DEEP CORE STUDIES OF THE CRYSTAL STRUCTURE AND FABRICS OF ANTARCTIC GLACIER ICE

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PREFACE

This report was prepared by Mr. Anthony J. Gow, Geologist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The work reported here formed part of the research conducted on ice cores from two holes drilled in Antarctica during the International Geophysical Year, 1958-59. The original drilling program was sponsored by the U.S. National Committee of the I.G.Y. Subsequent financial support of this research was provided by Grants GA-2, GA-66 and GA-156 from the Office of Antarctic Programs, National Science Foundation. The author gratefully acknowledges this support and the direct interest in the core analysis program by Dr. A.P. Crary, Chief Scientist, U.S. Antarctic Research Program, NSF (now Deputy Division Director, Environmental Sciences, NSF).

The author also expresses appreciation to various colleagues and to Task Force 43, U.S. Navy, for their valuable support in the field. In particular, he is indebted to Mr. R.W. Patenaude and Mr. J.V. Tedrow and crew for their masterful drilling of the two deep holes at Byrd Station and Little America V.

This report was technically reviewed by Dr. C.C. Langway, Jr. and Dr. C. Keeler.

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DEEP CORE STUDIES OF THE CRYSTAL STRUCTURE AND FABRICS OF ANTARCTIC GLACIER ICE

by

Anthony J. Gow

INTRODUCTION

During the International Geophysical Year (1957-58) two deep core holes were drilled by the U.S. Army Snow, Ice and Permafrost Research Establishment (USA SIPRE)* at Byrd Station and Little America V, Antarctica. These two sites were selected for core drilling largely on the basis of their contrasting glaciological regimes; Byrd Station is situated on the grounded ice sheet of West Antarctica and Little America V is located near the seaward edge of the large floating Ross Ice Shelf (Fig. 1). In addition to furnishing virtually undisturbed cores for studying the stratigraphic,

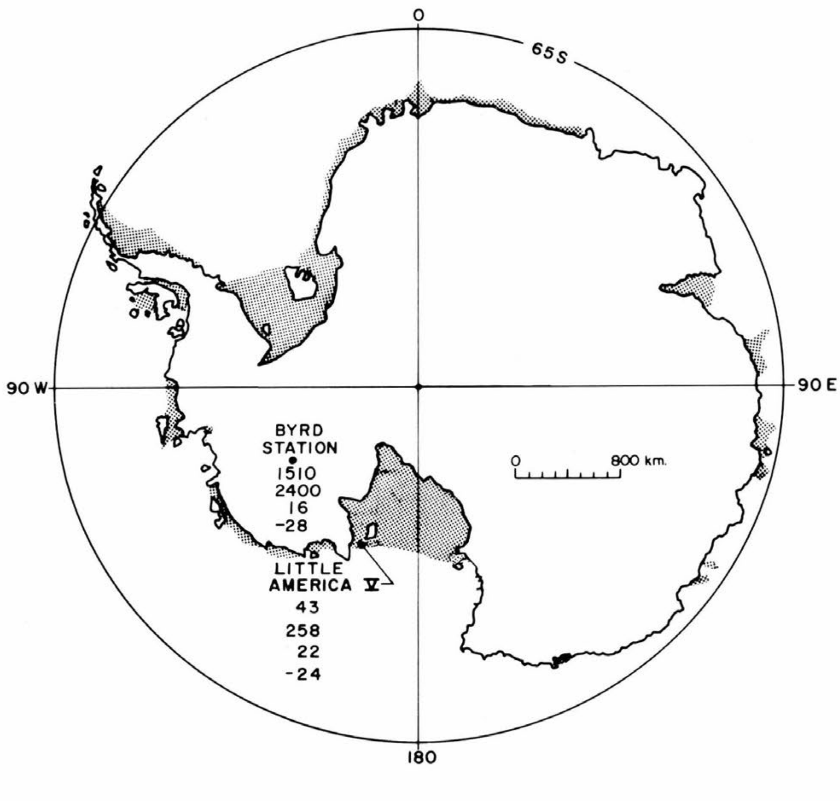

Figure 1. Locations of deep core drilling sites at Byrd Station and Little America V, Antarctica. The numbers at each location are the elevation in meters, estimated ice thickness in meters, mean annual accumulation in centimeters of water per year and the mean annual surface air temperature in degrees Celsius, in that order.

*SIPRE was merged with ACFEL, U.S. Army Corps of Engineers, in 1961, to form the U.S. Army Cold Regions Research and Engineering Laboratory.

physical, mechanical, geochemical and petrographic properties of these two major types of Antarctic glacial ice, the holes themselves were also used to measure temperatures and deformation in the ice sheet.

The drilling at Byrd Station (80°S, 120°W) reached a depth of 309 m in ice estimated to be about 2400 m thick (Bentley, 1964). At Little America V (78°10'S, 168°13'W) the drill penetrated the base of the ice shelf at 258-m depth, the first occasion that cores had been obtained from top to bottom of a polar glacier. Preliminary results of core studies are presented by Patenaude *et al.* (1959) and Ragle *et al.* (1960). Site descriptions and results of detailed studies of core stratigraphy, accumulation records, density variations and related parameters are given by Gow (1968a).

The present report is devoted to results of studies of the crystal structure and fabrics of cores from Byrd Station and Little America V. Preliminary observations by Gow (1963a, 1963b and 1964) revealed grossly dissimilar crystal structures in the ice at Byrd Station and Little America V, and it is the purpose of this report to describe the characteristic features of both profiles and to attempt to relate them to the differing deformational and thermal histories of the ice at these two locations.

ANALYTICAL PROCEDURES

Measurements reported here are based largely on the detailed examination of thin sections prepared from 5-mm-thick samples cut either parallel or normal to the long axis of the core. These samples measured 9.8 cm in diameter in the case of circular cross sections of core (horizontal sections) and were 9 to 10 cm square for samples cut parallel to the long axis of the cores (vertical sections). The finished sections, measuring 1 mm or less depending on the mean crystal size of the sample, were examined on a Rigsby stage, which is simply a large four-axis universal stage designed specifically for dealing with the generally large size of crystals found in glaciers. Full details of the preparation and examination of thin sections of ice are to be found in Rigsby (1951 and 1960) and Langway (1958).

All measurements on the thin sections were made at −10°C. Sections were stored in plastic bags at −30°C and can be preserved more or less indefinitely at this temperature. Repeated examinations of a number of thin sections over a period of several years have failed to reveal any detectable changes in either the textures of the ice or the orientations of the crystals.

Measurement of crystal size

Data on crystal size variations in the ice were obtained from counts of the number of crystals in a given area in a thin-section photograph. All crystals were counted except the very smallest "tip" cuts, which generally constitute less than 1% of the area of crystals counted. However, since they may represent as much as 5% of the total number of crystals in the section these "tip" cuts tend to cause the mean crystal size to be underestimated if included in the count. The parameter, number of crystals/cm^2, can be converted readily to a mean crystal cross section by simply dividing the area of crystals counted by the total number of crystals.

Not less than 300 crystals were included in a single determination at Byrd Station and more than 2500 crystals were counted in one multiple section count at 116-m depth. Fewer crystals were measured in thin sections from Little America V mainly because of the much larger size of crystals in the ice shelf than at corresponding depths in the ice sheet at Byrd Station. However, crystal size counts at Little America V were not made on sections (or contiguous sections) containing less than 120 crystals; more than 300 crystals were counted in some sections.

