Williamson (1976) show that oriented crystal structure, involved principally with a clustering of crystallographic *c*-axes about a single (vertical) axis of symmetry, certainly exists to within 400 m of the surface of the ice sheet and thus represents about 80% of the ice column in the immediate vicinity of the drill hole. Major features of this fabric profile are illustrated in Figure 1. Maximum vertical orientation of crystal axes occurs in a zone from 1 200 to 1 800 m depth. Below about 1 810 m this very strong axial orientation of crystals gives way to a fabric composed of several discrete maxima generally arranged in ring-like fashion about the vertical. Sonic logging of the drill hole by Bentley (1972) has also confirmed the existence of a strong vertical alignment of *c*-axes and Bentley (1971), on the basis of seismic records, has also demonstrated the existence of highly anisotropic structure throughout much of the West Antarctic ice sheet. Such structural anisotropy could involve as much as 90% of the ice column at some locations.

Fabric studies (Gow and Williamson, 1976), in conjunction with other extensive investigations of the physical properties of the Byrd Station ice cores (Gow, 1970, 1971; Gow and Williamson, 1975; Gow and others, 1968), make them especially suitable for "calibrating" certain geophysical tools that might usefully be applied to investigations of crystal anisotropy in ice sheets. One such technique involves ultrasonic logging, a technique first applied to Greenland and Antarctic ice cores by Bennett (1972). More recent studies include measurements by Kohnen and Langway (1977) on ice cores from Milcent and Crête, Greenland, and measurements on cores from the Ross Ice Shelf by Kohnen and Bentley (1977).

In this report we wish to discuss some results of recent measurements of ultrasonic velocities performed on ice cores from Byrd Station. Sonic logging of these cores, in a sense, amplifies and extends the original bore-hole logging of Bentley (1972), but with the notable difference that Bentley's measurements were restricted to P-wave-velocity determinations along the bore-hole axis, whereas our measurements were made in the diametral direction ($V_{\text{p}}\rightarrow$) as well as along the vertical core axis ($V_{\text{p}}\downarrow$), the axis corresponding to the bore-hole axis. This dual velocity measurement permits immediate evaluation of the velocity difference (ΔV), a very important parameter whose magnitude depends entirely on the orientation of crystals in the ice core.* Our research served two principal objectives, namely, determination of the relationship between ultrasonic velocities and the *c*-axis fabrics, and evaluation of the relaxation characteristics of the drilled cores, especially the directional aspects of relaxation.

Experimental techniques

A Krautkrämer USIP II System, utilizing barium titanate transducers, was used for measuring the transverse and axial velocities of cores ranging in length from 70 to 15 mm. The equipment was operated at a frequency of 2 MHz to ensure an optimal relation between time resolution, sample dimensions, and energy attenuation. All measurements were performed

* At any given temperature, the P-wave velocity in the ice will depend on the density of the ice as well as the *c*-axis fabric. Since density is a scalar property, the magnitude of ΔV should be influenced only by the ice-crystal fabric.

Fig. 1 (left). c-axis fabrics, Byrd Station, Antarctica. Data from horizontal core sections. Contour range from ½% to 5% per 1% area for fabrics near top of the ice column to 25% per 1% area in deep ice fabrics. Symbols a–g are keyed to Figure 3.

in a cold room operating at a nominal temperature of −10°C. Sample dimensions were measured with a micrometer to ±0.1 mm. Errors in the velocity measurement are estimated not to exceed ±20 m s⁻¹. Core densities were measured to an accuracy of 0.000 3 Mg m⁻³ by hydrostatic weighing in iso-octane. Most of the cores examined ultrasonically were sampled earlier for thin-section fabric studies. Re-examination of these thin sections together with observations on several new thin sections of the same cores revealed no detectable changes in either the textural properties or the *c*-axis orientations of the ice.

