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REPORT 79-10

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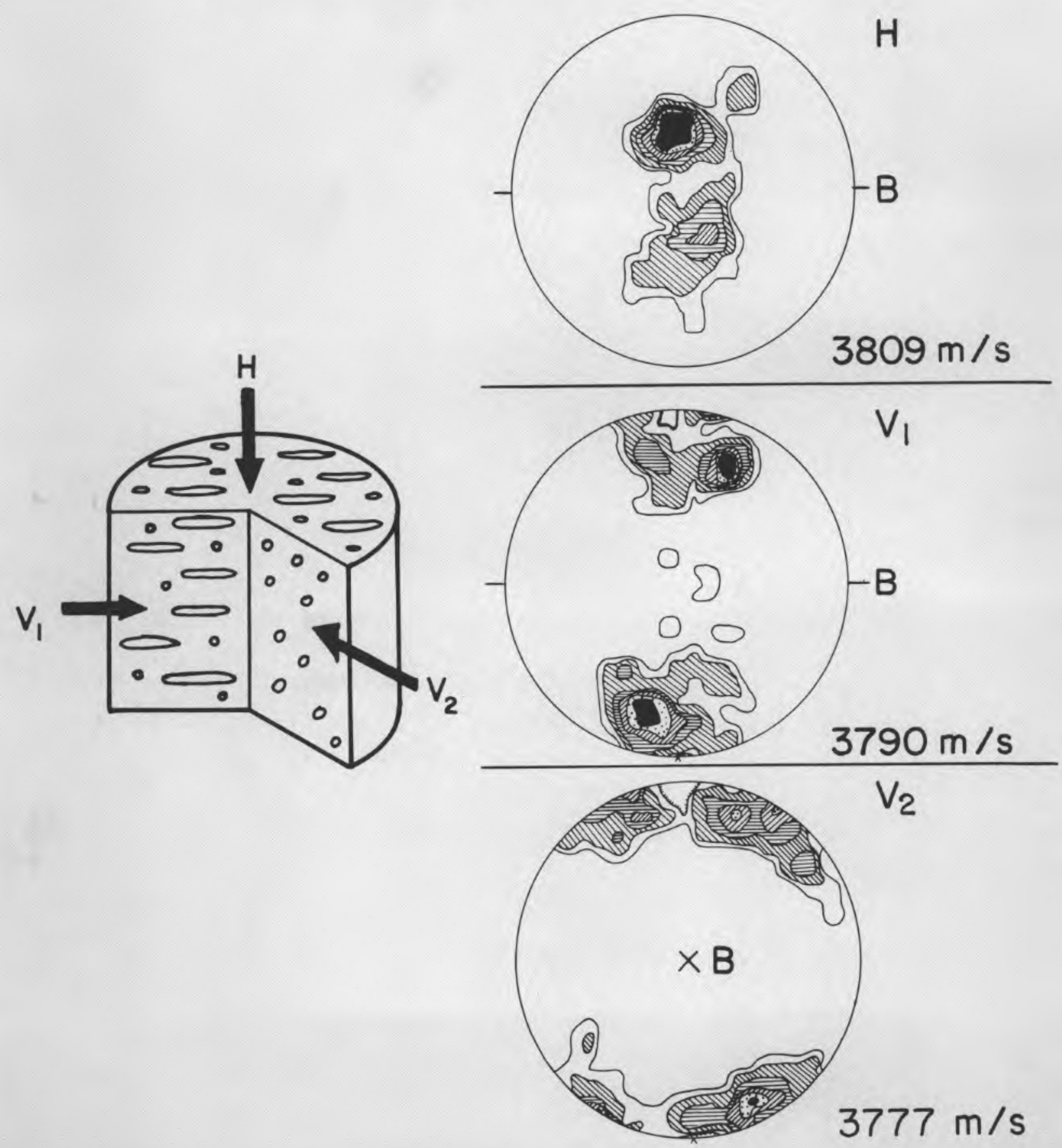

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Ultrasonic velocity investigations of crystal anisotropy in deep ice cores from Antarctica

Heinz Kohnen and Anthony J. Gow

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Ice cores from Byrd Station and Little America V have been used to test an ultrasonic technique for evaluating crystal anisotropy in the Antarctic Ice Sheet. P-wave velocities measured parallel ($V_p\downarrow$) and perpendicular ($V_p\rightarrow$) to the vertical axes of cores from the 2164-m-thick ice sheet at Byrd Station have yielded results 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. Velocity differences (ΔV) in excess of 140 m/s for core samples from deeper than 1300 m attest to the strong single pole clustering of crystallographic c-axes about the vertical, especially in the zone from 1300-1800 m. Such oriented structure is compatible only with strong horizontal shearing in this zone. The existence in an ice sheet of widespread shearing several hundred meters above its bed raises serious questions

as to the validity of current concepts of the flow of large ice masses that tend to gloss over or ignore crystal alignments of this magnitude. In ice cores from the bottom 350 m at Byrd Station, the crystals are so large (up to 30 cm^2 in cross-sectional area) that samples used for ultrasonic measurements usually contain too few crystals to yield fully reliable ΔV data. It has been determined that a sample should contain at least 50 crystals if velocity bias resulting from group clustering of c-axes in coarse-grained ice is to be avoided. A small but significant decline in $V_p\downarrow$ with aging of the ice cores, as deduced from ultrasonic measurements made in the liquid-filled drill hole, is attributed to the presence of oriented intracrystalline cracks that form in the cores as they relax from the environmental stresses. A similar series of P-wave velocity measurements performed on cores from the 258-m-thick Ross Ice Shelf at Little America V has also yielded data in good agreement with the observed c-axis fabrics. However, these particular cores are characterized by two distinctive fabrics that exhibit a circular distribution of c-axes about a vertical symmetry axis, but which cannot generally be distinguished from one another solely on the basis of ΔV values. To resolve ambiguities of this kind, the ultrasonic measurements must be supplemented by periodic inspections of fabrics in thin sections. As a general rule, thin-section checks of c-axis orientations and ice textures should always be made in conjunction with ultrasonic velocity measurements, not only to verify the exact nature of the fabrics, but also to determine any inclination of the fabric symmetry axis with respect to the direction of P-wave transmission. Subject only to these precautions, the ultrasonic technique has proven to be a fast and powerful tool for determining crystal fabrics in ice sheets. Results from Byrd Station and Little America V, together with fabric data from several other locations in East Antarctica, suggest that crystal orientations within the Antarctic Ice Sheet tend to be characterized by either single or multi-pole clustering of c-axes about a vertical symmetry axis.

PREFACE

This report was prepared by Dr. Heinz Kohnen, Geophysicist, of Westfalishen Wilhelms Universität (Münster, Federal Republic of Germany), and Dr. Anthony J. Gow, Geologist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by National Science Foundation Grant DPP-76-18401.

The authors wish to thank Dr. Steven Arcone and Stephen Ackley of CRREL for technically reviewing this report and providing constructive comments.

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ULTRASONIC VELOCITY INVESTIGATIONS OF CRYSTAL ANISOTROPY IN DEEP ICE CORES FROM ANTARCTICA

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INTRODUCTION

Anisotropic (oriented) crystal structure is important in determining the rheological behavior of polar ice sheets, especially in 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 by Gow and Williamson (1976) of c-axis fabric in ice cores from a 2164-m-deep drill hole at Byrd Station and from seismic records (Bentley 1971, Kohnen and Bentley 1973). The deep drill hole at Byrd Station penetrated to the bottom of the ice sheet and petrofabric investigations of the 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, thus representing about 80% of the ice column in the immediate vicinity of the drill hole.