Measurement of crystal orientation

In ice the crystallographic c-axis corresponds to the optic axis, and procedures for determining the orientation of crystallographic c-axes in ice are essentially the same as those used in fabric studies of quartz crystals in quartzites and foliated granites, etc. The number of crystals measured in any given section of ice depends on a number of factors, including the size and manner of aggregation of the crystals and the nature of the fabric.* Approximately 200 crystal orientations were measured in each thin section at Byrd Station. At Little America V, however, where the fabrics proved to be very much stronger than at Byrd Station, as few as 80 c-axis determinations sometimes sufficed to establish the pattern of preferred orientation.

RESULTS AND DISCUSSION

Byrd Station crystal structure and fabrics

General properties. At Byrd Station firn transforms into ice at around 65-m depth. Though no longer permeable this ice is still porous; it contains 10% air by volume and structurally it resembles the end product of the solid sintering of a single-phase polycrystalline material. At 100-m depth the porosity has decreased to less than 2%. This occurs by compression of the entrapped bubbles which continue to shrink in size until at a depth of 308 m the porosity is reduced to about 0.4%, equivalent to an average bubble pressure of 25 bars. A preliminary examination of thin sections of cores has also disclosed a general increase in the size of crystals with increasing depth. The nature and extent of these changes at three representative levels in the ice sheet at Byrd Station are illustrated in the thin-section photographs in Figure 2.

Ice from 71 m comprises equidimensional crystals inclosing tubular air bubbles. This transforms via the structure at 163-m depth into a mosaic of larger, less regularly shaped crystals inclosing small spherical bubbles of air at 305 m. A few crystals exhibit undulose extinction at this depth and "porphyroblastic crystals" (crystals that are significantly larger than their neighbors) have also begun to make their appearance. Some splitting of bubbles is also evident. Since this splitting is propagated generally within the basal planes of crystals (Gow, 1968b) it also provides some preliminary information on the orientation of crystals.

Additional studies on crystal-bubble relations in ice from Byrd Station (Gow, 1968b) have demonstrated (1) that the concentration of bubbles remains remarkably constant at approximately 220 bubbles/cm^3, (2) that bubbles in deeper ice are compressed in almost exact equilibrium with the overburden pressure (the lag between bubble pressure and overburden pressure decreases from 4-5 bars at the firn-ice transition to less than 1 bar at 200 m), and (3) that bubbles show no tendency to be swept towards crystal boundaries during crystal growth. The latter observation would indicate that crystal boundaries are able to migrate right past bubbles without seriously disturbing their distribution in the ice.

Crystal growth. The mean cross-sectional area of crystals in ice from Byrd Station was observed to increase approximately sixfold from 3.1 mm^2 at 65-m depth to nearly 20 mm^2 at 307-m depth (see Table I and Fig. 3 for results). The largest crystals in the deepest cores seldom exceeded 1.5 cm^2 in cross section. When ages† (computed on the basis of a constant accumulation rate of 15.6 g $cm^{-2}yr^{-1}$ obtained from stratigraphic studies of cores from the top 88 meters) are substituted

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*In this report the term *fabric* is restricted to describing just the oriented features revealed in the thin sections of ice, e.g., c-axis orientations and bubble alignment. Other features such as sizes and shapes of crystals are described under *structure*.

†The ages of deeper samples must also be adjusted for the thinning of annual layers by plastic deformation of the ice. This was done using the simple correction factor of Nye (1963) that assumes a constant vertical strain rate for the ice sheet. Calculations were based on an assumed ice thickness of 2400 m.

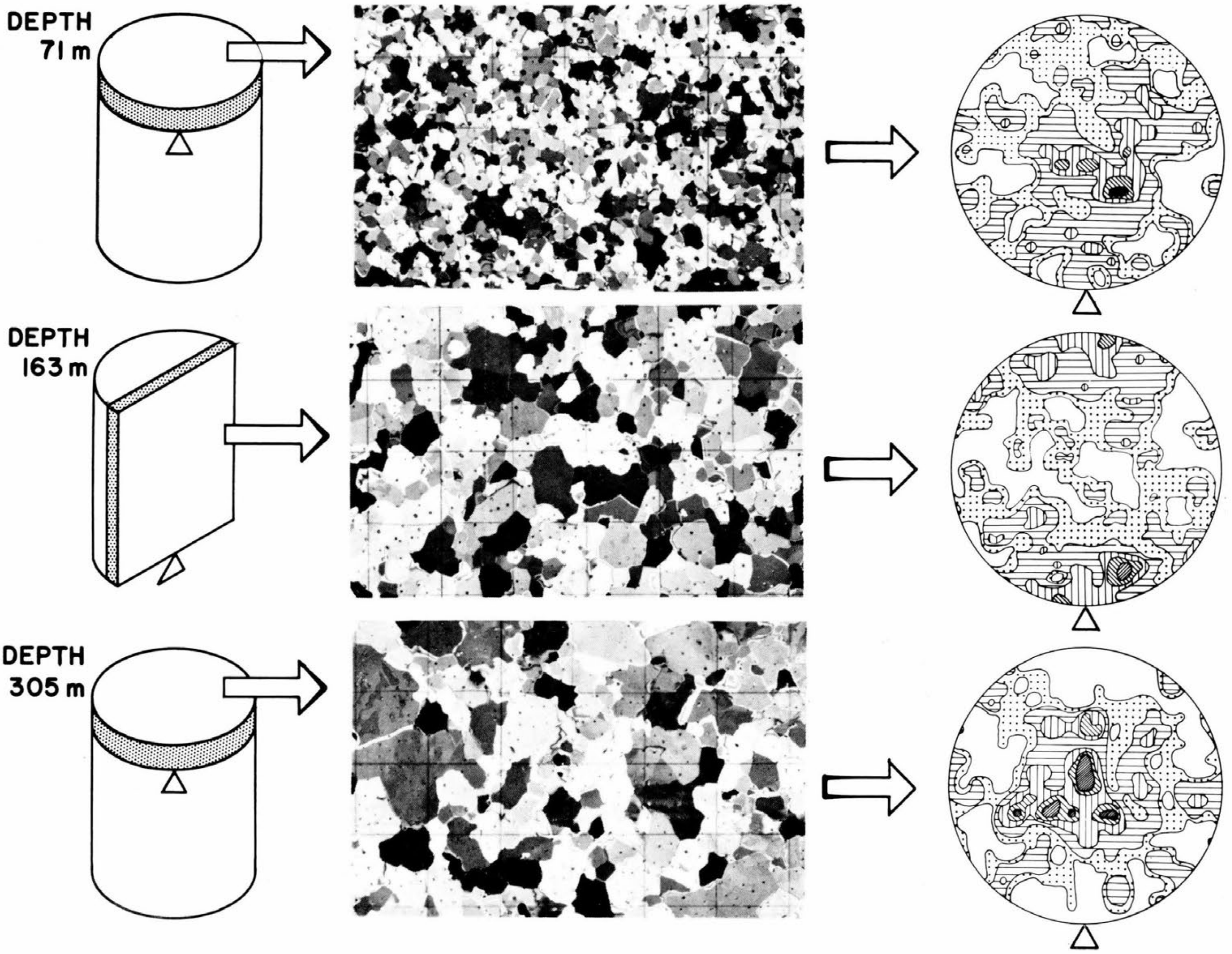

Figure 2. Crystal structures and fabrics (c-axes) of thin sections of ice from the deep hole at Byrd Station. Small inclusions in photographs are air bubbles. Note how crystal size increases and bubble size decreases with increasing depth. The age difference between 71 m and 305 m is approximately 1500 years. The grid spacing in photographs measures 1 cm. Fabric orientations are as indicated. All fabric diagrams were constructed from plots of c-axes made on the lower hemisphere of the Schmidt equal area net. Contours at 4%, 3%, 2%, 1% and 0.5% per 1% area. (After Gow 1963a.)

for depths of samples, an essentially linear relation between mean crystal cross section and age is obtained (Fig. 4). Since temperatures in the ice between 65 m and the bottom of the drill hole are known to vary by less than 0.3°C (Gow, 1963b), this growth can be considered to have occurred under essentially isothermal conditions (see temperature profile in Fig. 5). These crystal growth relations, thus, conform precisely with those established for isothermal grain growth in metals (Burke and Turnbull, 1952), $D^2 = D_0^2 + kt$, where D^2 is the mean crystal cross section (mm^2) after time t (years), D_0^2 is the crystal size at $t = 0$ and k is the rate constant.