Results and discussion

Profiles obtained from measurements of ultrasonic velocity on Byrd Station ice cores are presented in Figure 2. Both sets of P-wave velocity measurements ($V_p\downarrow$ and $V_p\rightarrow$) have been corrected to *in-situ* temperatures and densities to facilitate comparisons with Bentley's (1972) down-hole velocity log. Axial ($V_p\downarrow$) velocities show very good agreement with Bentley's velocity profile down to about 1 200 m before beginning to diverge appreciably. The apparent reduction in $V_p\downarrow$ of the nine-year-old cores is real and can be attributed substantially to the existence of cleavage cracks that are propagated along the basal planes of ice crystals during relaxation of the cores. This propagation of cracks is concentrated in the transverse plane of cores from the zone of strong axial fabrics below 1 200 m, giving rise to a distinctive crack fabric, that causes a small but measurable reduction of velocity in the direction normal to the plane of the cracks, that is in the direction of $V_p\downarrow$. These data point up the significance of the directional nature of relaxation and the importance of oriented crystal structure in deter-

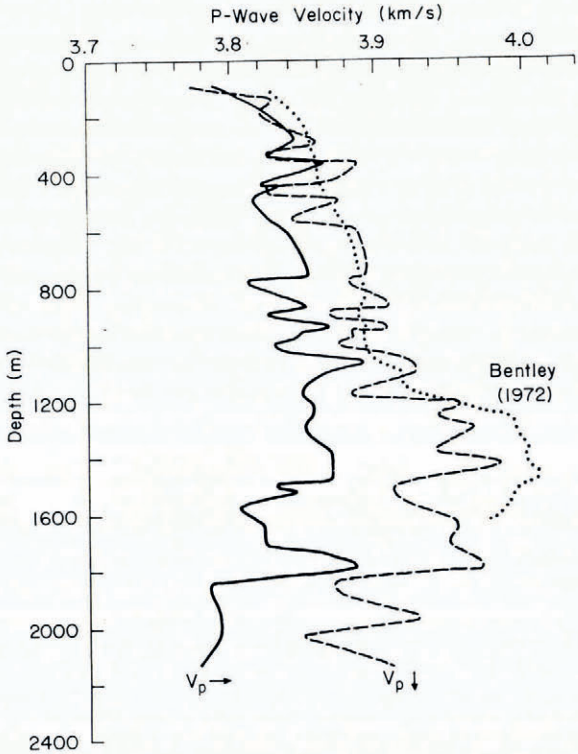

Fig. 2. Axial ($V_p\downarrow$) and diametral ($V_p\rightarrow$) ultrasonic P-wave-velocity profiles for ice cores from Byrd Station deep drill hole. Bentley (1972) velocity profile was obtained from measurements along bore-hole axis. Note that $V_p\downarrow$ is parallel to the bore-hole axis.

mining the orientation of cleavage cracks that form in cores during relaxation from environmental stresses. A similar depression of seismic velocities, normal to the plane of oriented cracks, has also been observed in rock cores even in rocks where the volume fraction of oriented cracks is only a small part of the total porosity (for example, see Anderson and others (1974)).

Figure 3 illustrates how well changes in ΔV ($V_p\downarrow - V_p\rightarrow$) can be correlated with changes in the *c*-axis fabric as defined by α, the half-apex angle of the cone containing all but the 10% most divergent *c*-axes in a given fabric. As noted above, ΔV is determined solely by the fabric, so that any significant change in the ice fabric should be reflected in a change in ΔV. In order to quantify the fabric, we selected α as the relevant parameter mainly on the assumption that the dominantly axial fabric patterns observed at Byrd Station can be reasonably approximated by conical distributions of the *c*-axes about the vertical, with α decreasing as the concentration of *c*-axes increases. The mirror-image pattern obtained with ΔV and α further establishes the strong relationship between P-wave velocity and fabric. In the zone 1 200–1 800 m, where the magnitude of α is generally less than 23°, ΔV values may exceed 140 m s^{-1} which is within 30–40 m s^{-1} of the total velocity difference for P-waves propagated parallel and perpendicular to the *c*-axis of a single crystal. This analysis was not extended below 1 800 m, mainly because of the very large size of crystal encountered in this region. Samples used for ultrasonic velocity measurements generally contained too few crystals for any satisfactory verification of the $\Delta V/\alpha$ relationship.