Major features of the c-axis fabric profile obtained by Gow and Williamson (1976) are illustrated in Figure 1. Maximum vertical clustering of crystallographic c-axes occurs in a zone of fine-grained ice at 1200- to 1800-m depth. Below about 1810 m this very strong axial orientation of crystals (in which very few crystal axes deviate by more than 25% from the vertical) is replaced by a change to a more dispersed, occasionally ring-like distribution of c-axes about the vertical. This distinctive change in fabric is also accompanied by a very large increase in the size of crystals. Sonic logging of the drill hole by Bentley (1972) has confirmed the existence of this strong vertical alignment of c-axes at depth. 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, involving as much as 90% of the ice column at some locations.

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

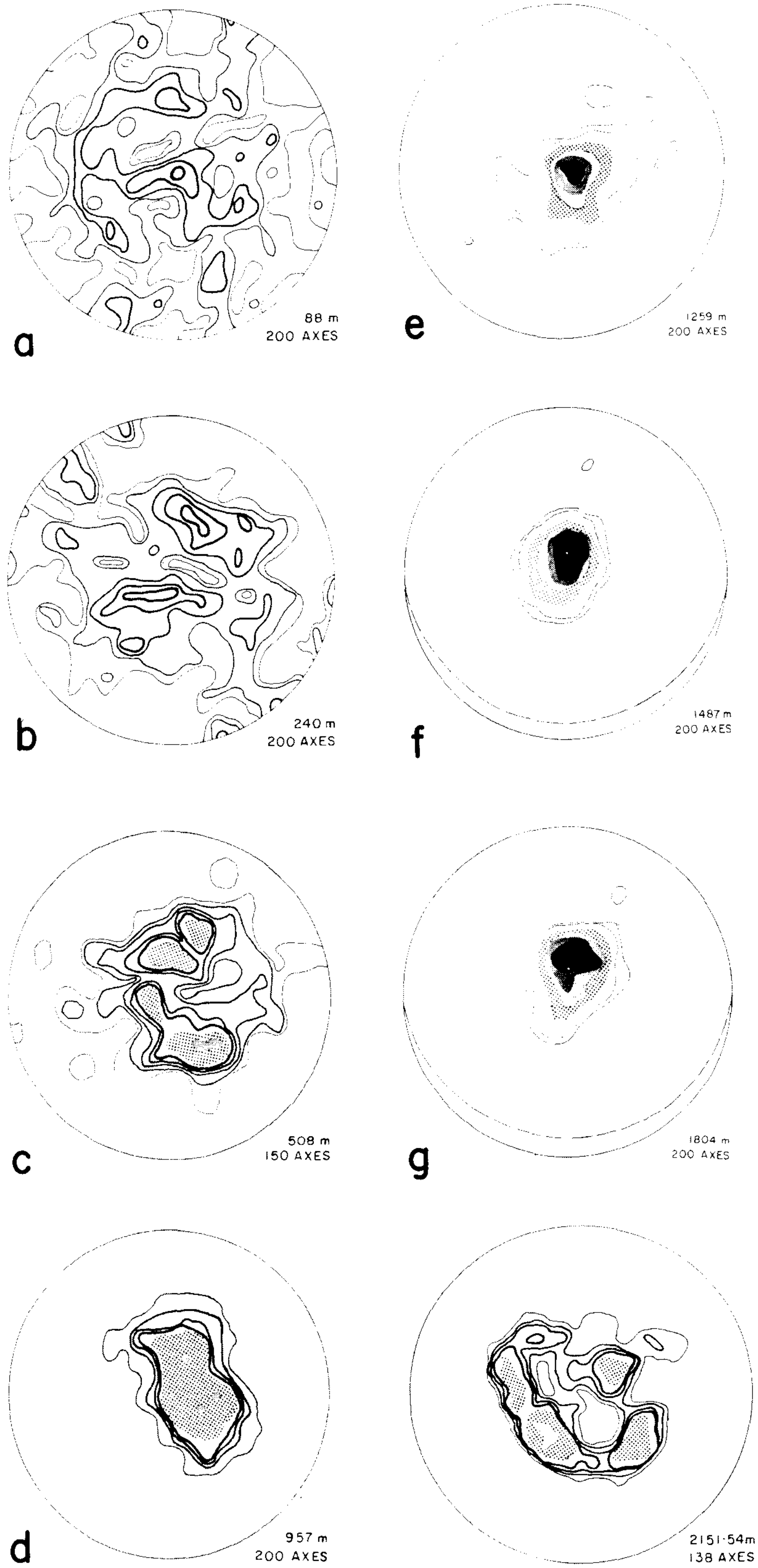

Figure 1. C-axis fabrics of deep ice cores, Byrd Station, Antarctica. Data from horizontal core sections. Contour intervals on stereographic plots range from ½% to 5% per 1% area for fabrics near top of the ice column to 25% per 1% area in deeper ice. Fabrics a-g are keyed to Figure 7.

In this report, measurements of ultrasonic velocities performed on ice cores from the Byrd Station deep drill hole are discussed. This sonic logging of 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 transverse (diametral) direction ($V_P\rightarrow$) as well as along the vertical axis ($V_P\downarrow$) of the cores. This two-way measurement of *P*-wave velocity permitted immediate evaluation of the velocity difference $V_P\downarrow - V_P\rightarrow$ (ΔV), a very important parameter whose magnitude depends almost entirely on the orientation of crystals in the ice cores. At any given temperature the *P*-wave velocity 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 fabric. That the magnitude of ΔV should depend on the ice fabric is a natural consequence of the fact that the *P*-wave velocity along the c-axis of the hexagonally-structured ice crystal is about 170 m/s faster than that perpendicular to the c-axis (Brockamp and Querfurth 1964, Bennett 1972). This variation of velocity with the direction of propagation through the ice crystal also extends to polycrystalline aggregates, for example, glacial ice composed of crystals exhibiting a preferred orientation of their c-axes.

Our principal concern in this report is with the ultrasonic velocity-ice fabric relationship of ice cores from Byrd Station. In addition, we wish to present some data on cores from a second hole that penetrated the bottom of the Ross Ice Shelf at Little America V. This hole was drilled in 1958-59 during the International Geophysical Year; the total thickness of ice penetrated was 258 m. These cores have also been subjected to extensive examination of their physical and structural properties (Gow 1963, 1968a, 1968b, 1970b).

LABORATORY MEASUREMENTS

Sample sources

A total of 74 samples of Byrd Station core and 20 samples from the Little America V core were selected for ultrasonic measurements. These samples, chosen from representative levels at both drill sites, included a number of samples used previously for optical thin-section studies of c-axis fabrics. Some of these sections were originally prepared and examined immediately after the drilled core had been pulled from the hole. Reexaminations of these original thin sections, together with observations on several new thin sections of the same cores, have revealed no detectable changes with time in the crystalline texture of the ice or the c-axis fabric in either the 10-year-old cores from Byrd Station or the nearly 20-year-old cores from Little America V. For most of this time the cores, thin sections and various test samples were stored in sealed bags or containers at a temperature of −35°C.

Ultrasonic velocity measurements

All measurements of ultrasonic velocity were performed at CRREL in a coldroom maintained at a set temperature of −10°C, and the temperatures of samples at the time of testing were measured to within 0.1°C. A Krautkrämer USIP 11 System (an ultrasonic impulse testing apparatus) utilizing barium titanate transducers was used for measuring *P*-wave velocities parallel and perpendicular to the vertical axes of the cores. The system was operated at a frequency of 2 MHz to ensure optimal balance between time resolution, sample dimensions, and energy attenuation. The time scale of the oscilloscope was calibrated using aluminum rods of different lengths. Wave speeds in the aluminum rods and their temperature dependence were determined at the University of Münster before measurements were begun on core samples at CRREL.