These data on isothermal crystal* growth in ice are particularly interesting because of the great length of time involved compared with laboratory observations on grain growth in metals; the ice at the bottom of the drill hole at Byrd Station is estimated to be at least 1900 years old. The value of the rate constant k for ice at Byrd Station is 0.01 $mm^2 yr^{-1}$. Measurements of firn crystal growth above 65 m, obtained in a slightly different way from those on ice cores below 65 m, also yielded a linear relation with age though with a slightly higher growth rate, 0.012 $mm^2 yr^{-1}$ (see

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**Crystal* as used here is synonymous with the metallurgists' *grain*.

Table I. Crystal size variations with depth in the Antarctic Ice Sheet at Byrd Station.

Depth (m)	*Mean crystal area (mm^2)*	*No. of crystals in count*
65	3.1*	2417
71	4.2	1000
80	4.6	1013
90	5.0	1252
100	5.3	827
116	6.9*	2509
135	8.0	753
163	10.4	560
193	11.5	609
216	10.9*	1196
242	16.3	465
280	20.4	304
305	20.3*	836
307	19.5	304

*Average of three or four separate determinations spaced 15-20 cm apart.

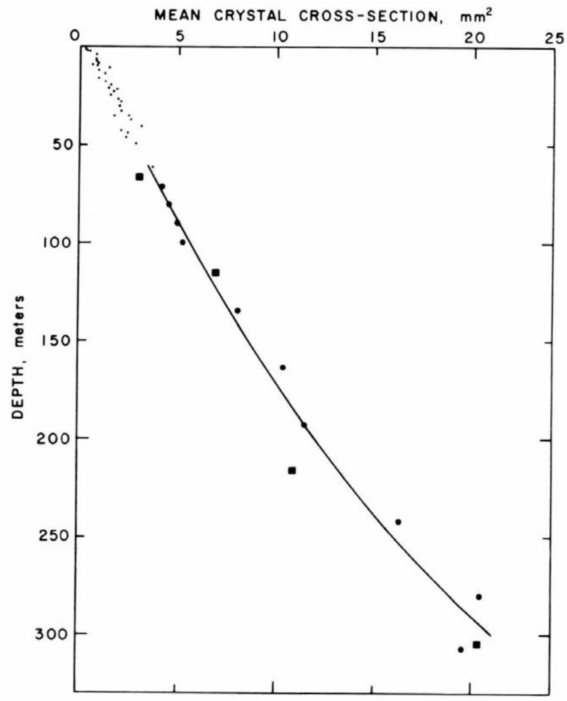
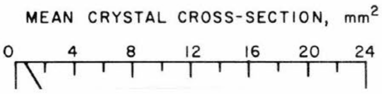
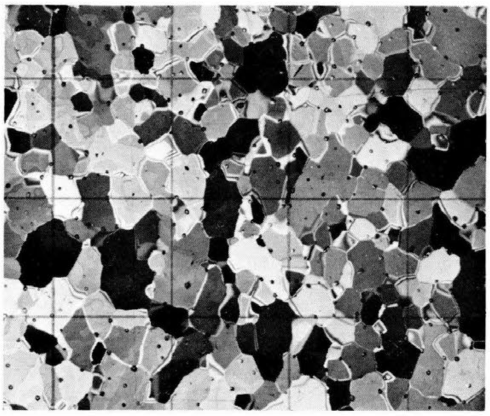
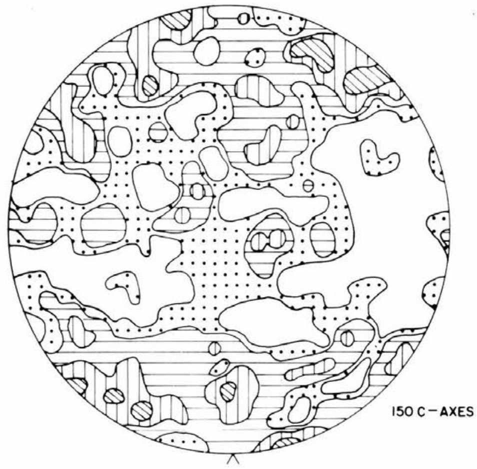


Figure 3. Crystal size variations with depth in the Antarctic Ice Sheet at Byrd Station. Squares are average values of several closely spaced sections. Crystal size data in firn (small solid circles) are also included.

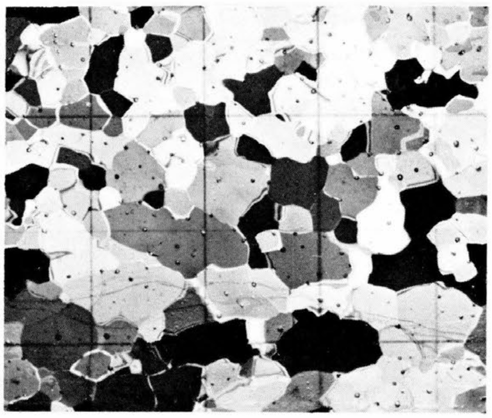


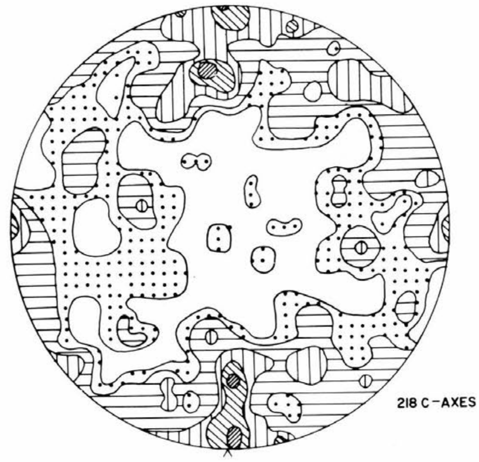
Depth
193 m



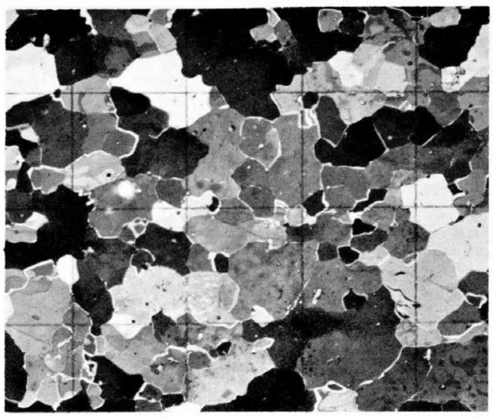


Depth
216 m





Depth
264 m



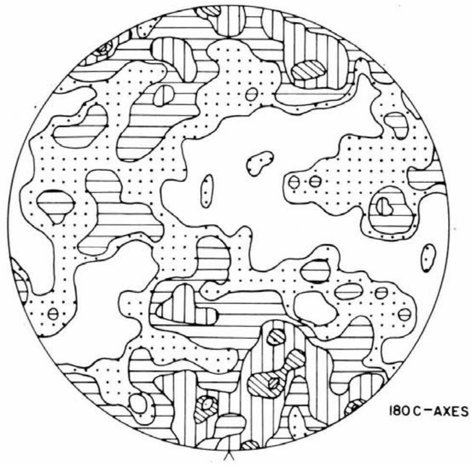


Figure 6 (Cont'd). Crystal structure and c-axis fabrics of six vertical core sections (same orientation as for ice from 163 m in Fig. 2) from Byrd Station. Photographs taken between crossed polaroids. Grid spacing measures 1 cm. Fabric contours at 4%, 3%, 2%, 1% and 0.5% per 1% area.