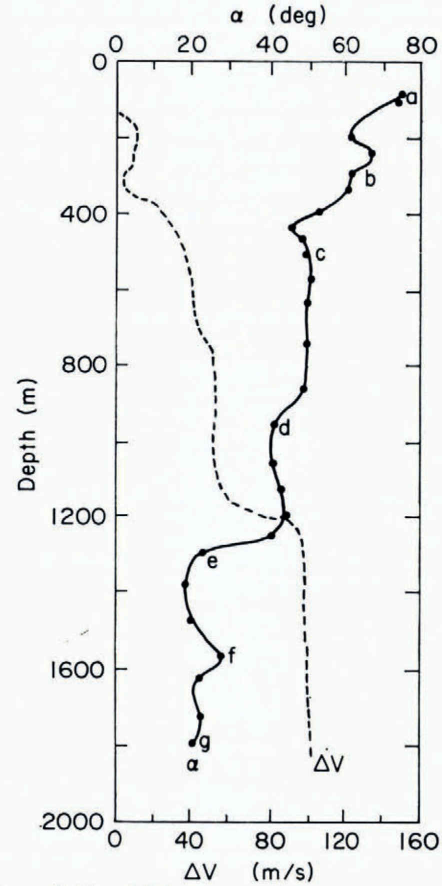

Fig. 3. Relationship of velocity difference (ΔV) and fabric parameter (α) versus ice depth at Byrd Station. See text for explanation of α. Symbols a–g refer to locations of c-axis fabric plots shown in Figure 1.

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Conclusions

Based on results obtained at Byrd Station, we would advocate that all future studies of cores from deep drill holes include measurements of ultrasonic velocities, both as a means of monitoring the relaxation characteristics of the drilled cores and for determining the gross trends of *c*-axis orientation in the ice sheet. However, these measurements must be supplemented by optical thin-section studies in order to verify (1) the exact nature of the fabric at any given depth and (2) any inclination of the fabric symmetry axis with respect to the direction of propagation of the P-wave velocity. Bentley (1971), for example, has speculated from seismic records in West Antarctica that the symmetry axis for single-pole fabrics may deviate appreciably from the vertical; at some locations the symmetry axis may even approach the horizontal. However, Barkov's (1973) orientation data from Vostok, East Antarctica, indicate that fabrics in this part of the ice sheet are also dominated by a vertical symmetry axis. The situation in Greenland cannot be ascertained because of the absence of published data on the internal structure and fabrics of the ice.

At Byrd Station, some slipping of ice along the bedrock must occur since the basal ice is at the pressure-melting point and liquid water is known to exist at the glacier bed. However, the textures and fabrics of the ice cores indicate that plastic deformation in the zone of strong single-maximum fabrics, and actual displacement of ice along horizontal shear planes situated well above bedrock, are also major contributors to the flow of the ice sheet at Byrd Station. These findings of highly anisotropic crystal structure at Byrd Station are especially significant with respect to widely held theories of ice flow that tacitly assume an isotropic condition of the ice. Indeed, the common practice of approximating the age of ice cores on the basis of arbitrary and simplistic models of ice flow, that either ignore or gloss over the anisotropic state of the ice, could lead to very serious errors in dating ice cores. If the situation demonstrated for the ice cores at Byrd Station is any guideline, then the need for comprehensive analysis of the structure and fabric of ice-sheet cores by any means available cannot be overemphasized.

REFERENCES

Anderson, D. L., *and others*. 1974. The effect of oriented cracks on seismic velocities, [by] D. L. Anderson, B. Minster, and D. Cole. *Journal of Geophysical Research*, Vol. 79, No. 26, p. 4011–15.

Barkov, N. I. 1973. Rezul'taty issledovaniya skvazhiny i ledyanogo kerna na stantsii Vostok v 1970–1972 gg. [Results of the investigation of the bore hole and ice core at the Vostok station in 1970–72]. *Materialy Glyatsiologicheskikh Issledovaniy. Khronika. Obsuzhdeniya*, Vyp. 22, p. 77–81.

Bennett, H. F. 1972. Measurements of ultrasonic wave velocities in ice cores from Greenland and Antarctica. *U.S. Cold Regions Research and Engineering Laboratory. Research Report* 237.

Bentley, C. R. 1971. Seismic anisotropy in the West Antarctic ice sheet. (*In* Crary, A. P., *ed. Antarctic snow and ice studies II*. Washington, D.C., American Geophysical Union, p. 131–77. (Antarctic Research Series, Vol. 16.))

Bentley, C. R. 1972. Seismic-wave velocities in anisotropic ice: a comparison of measured and calculated values in and around the deep drill hole at Byrd Station, Antarctica. *Journal of Geophysical Research*, Vol. 77, No. 23, p. 4406–20.