The basic procedure was to begin measurements on a sample 70 mm in diameter by 100 mm long and to progressively reduce the specimen size to about 15 mm, making four or five separate measurements of the travel time in both the axial and transverse directions of the core. These measurements yielded travel time curves of the kind illustrated for several representative samples in Figure 2. Velocities were then obtained from linear regression fits of the travel time data. Specimen dimensions were measured with a micrometer to an accuracy of ±0.1 mm; errors in determining the final velocities were found not to exceed ±20 m/s.

Density measurements

Core samples, especially those from the deep hole at Byrd Station, have undergone appreciable relaxation (volumetric expansion)

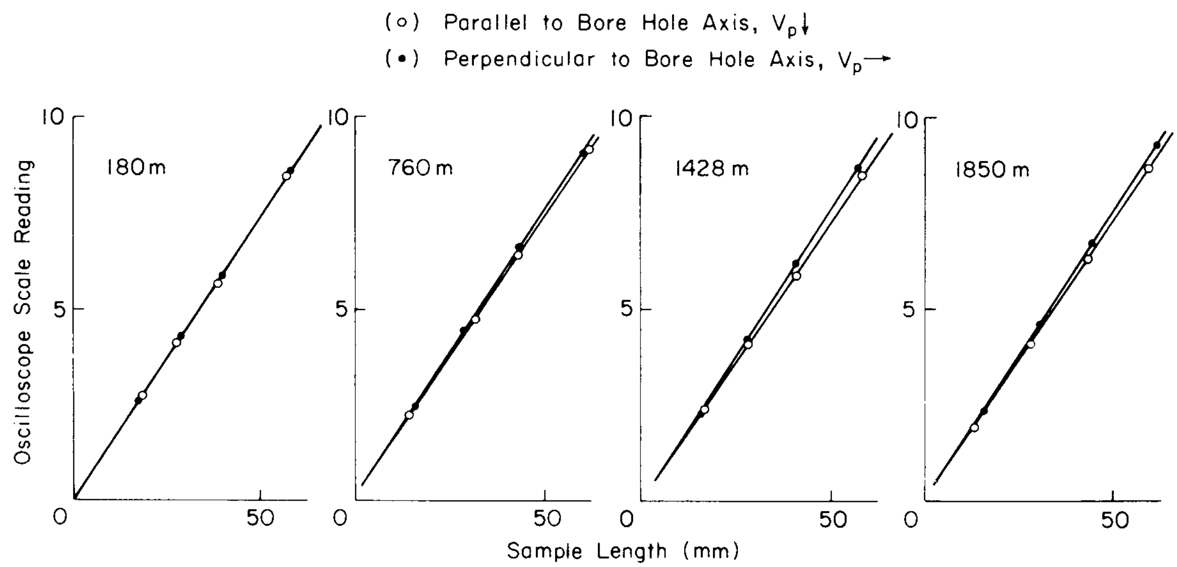

Figure 2. Travel time curves for core samples from different depths at Byrd Station. One oscilloscope scale unit measures approximately 1.75 microseconds. Divergence of travel time curves is directly related to the anisotropic state (oriented condition) of the ice crystals in the cores.

since they were drilled in 1967-68 (Gow 1971). In order to monitor this relaxation, core densities were redetermined simultaneously with the velocity measurements. Core densities were measured to an accuracy of ± 0.0003 Mg/m^3 by hydrostatic weighing in reagent grade iso-octane.

Effects of inclined drilling at Byrd Station

During drilling at Byrd Station the hole became inclined and this caused a corresponding tilting of the core. Since our velocity measurements were made along the transverse and axial directions of the core, this inclination effect needed to be corrected in order to obtain true vertical and horizontal *P*-wave velocities in the ice. Gow and Williamson (1976) have established that the fabric symmetry axis is vertical or very close to vertical so that the magnitude of the correction depends in part on the degree of concentration of c-axes about this fabric symmetry axis and in part on drill hole inclination. The inclination of the drill hole also determines the angular relation between the fabric symmetry axis and the direction of propagation of the axial ($V_P\downarrow$) and transverse ($V_P\rightarrow$) *P*-wave velocities. Estimates utilizing theoretical velocities for given c-axis distributions (Bennett 1972) that take account of the two above effects indicate that this correction should begin to exceed the experimental error (± 20 m/s) only in ice cores exhibiting very tight single pole fabrics, such as those in the zone from 1200-1800 m. At Little America V the hole remained vertical during drilling so that no correction was needed.

RESULTS

Byrd Station

Density and ultrasonic velocity data for the Byrd Station cores are presented in Table 1. The density data are also plotted in Figure 3, together with the original measurements of density and temperature made in 1967-68. The drill site densities (corrected for in-situ temperatures and pressures) were measured immediately after ice cores were pulled to the surface in order to minimize the effects of relaxation (Gow 1971). Densities remeasured nearly 10 years later graphically demonstrate the extent to which the cores have relaxed in the interim. This relaxation results from a variety of mechanisms, including decompression of pre-existing air bubbles, cavity formation and microfracturing. Microfracturing also includes the widespread propagation of cleavage cracks along the basal planes of the ice crystals. This relaxation is interesting in that the deepest ice cores have relaxed the least. Greatest relaxation, due primarily to the decompression of air bubbles in the ice, has occured in the region of brittle, bubble-rich cores from 300- to 800-m depth. In this particular zone, cores

Table 1. Ultrasonic velocity and density data for Byrd Station deep ice cores (all data corrected to -10°C.

Depth (m)	$V_P\downarrow$ (m/s)	$V_P\rightarrow$ (m/s)	ΔV (m/s)	Density Mg/m^3)	Remarks
88	3735	3746	−11	0.8963	
140	3786	3769	17	0.9084	
180	3781	3781	0	0.9095	
221	3791	n.d.*		0.9105	Small sample
259	3737	3714	23	0.9106	Cracked sample, omitted
281	3815	3804	11	n.d.	
330	3782	3786	−4	0.9081	
340	3797	3789	8	0.9064	
349	3802	3798	4	0.9105	
357	3848	3823	25	0.9112	
368	3843	n.d.		0.9113	Small sample
411	3833	3793	40	0.9104	
434	3817	3779	38	0.9104	
439	3781	3794	−13	0.9111	
471	3786	n.d.		0.9103	Small sample
490	3834	3774	60	0.9097	
557	3832	3781	51	0.9106	
565	3817	3786	31	0.9104	
601	3844	3797	47	0.9099	
672	3754	3687	67	0.9098	Cracked sample, omitted
760	3851	3809	42	0.9099	
778	3837	3768	69	0.9083	
867	3871	3808	63	0.9103	
890	3822	3782	40	0.9102	
906	3829	3750	79	n.d.	
922	3855	n.d.		0.9106	Small sample
947	3870	3822	48	0.9102	
958	3843	3804	39	0.9127	Averaged values of two contiguous cores
978	3843	3797	46	0.9135	
997	3835	3792	43	0.9116	Samples located less than 1 m apart
998	3825	3784	41	0.9109	
1024	3836	3763	73	0.9117	Samples located less than 1 m apart
1024	3859	3798	61	0.9121	
1068	3891	3850	41	n.d.	
1105	3888	3819	69	0.9142	Samples located less than 1 m apart
1105	3907	3808	99	0.9148	
1137	3786	3746	40	0.9135	Cracked sample, omitted
1172	3834	3809	25	0.9134	Averaged values of two contiguous samples
1210	3859	3788	71	n.d.	
1259	3946	3833	113	0.9142	
1298	3912	3807	105	n.d.	Samples located less than 1 m apart
1298	3946	3826	120	0.9152	
1384	3909	3836	73	0.9135	
1428	3931	3837	94	0.9130	Samples located less than 1 m apart
1428	3978	3836	142	0.9148	
1479	3915	3843	72	n.d.	
1500	3917	3816	101	0.9140	
1523	3888	3820	68	0.9163	
1576	3903	3784	119	0.9160	
1633	3918	3793	125	0.9152	Samples located less than 1 m apart
1633	3961	3811	150	0.9169	
1689	3858	3784	74	0.9148	Cracked sample, omitted
1711	3924	3836	88	n.d.	
1736	3948	3841	107	0.9159	

Table 1 (cont'd). Ultrasonic velocity and density data for Byrd Station deep ice cores (all data corrected to -10°C).