Depth 100 m

Depth 116 m

Depth 135 m

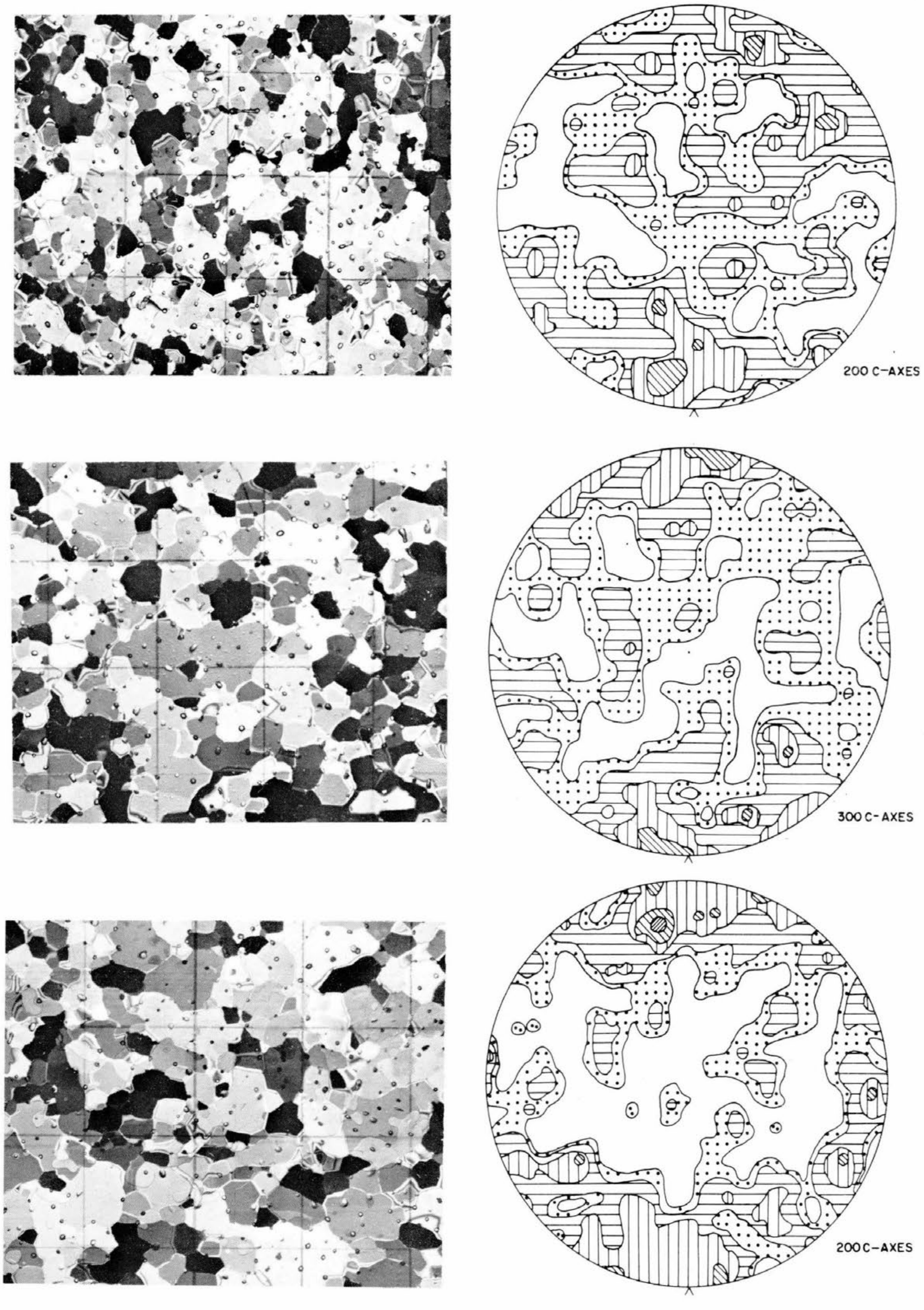


Figure 6. Crystal structure and c-axis fabrics of six vertical core sections (same orientation as for ice from 163 m in Fig. 2) from Byrd Station. Photographs taken between crossed polaroids. Grid spacing measures 1 cm. Fabric contours at 4%, 3%, 2%, 1% and 0.5% per 1% area.