Gow, A. J. 1970. Preliminary results of studies of ice cores from the 2164 m deep drill hole, Byrd Station, Antarctica. [*Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique.*] [*International Council of Scientific Unions. Scientific Committee on Antarctic Research. International Association of Scientific Hydrology. Commission of Snow and Ice.*] *International Symposium on Antarctic Glaciological Exploration (ISAGE), Hanover, New Hampshire, U.S.A., 3–7 September 1968*, p. 78–90. [(Publication No. 86 [de l'Association Internationale d'Hydrologie Scientifique].)]

Gow, A. J. 1971. Relaxation of ice in deep drill cores from Antarctica. *Journal of Geophysical Research*, Vol. 76, No. 11, p. 2533–41.

Gow, A. J., *and* Williamson, T. C. 1975. Gas inclusions in the Antarctic ice sheet and their glaciological significance. *Journal of Geophysical Research*, Vol. 80, No. 36, p. 5101–08.

Gow, A. J., *and* Williamson, T. C. 1976. Rheological implications of the internal structure and crystal fabrics of the West Antarctic ice sheet as revealed by deep core drilling at Byrd Station. *U.S. Cold Regions Research and Engineering Laboratory. Report* 76-35.

Gow, A. J., *and others*. 1968. Antarctic ice sheet: preliminary results of first core hole to bedrock, [by] A. J. Gow, H. T. Ueda, and D. E. Garfield. *Science*, Vol. 161, No. 3845, p. 1011–13.

Kohnen, H., *and* Bentley, C. R. 1977. Ultrasonic measurement on ice cores from Ross Ice Shelf, Antarctica, drill hole. *Antarctic Journal of the United States*, Vol. 12, No. 4, p. 148–50.
Kohnen, H., *and* Langway, C. C., *jr.* 1977. Untersuchungen mit Ultraschall an Eisbohrkernen aus Zentralgrönland. *Polarforschung*, Jahrg. 47, Nr. 1–2, p. 1–10.

DISCUSSION

C. R. Bentley: Recent sonic logging experiments in a hole to bedrock in an ice cap on Ellesmere Island reveal a distinct increase in P-wave velocity in the Wisconsin ice. The velocities further suggest that the principal fabric change is shallower, and R. M. Koerner (personal communication) believes it reasonable by analogy to Devon Island to assume that there is no particular tightening of the *c*-axis concentration in the Wisconsin ice. Recognizing the difficulty in the Byrd Station core, where several changes occur in the same depth range, have you tried to correlate P-wave velocity with bubble content, bubble elongation, grain-size, dirt content, etc.? The effect of these properties on the velocities would be small compared to the fabric changes but might nonetheless be significant, and useful in interpreting sonic velocity elsewhere.

A. J. Gow: Studies of the physical properties of the Ellesmere Island ice cores have not yet been performed and, until they are, I feel any objective discussion of the velocity increase you measured down-hole would be a bit premature at this time. I might hazard a guess that when the cores are analysed you will find that fabrics are responsible for the velocity increase. Other effects, such as bubble concentrations, grain-size, dust content, etc., would be difficult to separate from fabric effects which, as you agree, over-ride all other effects with regard to velocities and velocity differences in the ice cores from Byrd Station. Dr Koerner informs me that cores from the same level that you observed your velocity increase contain no visible concentrations of debris so presumably this particular effect can be eliminated.

H. Kohnen: We looked for effects other than that caused by crystal anisotropy, which is certainly the dominating effect that over-rides all other effects. We have investigated the influence of preferred orientation of elongated bubbles in the Little America V ice cores. Our examination of several different samples in these cores indicates a minimal effect. However, an elongated, oriented bubble fabric is not fully developed in Little America ice and more data are needed to determine whether a preferred bubble fabric does exert a significant effect on P-wave velocities. At Byrd Station, crystal size is known to affect velocities and velocity differences in ice samples composed of only a few crystals. These investigations are not yet completed. As demonstrated in our paper, the effects of relaxation can lead to the formation of oriented cracks that can cause significant reduction in velocities for P-waves propagated normal to the crack fabric. In order to investigate some of these effects, it is absolutely essential to obtain velocity data on freshly-drilled ice cores.

J. W. Glen: Since the authors have used difference in velocity as the parameter of interest, I do not think we should expect grain-size as such to be important—grain shape might be if the grains were not equi-axed.

Gow: In general, I would agree with what you say. However, grain-size (and grain-shape) effects are known to be significant in ice below 1 800 m at Byrd Station. In this ice the size of crystals is so large that samples used for ultrasonic velocity measurements usually contained fewer than ten crystals, often complexly interlocked. This situation can lead to significant velocity bias.