Depth (m)	$V_P\downarrow$ (m/s)	$V_P\rightarrow$ (m/s)	ΔV (m/s)	Density Mg/m³)	Remarks
1794	3974	3869	105	0.9156	
1850	3863	3780	83	0.9160	
1916	3883	3742	141	0.9169	
1976	3938	3797	141	0.9174	
2002	3901	3799	102	n.d.	
2032	3857	3802	55	0.9156	
2096	3926	n.d.		0.9157	Small sample
2138	3919	3779	140	n.d.	Samples located less than 1 m apart
2138	3942	3816	126	0.9161	

$V_p\downarrow$: Velocity measured parallel to vertical axis of core.
$V_p\rightarrow$: Velocity measured normal to vertical axis of core
ΔV: Velocity difference, $V_p\downarrow$-$V_p\rightarrow$
* No data

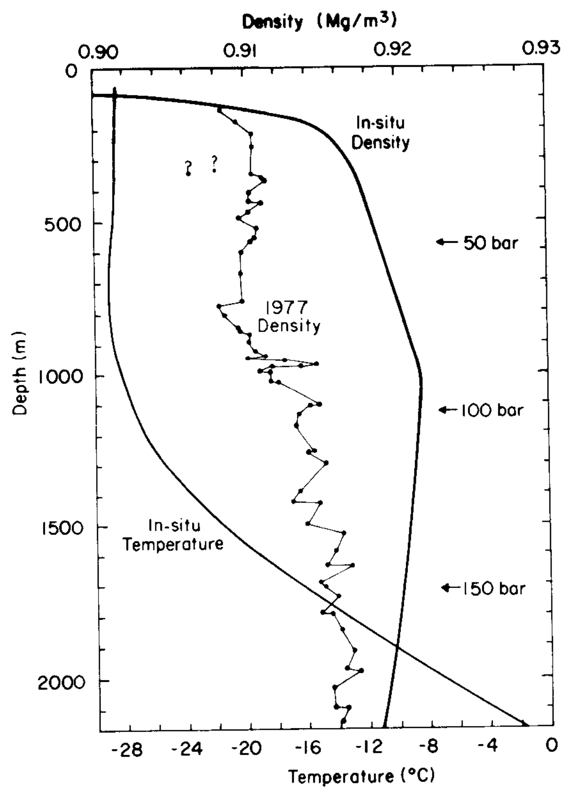

Figure 3. In-situ temperature and density profiles, Byrd Station, Antarctica. Densities remeasured in August 1977 demonstrate extent to which cores have relaxed since 1967-68 when the deep hole was drilled. Some representative values of overburden pressure are also indicated.

have relaxed to a nearly uniform density of 0.91 Mg/m³ (see Fig. 3). Below 800 m the densities of relaxed cores generally increase with increasing depth. This decreased relaxation state in cores from deeper than 800 m is attributed partly to the loss of air bubbles from the ice and partly to the existence of an oriented crystal structure (Gow 1971).

Fluctuations in density generally correlate well with fluctuations in both $V_P\downarrow$ and $V_P\rightarrow$ in Table 1, and significant increases observed in both velocity profiles below 800 m can be ascribed in part to the increasing density of the samples. However, the increase in $V_P\downarrow$ is appreciably greater than that for $V_P\rightarrow$ and the resultant increase in ΔV is entirely compatible with the pattern of fabric changes exhibited in Figure 1. This result serves to establish the intimate connection between sonic anisotropy and the anisotropic state of the crystals in the ice sheet at Byrd Station.

The close connection between sonic anisotropy and the anisotropic state of the crystals in the ice sheet is further demonstrated in Figure 4 where both sets of velocity data ($V_P\downarrow$ and $V_P\rightarrow$ in Table I) have been corrected to in-situ temperatures and densities to facilitate comparison with Bentley's (1972) down-hole velocity log. Bentley's data were restricted to measurements parallel to the bore hole axis, which corresponds in direction (and tilt) to our axial (V_P↓) propagation direction in the ice cores. The V_P↓ measurements show generally good agreement with Bentley's velocity profile down to about 1200 m but begin to deviate significantly below this depth, with our V_P↓ values being appreciably lower than those obtained at corresponding depths by Bentley. The apparent reduction in V_P↓ for the 10-year-old cores (even after adjusting to in-situ temperatures and densities) is real and can be substantially attributed to the effects of abundant cleavage cracks propagated along the basal planes of the ice crystals

This propagation of cracks in the deep ice samples is especially concentrated in cores from the zone of strong axial fabrics where the formation of a distinctive crack fabric has caused a significant reduction of velocity in a direction normal to the plane of the cracks, i.e. in the direction of V_P↓. As noted above, Bentley was not able to measure velocities corresponding to our V_P→; however, estimates based on fabrics indicated that cleavage cracks would also cause some reduction in V_P→, though this reduction would probably be less than that for V_P↓. These data point up the significance of the directional nature of the ice core relaxation and the importance of oriented crystal structure in determining the orientation of cracks that form in ice cores as they relax from environmental stresses. This relaxation of the ice with time is also indicated from preliminary measurements of velocity made on two pieces of the Byrd Station core in 1974 (data denoted by squares in Fig. 4). Both sets of velocity measurements show a significant decrease in V_P↓ and V_P→ since 1974. A very similar depression of seismic velocities is also observed in rock samples containing oriented cracks, even in rocks where the volume fraction of such cracks is only a small part of the total porosity (for example, see Anderson et al. 1974). Additional studies of the relaxation process, especially the directional aspects of relaxation as indicated by velocity changes, are discussed elsewhere (Gow and Kohnen in prep.).

As noted above, the velocity difference ΔV is determined almost entirely by the ice crystal fabric so that any significant change in c-axis orientation should be reflected in a measurable change in ΔV. The qualitative aspects of the ΔV/c-axis fabric relationship are clearly indicated from comparison of data in Figures 1 and 4. However, to establish a quantitative relationship between the two, we have chosen as the relevant parameter α, the half-apex angle of the cone containing 90% of the c-axes in a given fabric but excluding the 10% most divergent c-axes. This parameter α has been selected mainly on the assumption that the dominantly axial fabric pattern observed in ice cores 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. Representative examples of such conically distributed c-axis fabrics are presented in the c-axis scatter plots in Figure 5. The only major change in this pattern occurs in cores from the bottom 350 m of ice where the single maximum fabric is now replaced by a more dispersed, occasionally ring-like distribution of c-axes about the vertical. The ring-like pattern probably conforms more closely with a distribution of c-axes on the surface of a cone than with a solid cone distribution (see for example the distribution of c-axes in ice at 2099 m in Fig. 5).

As implied above, our measured values of V_P↓ and V_P→ need to be corrected for the effect of inclined drilling in order to obtain true values of ΔV. These corrections do not exceed 10 m/s in the top 1000 m of ice at Byrd Station, and the maximum correction for ice with α values of the order 20° - 25° only rarely exceeds 30 m/s. However, since our measurements of velocity are all biased in the same direction, all ΔV values are corrected throughout for tilt and fabric effects, using the theoretical relationships derived by Bennett (1972). In the zone from 1200 to 1800 m the corrected ΔV values may exceed 140 m/s; this value is only 20-30 m/s lower than the total velocity difference for *P*-waves propagated parallel and perpendicular to the c-axis of a single crystal.