Depth
193 m

Depth
216 m

Depth
264 m

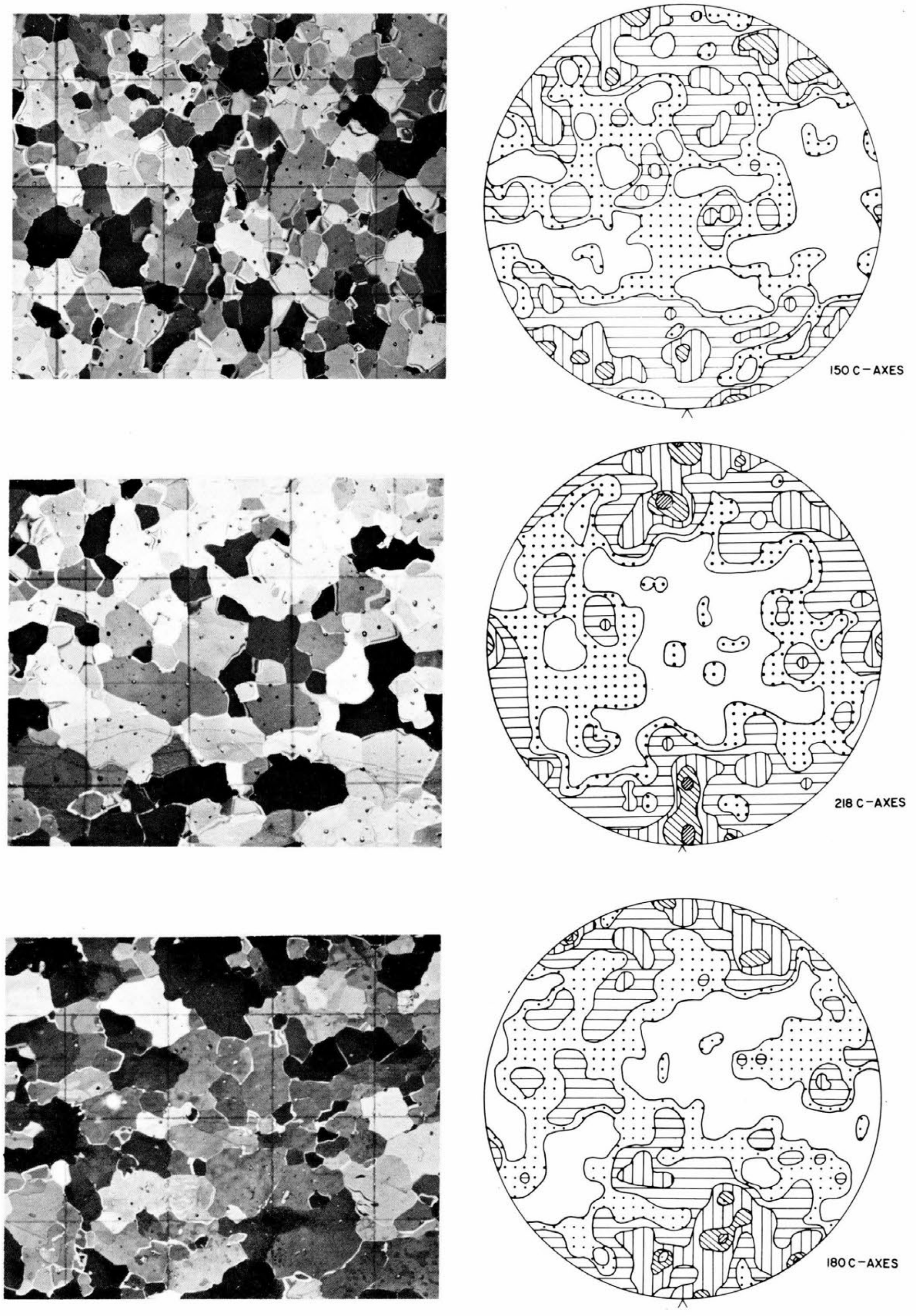


Figure 6 (Cont'd). Crystal structure and c-axis fabrics of six vertical core sections (same orientation as for ice from 163 m in Fig. 2) from Byrd Station. Photographs taken between crossed polaroids. Grid spacing measures 1 cm. Fabric contours at 4%, 3%, 2%, 1% and 0.5% per 1% area.

that isothermal growth of crystals in the upper layers of the ice sheet at Byrd Station is controlled more by equilibrium requirements at grain boundaries than by the existence of so-called favorably oriented crystals or nuclei; i.e., growth is not simply a question of crystals of some set orientation absorbing neighboring crystals and imposing their orientation upon the new structure. A similar lack of oriented fabrics was also observed by Langway (1962) in ice to 300-m depth at Site 2, Greenland.

Since shear deformation seems essential to the formation of oriented crystal fabrics in ice (this has been amply demonstrated in both laboratory experiments and field studies, e.g., Rigsby, 1960; Kamb and Shreve, 1963; Kamb, 1964), it would seem safe to conclude that negligible distortion is occurring in the top 300 m of the ice sheet at Byrd Station. Additional evidence in support of this contention is the lack of dimensional orientation of either crystals or bubbles in the ice at Byrd Station and the observation (Gow, 1963a), based on several years' measurements, that the deep hole itself has not deviated significantly from the vertical since it was drilled. The textures and weakly developed fabrics in ice at Byrd Station thus compare favorably with those observed in rocks that have recrystallized under simple lithostatic pressure in the earth's crust. While such rocks may show evidence of grain growth, this growth is not generally accompanied by any important changes in lattice orientation. However, with the onset of shear in the deeper parts of the ice sheet preferred orientation of crystals could be expected to develop.

Little America V crystal structure and fabrics

General properties. The general process by which snow transforms to bubbly ice at Little America V is essentially the same as that observed at Byrd Station but with two notable differences. A very anomalous increase in the rate of compaction (densification) of snow occurred at about 36-m depth, and this was accompanied by a very rapid obliteration of seasonal snow layering (stratigraphy) as the firn-ice transition was approached (Gow, 1968a).

The transition from firn to ice occurred at a depth of 52 m. This ice was composed of randomly oriented, equidimensional crystals of an average cross section of 7 mm^2, which is approximately twice the size of crystals observed at the firn-ice transition at Byrd Station. Subsequent changes in structure of the ice at Little America V were characterized by (1) a rapid rate of growth of crystals, (2) the appearance of "strain shadows" in crystals at around 65-m depth, and (3) the formation of oriented fabrics by 100 m. These changes and those affecting snow stratigraphy and compaction above 52 m (described in greater detail by Gow, 1963b and 1968a) can all probably be attributed to the action of large horizontal stresses in the upper layers of the Ross Ice Shelf. The same stresses are probably also responsible for the creation of a number of rifts, crevasses and depressions in the general area of Little America V (see Crary, 1961).

Considerable strain was evident in crystals below 65 m and the undulose extinction arising from it was intensively developed in ice from between 95 and 130-m depth, especially in some sections cut parallel to the basal planes of crystals. However, undulose extinction was much diminished in sections cut normal to the basal planes of crystals; this would suggest that "strain shadows" are formed by bending or warping of the glide planes during deformation. Extinction bands were observed in several crystals, with variations of up to 2° being noted in some crystals. Such banding might be attributed to "kinking" of the type that Nakaya (1958) observed after he had deformed single crystals of ice by bending.

A very definite dimensional orientation of crystals (represented by a "flattening" of crystals in the horizontal plane of the ice shelf) was noted in vertical sections from below 100 m, and a thoroughly interpenetrative texture had evolved by 150 m. This intergrowth texture, resembling a three-dimensional jig-saw puzzle gave way to more smoothly sutured crystal outlines in cores from near the bottom of the ice shelf.

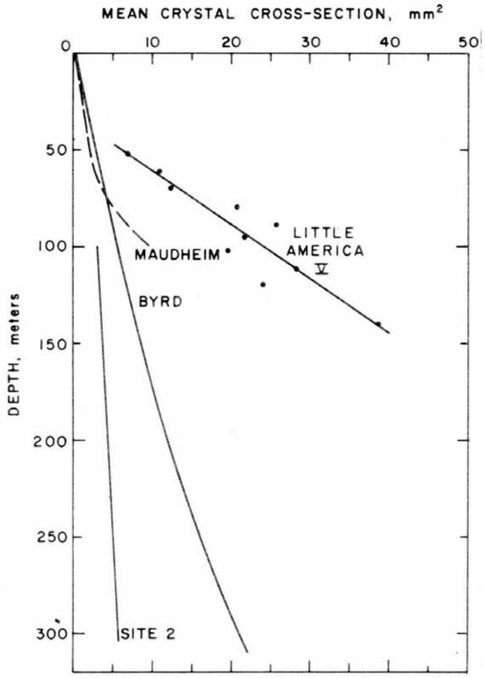


Figure 7. Crystal size variations to depth of 140 m in Ross Ice Shelf at Little America V. Exaggerated crystal growth occurs below 140 m and crystal cross sections in excess of 10 cm² are not uncommon. Crystal growth trends at Byrd Station and Maudheim, Antarctica, and from Site 2, Greenland, are included for comparison.

Crystal growth. A plot of crystal size versus depth in the Ross Ice Shelf is included in Figure 7. Results are also listed in Table II. Crystal cross sections were observed to increase from 7.0 mm^2 at 52 m to nearly 40 mm^2 at a depth of 140 m. A transition to an interpenetrated crystal structure occurred between 140 and 150 m. The size of crystals increased abruptly below 140 m and in some sections from near the bottom of the ice shelf crystals as large as 10 cm^2 and more were observed. These included several crystal cross sections of identical c-axis orientation that very probably comprise different parts of the same crystal. Because of this complication no attempt was made to continue with precise measurements of crystal size below 140 m. The same kind of complexity of crystal structure is also known to exist in temperate glaciers (Bader, 1951; Rigsby, 1968). Rigsby also believes that this complexity of structure could lead to faulty interpretation of fabrics.