In the case of cores from Byrd Station, the ΔV correction factor can be evaluated independently on the basis of layers of volcanic ash that occur abundantly in cores from the zone of single-pole fabrics at 1200-1800 m. These ash layers are inclined in the cores at angles about equal to the measured inclination of the drill hole and from these observations, in conjunction with fabric symmetry relationships, Gow and Williamson (1976) were able to establish that the true disposition of the ash layers is indeed horizontal. Using several pieces of core that each contained a prominent ash band, we first obtained V_P↓ and V_P→ for the core as drilled; then using the ash bands for reference, each core piece was shaped carefully on a band saw to permit measurements

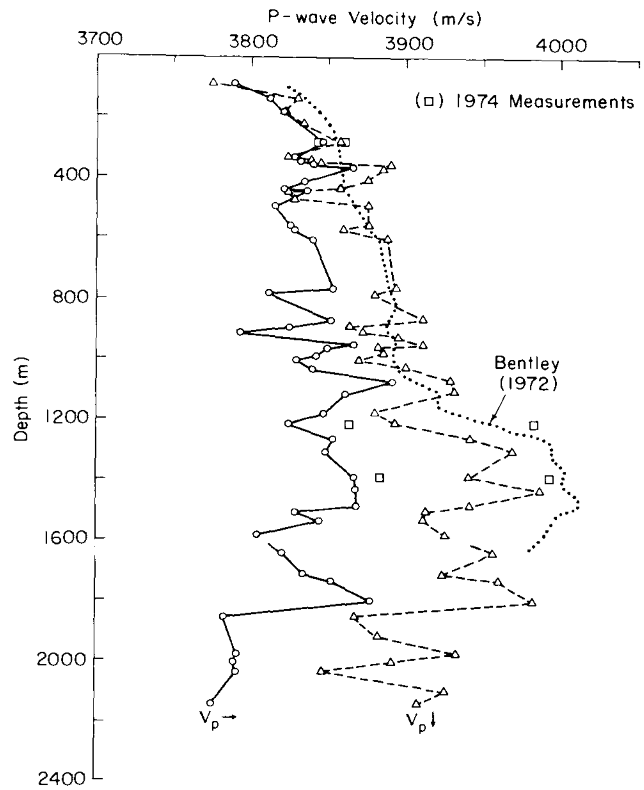

Figure 4. Axial ($V_p\downarrow$) and transverse ($V_p\rightarrow$) ultrasonic P-wave velocity measurements for ice cores from Byrd Station deep drill hole. Bentley's (1972) velocity profile was obtained from measurements along the bore hole axis. Note that $V_p\downarrow$ is parallel to the bore hole axis. All velocity data corrected to in-situ densities and temperatures.

of the true vertical and horizontal velocities. This series of measurements yielded maximum vertical and horizontal velocity differences of 46 m/s and 9 m/s respectively. The mean correction for this series of samples was 18 m/s for vertical velocities and 4 m/s for horizontal velocities. These data are in reasonable agreement with the magnitudes of corrections that would be obtained from Bennett's (1972) theoretical curves.

A plot of velocity differences (ΔV) vs the corresponding half cone angles (α) is presented in Figure 6. Data are obtained mainly from samples on which both velocities and c-axis fabrics were measured. A few data points for nonmatching samples from the top 600 m of core are also included. In this section of core, ΔV and fabric data have not generally been obtained on the same samples; however, data pairs included in Figure 6 are all restricted to samples located within 20 m of each other. The general trend of the data for α values in the range of 60° to 20° is indicated by the dashed line in Figure 6. The small difference in slope between this line and the linear portion of Bennett's theoretical curve might be attributed to the fact that Bennett's curve was calculated on the basis of a uniform distribution of axes within a cone, whereas the natural distribution (Fig. 5) more closely approximates a Fisherian distribution, i.e a normal distribution on a sphere. Also , considering the relaxed nature of our samples, particularly the effects of oriented cracks, the agreement between the theoretical and measured values is as good as can be expected.

Figure 7 illustrates the extent to which changes in the ΔV/depth function can be correlated with changes in the c-axis fabric

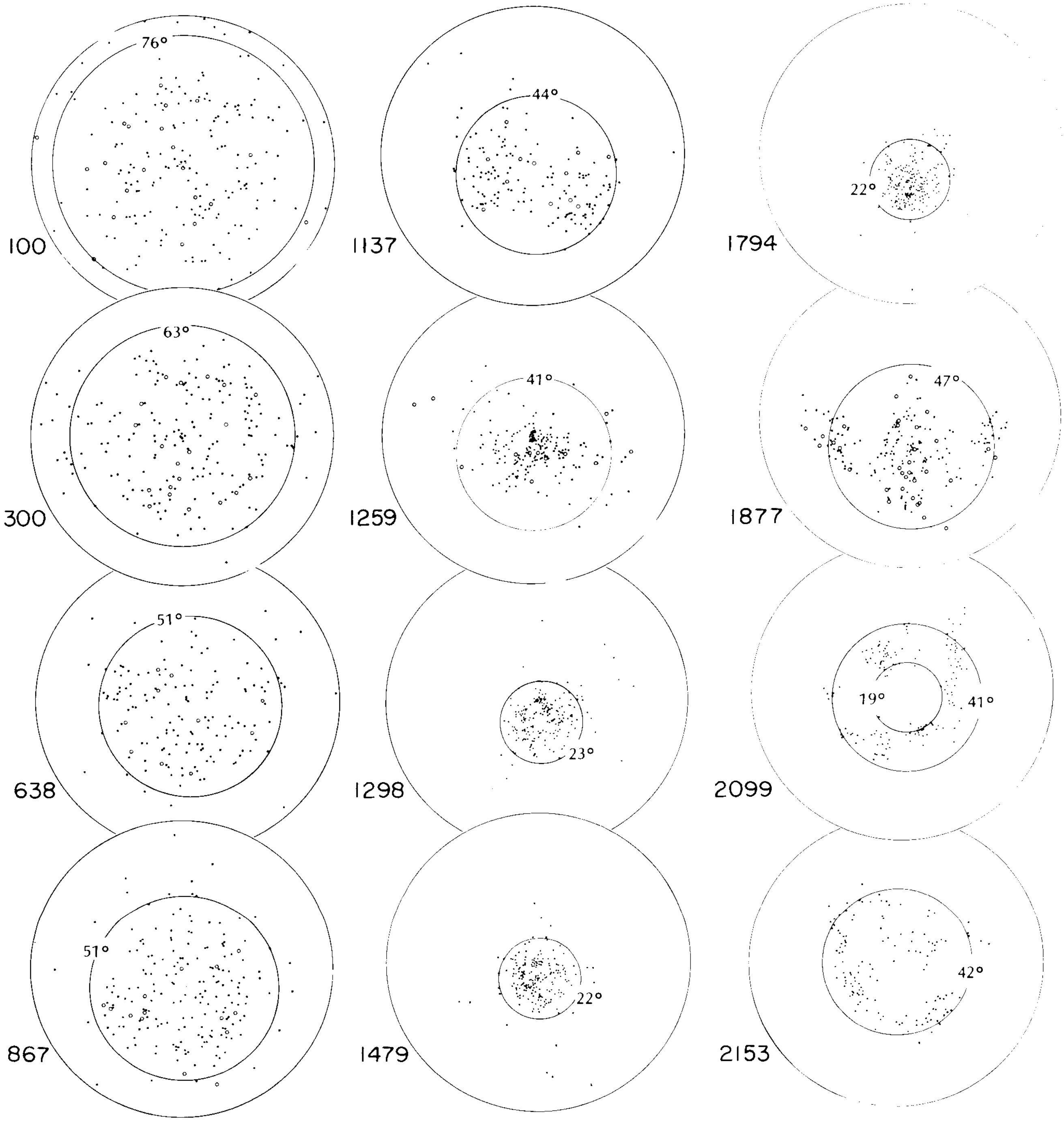

Figure 5. C-axis plots for determining the half-apex solid cone angles (α) in ice fabrics at different depths (m) from Byrd Station. Cones are constructed to include all c-axes in a given fabric except the 10% most divergent c-axes; α values vary from near random (76°) at 100 m to 23° and less in a zone of highly preferred crystal orientation at 1200- to 1800-m depth. In the bottom 350 m of ice at Byrd Station, ring-like distributions may develop, e.g. at 2099 m.

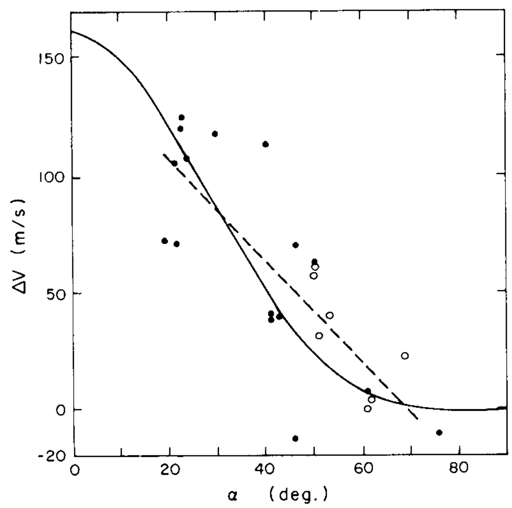

Figure 6. Plot of the P-wave velocity difference ΔV and α for Byrd Station ice cores. Solid circles are for samples on which both ΔV and α were measured; open circles are for data from core pieces located within 20 m of each other. Also shown are a ΔV curve calculated from Bennett (1972) and a curve (dashed) representing the average trend of the experimental data.

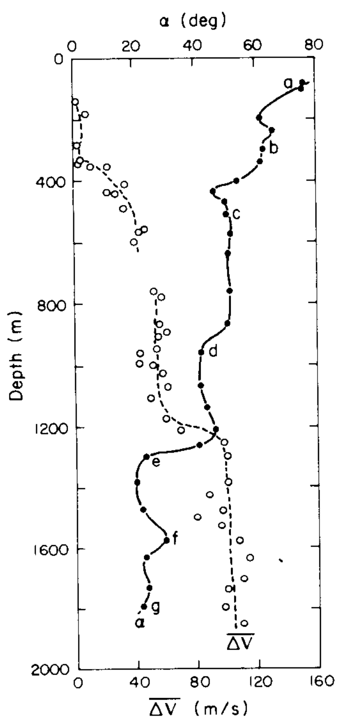

Figure 7. Functional relationship of P-wave velocity difference ΔV and c-axis fabric parameter α vs ice depth at Byrd Station. ΔV profile was constructed on basis of a nonweighted running mean of three values (data from Table 1); α values plotted as measured from c-axis fabrics, examples of which are shown in Figure 5. Symbols a-g refer to locations of c-axis fabric plots shown in Figure 1.

parameter α. The velocity differences are smoothed on the basis of a nonweighted running mean of three values in order to emphasize the very striking depth dependence of *ΔV* and α. This step-like mirror image pattern obtained with ΔV and α further establishes the strong relationship between *P*-wave velocity and the ice crystal fabric.

P-wave velocity characteristics of the Byrd Station ice cores are entirely consistent with a gradually increasing concentration of vertically oriented crystal axes down to a depth of 1200 m, followed within the next 100 m by a rapid transition to a single-pole fabric in which very few crystals deviated by more than 25° from the true vertical. Formation of this highly oriented, fine-grained ice, which persists to 1800-m depth, is compatible only with a strong horizontal shear deformation in this part of the ice sheet. Additional evidence in support of greatly increased shearing in this zone is the undulatory extinction and kink banding exhibited by many of the ice crystals, and the widespread occurrence of bands of ultrafine-grained ice containing fragmented, highly oriented crystals suggestive of planes or zones of actual shear displacement in the ice sheet. These observations of structure, in conjunction with supportive evidence from ultrasonic velocities, raise serious questions as to current concepts concerning the flow mechanics of large ice masses. Most theories assume, for simplicity, that the structure of the ice is uniformly isotropic, which is clearly at variance with the highly anisotropic state of crystals in the ice sheet at Byrd Station. Also, the common assumption that the bulk of the flow occurs by bottom sliding and/or rapid shearing in the basal ice will need to be modified in light of the strong orientation anisotropy and evident shearing taking place in ice situated hundreds of meters above the bed. Similar objections also apply to current practices of dating ice cores on the basis of overly simplistic flow models that either ignore or gloss over the existence of widespread crystal anisotropy in ice sheets.

A complete transformation to coarse-grained ice occurs below 1810 m at Byrd Station. Crystal cross sections in excess of 30 cm^2 are not uncommon in cores from the bottom 350 m at Byrd Station. This great increase in the size of crystals, which occurs simultaneously with a change in fabric to a more dispersed distribution of c-axes about the vertical, is attributed by Gow and Williamson (1976) to annealing recrystallization of ice at elevated temperatures. At Byrd Station ice temperatures increase from −15°C at 1810 m to −1.7°C (the pressure melting point) at 2164 m, and such a gradient, in conjunction with the suspected appreciable age of the ice, should favor the growth of large crystals.

It was recognized, at the time when ultrasonic velocities were being measured, that coarse-grained core samples from near the bottom of the ice sheet might contain too few crystals to furnish truly representative values of $V_P\downarrow$, $V_P\rightarrow$, and ΔV. This limitation imposed by larger grain size is concerned principally with crystal orientation which, in a sample containing only a few crystals, could deviate appreciably from a fabric obtained from a larger, more representative sampling of crystals. In fact, thin section samples of the same dimensions as those used for ultrasonic measurements generally contained so few crystals that as many as 30 separate thin sections from a 2-to 3-m unbroken, oriented run of core were needed to obtain a statistically significant fabric. In Figure 5, for example, at least 20 separate thin sections were needed to determine the general pattern of c-axis orientation in ice at 2099 and 2153 m.

This localized dependency of fabric on crystal size in samples composed of a small number of large crystals was immediately suspected when most of the samples from below 1810 m yielded ΔV values that seemed much too large for the generalized fabrics observed at these depths. According to calculations made on the basis of the kind of fabric observed at 2099 m (see Fig. 5), ΔV values for this kind of ice should not exceed 50 m/s. Measurements on seven samples from the zone of 1850- to 2138 m (see Table 1) yielded a minimum ΔV value of 55 m/s and a maximum ΔV value of 141 m/s, and four of the seven samples yielded ΔV values greater than 100 m/s. Such velocity differences conform more with solid cone fabrics with semi-apex cone angles of less than 30° than they do with the fabrics actually observed. Our explanation, based on examinations of individual thin sections from several test samples, is that the c-axes tend to cluster more closely in samples containing just a few crystals than in the generalized fabric obtained by combining 20 or more separate sections. Also, the presence of one or two singularly large crystals may cause these crystals to be overrepresented in the measured velocity.