A comparison of crystal growth data from Little America V, Byrd Station, and Site 2, Greenland (Fig. 7), shows that the growth rate is between six and seven times greater at Little America V (0.36 mm^2m^{-1}) than at Byrd Station (0.056 mm^2m^{-1}) and almost thirty times greater than that at Site 2 (.013 mm^2m^{-1}). Although temperatures in the top 140 meters of ice at Little America V are appreciably higher than at Byrd Station they are not too different from those at Site 2; this would imply that other factors, particularly deformation, have been responsible for the more rapid rate of growth of crystals at Little America V. Crystal size data from the Maudheim Is-Shelf (Schytt, 1958) are also included in Fig. 7. Crystals are very much smaller at Maudheim despite the fact that temperatures everywhere in the ice at Maudheim are higher than those at Little America V. The absence of any strong patterns of preferred orientation of crystals down to 100 m at Maudheim would also tend to indicate that deformation has been much less of a factor in recrystallization at Maudheim.

Table II. Crystal size variations with depth in the Ross Ice Shelf at Little America V.

Depth (m)	*Mean crystal area (mm^2)*	*No. of crystals in count*
52	7.0	480
61	10.9	335
70	12.5	311
80	20.7	215
89	25.6	172
95	21.6	176
102	19.6	235
112	28.1	158
120	20.4	197
140	38.6	122

Crystal fabrics. Laboratory tests show that single crystals of ice deform most readily in shear by actual slippage along the crystallographic basal plane. This slipping or gliding of planes one over the other is further facilitated by bending in such a way that differential movement can occur along slip planes in a manner similar to bending a pile of papers (Nakaya, 1958; Rigsby, 1958). While the structure of ice restricts gliding rigorously to the basal plane it would appear that gliding can occur in any direction in this plane (Glen and Perutz, 1954; Steinemann, 1954; Kamb, 1964). With this combination of properties the crystals in actively deforming glacier ice should tend to become oriented with their basal slip planes aligned more or less parallel to the planes of maximum resolved shear. This in fact is what is observed in highly stressed ice in both polar and temperate glaciers. However, single-maximum fabrics (c-axes [0001] concentrated in a single maximum about the pole to the foliation and/or inferred shear plane) tend to give way to fabrics composed of several maxima, none of which coincides exactly with the pole to the shear plane. These multiple-maxima fabrics are especially characteristic of temperate glaciers and were once thought to be unique to temperate ice that had recrystallized under near stress-free conditions at the glacier surface. However, the same fabrics have now been encountered at Little America V and at several other localities in the deformed, cold ice of Antarctic glaciers.

Signs of preferred orientation of c-axes in the ice shelf at Little America V first began to appear with the onset of undulose extinction (strain shadows) in crystals between 65 and 70-m depth (Fig. 8). The pattern of orientation involved a gradual migration of c-axes into subvertical positions, i.e., for basal planes of crystals to orient into subhorizontal positions. At 116 m (Fig. 9), 75% of c-axes were oriented within 35° of the vertical. A clustering of c-axes into two, three or four maxima is a characteristic feature of all fabrics below 95 m.

An additional fabric element *lineation*, arising from the parallel arrangement of elongate tubular air bubbles, made its appearance at around 95 m and persisted to 140-m depth. Not all air bubbles in this zone are elongated. Most, in fact, are spherical, but as demonstrated in Figure 9 the elongate bubbles are invariably oriented parallel to one another and they tend also to be oriented within the horizontal plane of the ice shelf. The centers of many of these bubbles are constricted, possibly as a result of stretching. Although they may cross crystal boundaries, lie along boundaries or be entirely inclosed within a crystal, these elongated bubbles do not appear to show a preference for any particular position.

Bubble lineation was accompanied also by a crude dimensional orientation of crystals, arising from a "flattening" of crystals within the horizontal plane of the ice shelf. This relationship is clearly demonstrated in Figure 9 for ice from 116-m depth. Three mutually perpendicular sections were prepared of this ice: two sections cut parallel to the lineation and a third section cut normal to the lineation. No major variation in c-axis patterns can be discerned in these three sections, indicating that the fabrics are truly homogeneous. The lattice orientation is of the incomplete girdle type with two symmetrically oriented maxima located on the long axis of the girdle which is positioned normal to the bubble lineation and the plane of flattening of the ice crystals. This close relationship between the lattice and dimensional orientations of crystals is entirely compatible with intra-crystalline slip on the basal glide planes. The marked tendency for crystals to be interpenetrated in the direction of the lineation (possibly a flow direction) is further evidence in support of a movement picture controlled by basal glide. The widespread occurrence of strain shadows in crystals would also indicate that bending of glide planes has assisted materially in the orienting process.

Unfortunately, cores could not be oriented in the azimuth during drilling so that it is not possible to determine directly the relationship of the various fabric elements (lineation and girdle symmetry) to the direction of ice flow. However, measurements by Crary (1961) show that the ice shelf in the vicinity of Little America is expanding, and that the minimum strain rate ($81 \times 10^{-5} yr^{-1}$)

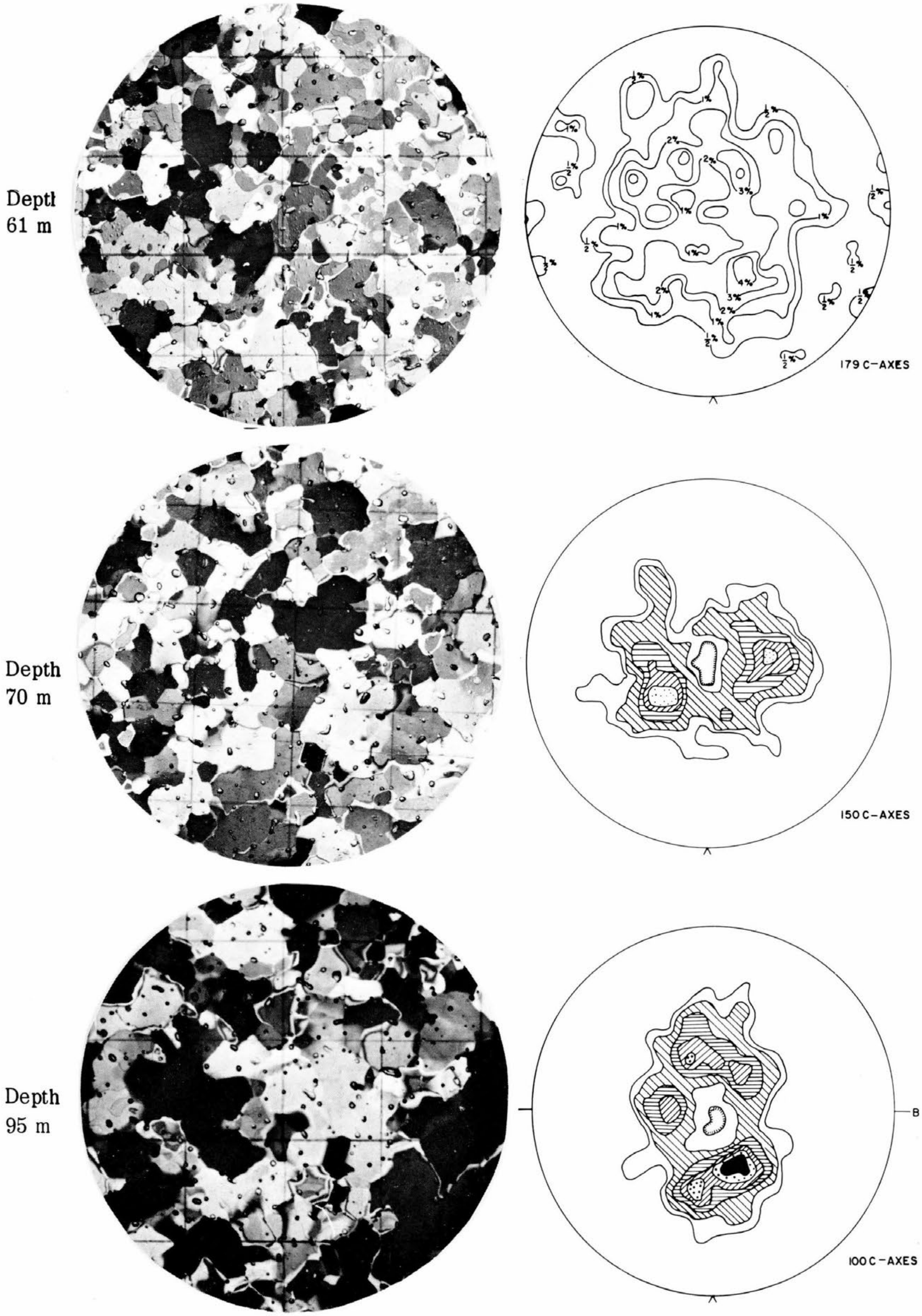


Figure 8. Crystal structure and c-axis fabric profiles of the Ross Ice Shelf at Little America V. Note (a) strain shadows in crystals below 95 m, (b) alignment of elongate air bubbles at 95 m and 112 m and (c) growth of very large crystals below 140 m. All fabric diagrams are from horizontally sectioned cores. Contour intervals for ice from 61 m as indicated. Contour intervals for all other diagrams at 10%, 8%, 6%, 4%, 2% and 1% per 1% area. The grid scale in photographs measures 1 cm.

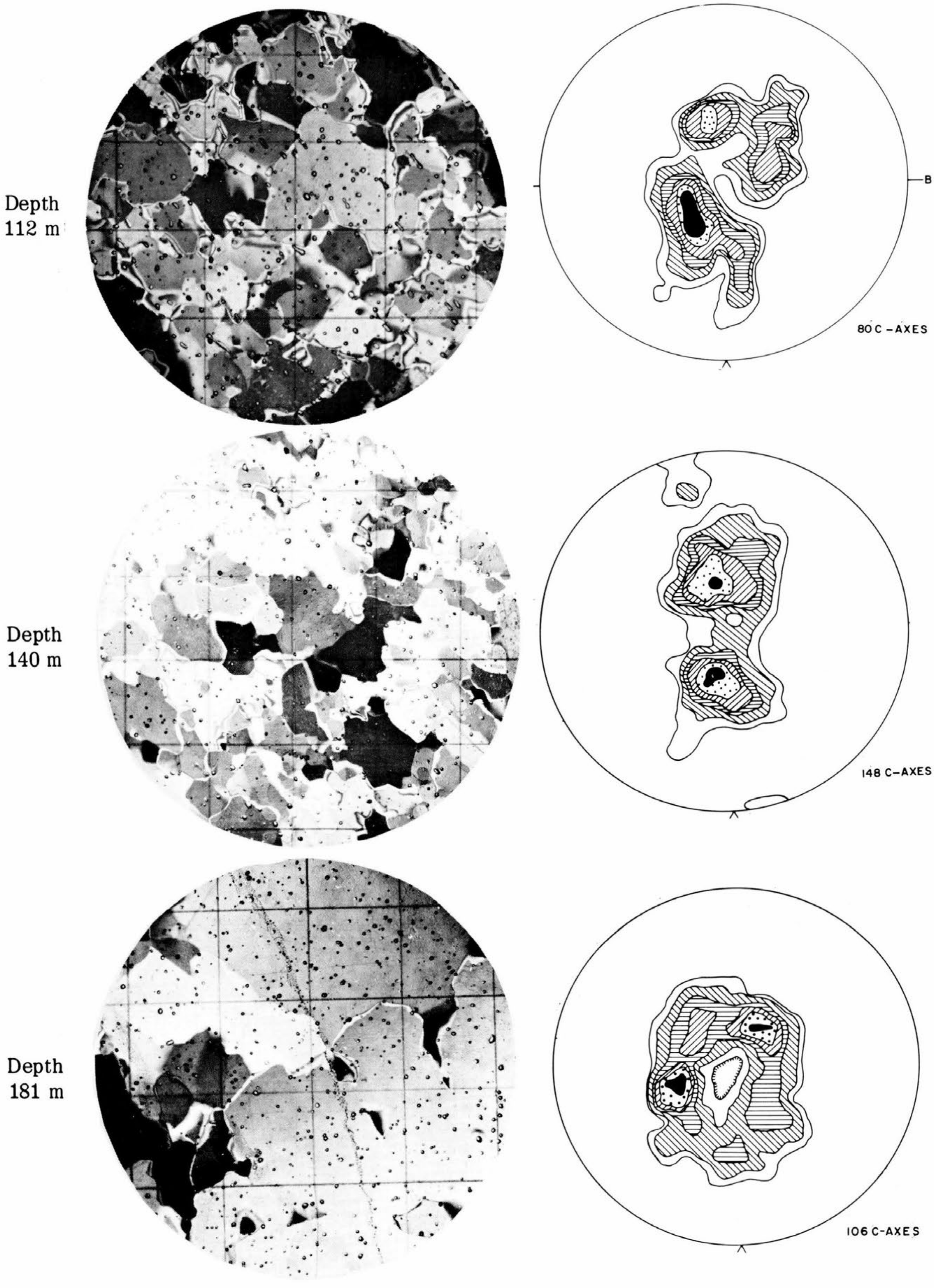
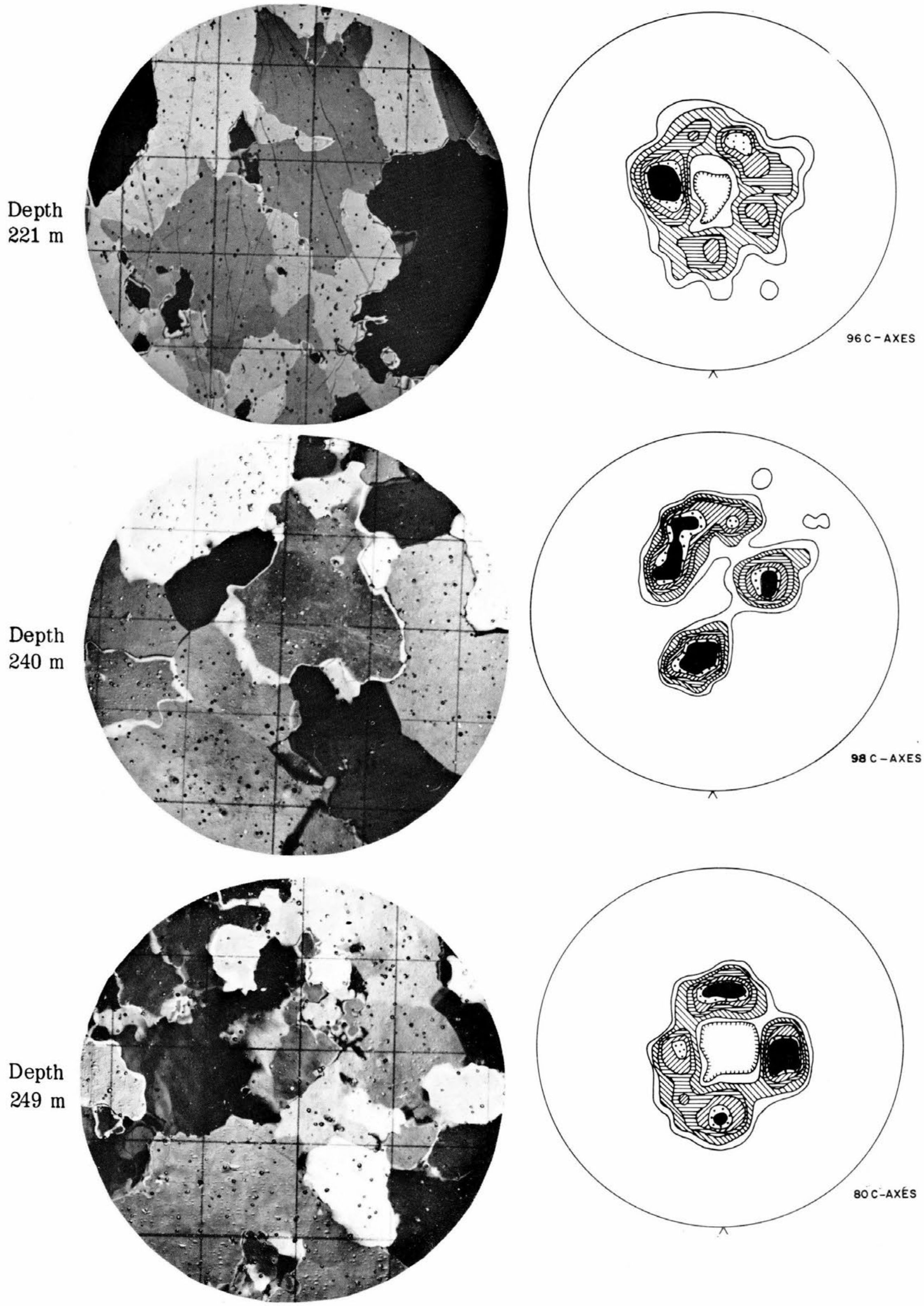