In any event, the crystal size/fabric factor in coarse-grained ice raises the important question of just what is a representative fabric insofar as ultrasonic velocity measurements are concerned, and how many crystals should a sample contain in order to give representative *P*-wave velocities by ultrasonic measurements. In an attempt to quantify the "grain size effect," velocity differences were calculated for different values of n (the number of crystals in a sample) in the relationship $\Delta V = V_n - V_\infty$, assuming a random c-axis distribution. (V_∞ is the velocity for a sample containing an infinite number of crystals and V_n is obtained by integrating reciprocal velocities for single crystals at given angles to the direction of the *P*-wave transmission.) Results (Fig. 8) indicate that, for an experimental error of ± 20 m/s in the velocity measurement, the velocity bias due to grain size

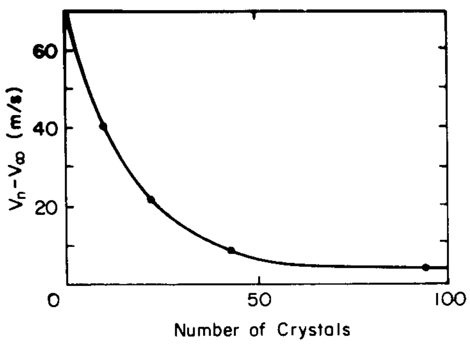

Figure 8. Curve of calculated P-wave velocity differences $V_n - V_\infty$ vs the number of crystals n in isotropic polycrystalline ice.

effects should be eliminated in samples containing about 50 or more crystals. Samples from the bottom 350 m of ice at Byrd Station rarely contain more than a dozen crystals. According to Figure 8, ΔV values that are 30 to 60 m/s too high could be expected, values which generally agree with those actually measured.

This localized dependency of the c-axis fabric on grain size in samples containing a limited number of complexly interlocked crystals is known to occur in temperate glaciers (Rigsby 1968) and could be expected to occur also in the warmer, basal parts of polar glaciers. Accordingly, in ice where large grains are expected, samples must be examined optically in thin sections to ensure that velocities are not being unduly biased by grain size effects.

Little America V

P-wave velocity measurements were also performed on samples taken nearly 20 years ago from a drill hole that penetrated the bottom of the Ross Ice Shelf at Little America V (Gow 1963). Cores from this hole were first examined ultrasonically in 1968 by Bennett (1972), whose results provide a basis of comparison with the present set of velocity data obtained at CRREL in September 1977. Results (Fig. 9) show that *P*-wave velocities in ice cores from below 100 m have decreased measurably in the nine years that have elapsed since Bennett made his measurements in 1968. As at Byrd Station, this velocity decrease can be attributed mainly to density changes occurring in response to continued relaxation of the ice cores. A comparison of densities measured in 1977 with those obtained on freshly drilled cores in 1958-59 indicates the extent of the relaxation that has occurred in the interim. Density changes can be ascribed in part to the enlargement of cracks created in ice cores taken from a dry (unloaded) drill hole and partly to decompression of trapped air bubbles, especially in cores from deeper than 180 m.

Fluctuations in velocity are in general accord with those measured by Bennett (1972), and substantial ΔV values measured as shallow as 95 m attest to a fairly rapid onset of anisotropic crystal structure in the ice shelf at Little America V. The general pattern of c-axis fabrics for the ice shelf is demonstrated in Figure 10. As at Byrd Station, the c-axes of crystals tend to cluster about a vertical axis of symmetry. This orientation takes the form of solid cone distributions in the zone from 60 to 95 m but transforms via an elongate two-pole fabric into a strong "cone in cone" orientation of c-axes below 151 m. This "cone in cone" (surface cone) distribution of axes in deeper ice at Little America V is characterized by the virtual absence of c-axes from the inner cone. However, a transitional type of fabric occurs between 95 and 151 m in which the c-axes of crystals tend to be distributed in an elongate maximum or incomplete girdle pattern. Because of the nonconical nature of this fabric, horizontal velocities could also be expected to vary with direction of propagation in the horizontal plane. A case in point is the sample from 116 m for which both the *P*-wave velocities and fabrics were measured in three mutually perpendicular directions to ascertain if small changes observed in the fabric were large enough to produce measurable changes in *P*-wave velocity. The preparation of this sample was facilitated greatly by the widespread occurrence of tubular bubbles oriented perpendicularly to the plane of the c-axis girdle. This occurrence of bubbles oriented symmetrically with respect to the fabric (the rheological implications of this relationship are discussed in Gow 1970b) permits visual orientation of the sample into any desired position. As shown on the cover of this report, the measured velocities correlate well with the observed differences in c-axis fabric.

A plot of velocity difference ΔV vs corresponding half cone angle α is presented in Figure 11. ΔV values conform reasonably well

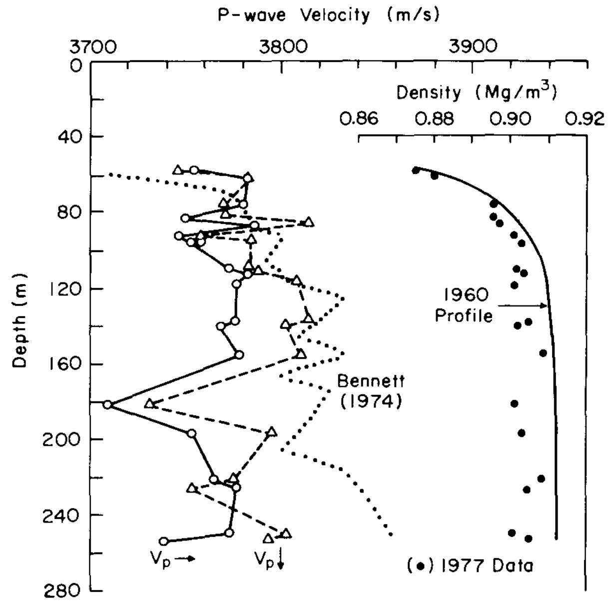

Figure 9. Axial (V_p↓) and transverse (V_p→) ultrasonic P-wave velocity measurements for ice cores from Little America V, Ross Ice Shelf, Antarctica. Trend of Bennett's (1972) data is shown by dotted line. Also shown are 1960 density profile and remeasurements of ice core densities made in 1977.

with the values to be expected from the measured fabrics, even including the data for the c-axis pattern transitional to the two major fabric types observed in cores from Little America V. Both fabric types are characterized by a symmetrical distribution of c-axes about the vertical axis. However, as Figure 11 clearly demonstrates, the fabric/velocity difference relationships differ markedly, even to the extent that ΔV values for the ring type (surface cone) fabrics become negative for α values in the range of 75° to 35°. The presence of the two fabric types at Little America V presents problems of interpretation that cannot be resolved solely on the basis of velocity measurements made in two or even three mutually perpendicular directions.* For instance, an α value of 35° for a single pole (solid cone) fabric would yield a ΔV value of about 75 m/s compared to a velocity difference of zero for a ring type (surface cone) fabric with the same half cone angle of 35°. Unless independent checks of c-axis orientations are made, it would not be possible to discriminate between surface and solid cone fabrics on the basis of ΔV values alone. In such cases, measurements of ultrasonic velocity must be supplemented periodically by thin section studies of c-axis orientations to resolve any ambiguities in interpretation. In short, our two-way measurement of ultrasonic velocities perpendicular and parallel to the long axes of ice cores constitutes a rapid means of investigating gross crystal anisotropy in ice cores, but occasional inspection of thin sections must also be performed in order to determine the precise nature of the fabric.

*The measurement of *P*-wave velocities in more than three directions is not a practical proposition with ice cores. The extra time needed to make the additional measurements would cancel out any advantage that this technique would have over direct measurements of c-axis fabrics in thin sections.

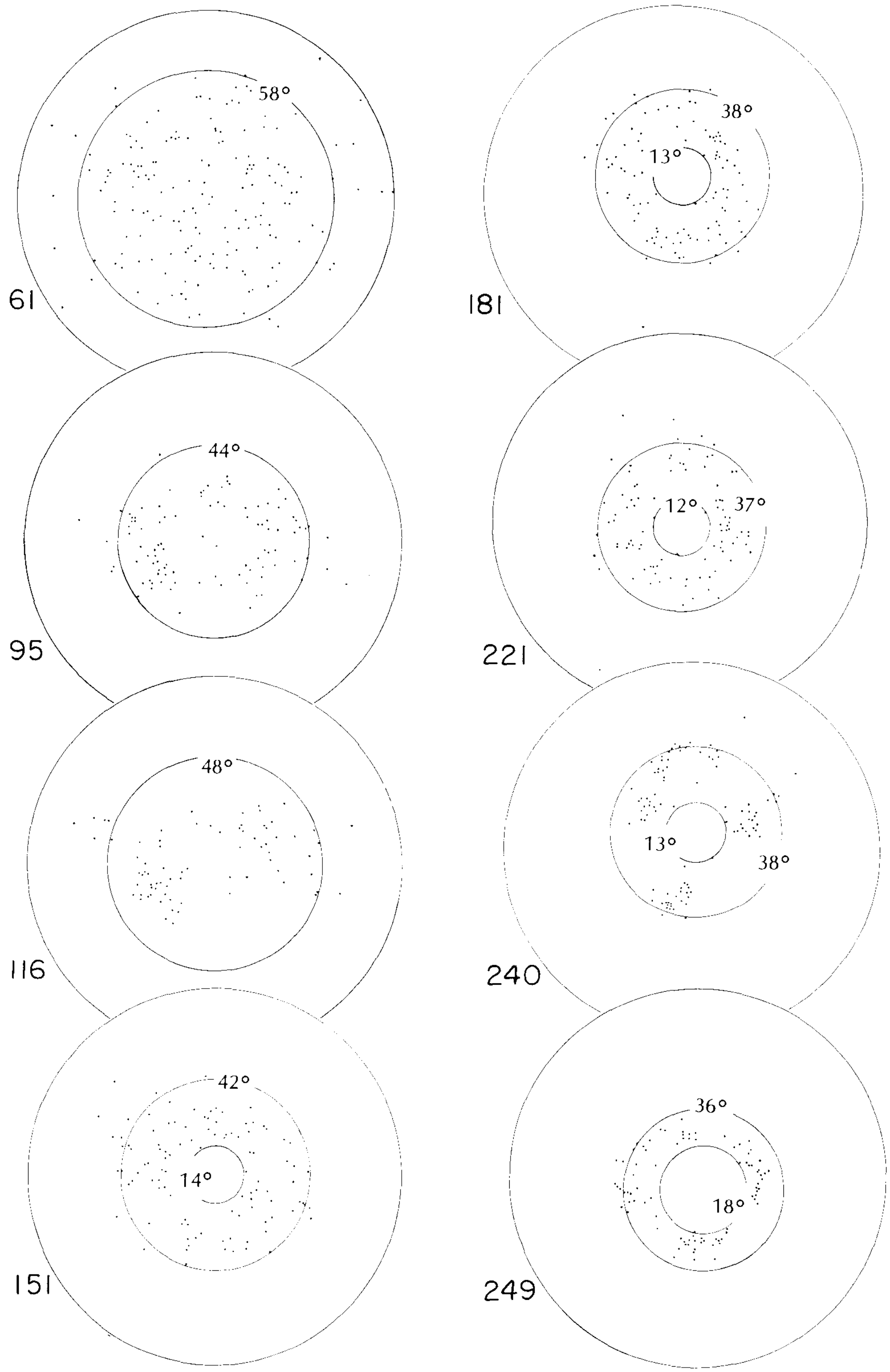

Figure 10. C-axis plots from Little America V for determining fabric parameter α, the half-apex angle of the cone containing all c-axes except the 10% most divergent c-axes in a given fabric. Note that by 151-m depth the simple solid cone distribution of axes has transformed into a ring-like pattern in which the central zone is completely devoid of c-axes.

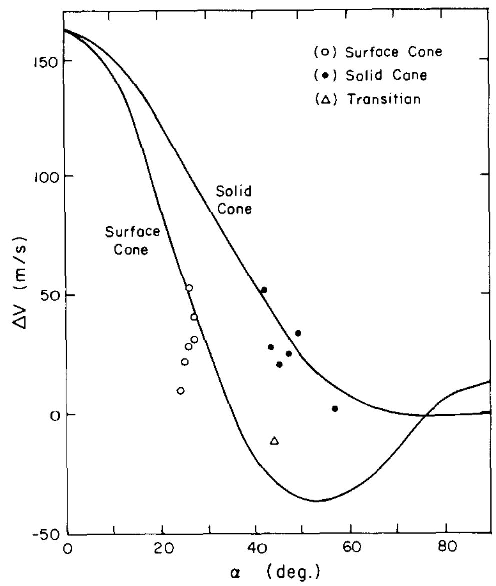

Figure 11. Plot of the P-wave velocity differences ΔV vs the half-apex cone angles α for ice cores from Little America V, Ross Ice Shelf, Antarctica. ΔV curves for solid and surface cones were calculated from Bennett (1972).

SUMMARY AND CONCLUSIONS

The practicality of using an ultrasonic technique to evaluate crystal anisotropy in ice sheets was tested, using cores from two deep drill holes in Antarctica. *P*-wave velocities measured parallel and perpendicular to the vertical axes of core samples yielded velocity difference data in very good agreement with the observed c-axis fabric profiles. Fabric/velocity difference correlations were facilitated by the fact that the major fabric patterns at the two drilling sites were characterized by circularly symmetrical distributions of c-axes about the vertical. While ultrasonic measurements of ice cores provide for rapid determination of the gross crystal orientation in a given sample, an unambiguous determination of the precise nature of the fabric can generally be made only on the basis of optical thin section measurements of c-axis orientation. Supplementary thin section studies should also be performed to 1) ensure that samples used for ultrasonic measurements contain enough crystals (of the order of 50 or more) to avoid velocity bias caused by the group clustering of c-axes that is frequently observed in coarse-grained glacial ice, and 2) determine any inclination of the fabric symmetry axis with respect to the direction of propagation of the *P*-wave velocity. Inclination of the symmetry axis can be a real feature of the fabric or it can be caused by the drilling of an inclined hole, as was the case at Byrd Station.

Bentley (1971) has speculated from seismic records in West Antarctica that the fabric symmetry axis may deviate appreciably from the vertical position observed at Byrd Station. However, Barkov's (1973) thin section orientation data from a deep hole at Vostok, together with Budd's (1972) summary of thin section fabric data from other locations in East Antarctica, indicate that the crystal orientation patterns at most locations on the grounded ice sheet are dominated by single or multiple-pole distributions of c-axes about a vertical symmetry axis. Preliminary measurements of fabrics in deep ice cores from Camp Century, Greenland, also show a preference for the c-axes to cluster about the vertical (Herron and Langway 1978).

Based on results described here we would advocate that all future studies of ice cores from deep drill holes include measurements of ultrasonic velocities, not only to determine gross trends of c-axis orientations in ice sheets but also as a means of monitoring the relaxation characteristics of drilled cores.

The ultimate reason for examining the state of crystal anisotropy in ice sheets is that the c-axis fabrics tend to reflect the style and intensity of deformation to which the ice has been subjected. As such, fabrics constitute the primary source of information for interpreting the strain history of the ice column represented by vertically drilled cores. Such studies are critical to any rational assessment of the dynamic behavior of ice sheets and to the reconstruction of realistic time scales needed to evaluate geochemical, stratigraphic and climatic records in cores, e.g. paleotemperature records based on stable isotope studies.

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