Figure 8 (Cont'd).



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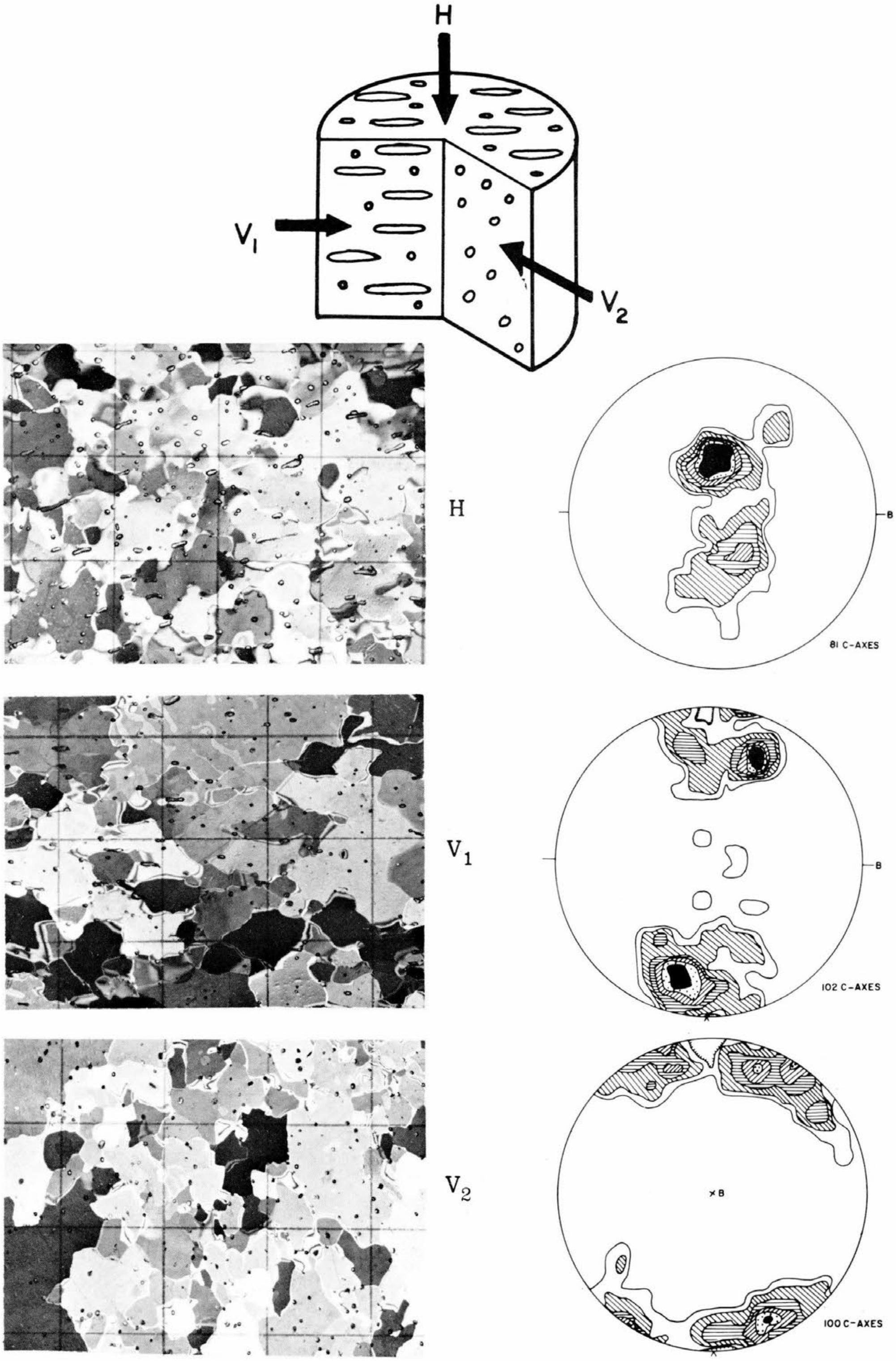

Figure 9. Crystal structure and fabrics of three mutually perpendicular sections of an ice core from 116-m depth at Little America V. Sketch of core illustrates relationship of sections to fabric lineation B (bubble elongation). Contours at 10%, 8%, 6%, 4%, 2% and 1% per 1% area. The grid scale in photographs measures 1 cm.

is approximately parallel to the direction of measured ice motion. If this were to coincide with the direction of alignment of elongated bubbles then the girdle-like distribution of c-axes would correspond with the direction of maximum strain rate ($129 \times 10^{-5} yr^{-1}$). Similar movement pictures (lineation parallel to transport direction and normal to c-axis girdles) have been reported for quartz-bearing rocks subjected to strong shearing in and near thrust zones (Fairbairn, 1954).

Multiple-maxima fabrics composed of three or four symmetrically oriented c-axis maxima were observed in deeper ice (> 150 m) at Little America V. These maxima were located generally within 25° of the vertical but there was no indication of any final coalescence of individual maxima into a single vertical maximum. This occurrence at Little America V of multiple-maxima fabrics in ice considerably below its melting point (see Fig. 5 for depth-temperature data) is conclusive evidence that this type of fabric is not unique to temperate glaciers, i.e., glaciers at or close to the melting point. Kizaki (1962) and Reid (1964) have also recorded the occurrence of multiple-maxima fabrics in Antarctic ice. These observations and the discovery by Kamb (1964) of very strong multiple-maxima fabrics in the highly stressed ice at the bottom of a temperate glacier (where single maximum fabrics might have been expected) would tend to indicate that neither temperature nor deformation exerts exclusive control on the formation of multiple-maxima fabrics in glaciers.

The development of three- and four-maxima fabrics in ice from deeper than 150 m at Little America V was accompanied by an exaggerated growth of crystals on the one hand and a significant decrease of ''strain shadows'' in crystals on the other. Crystal cross sections ten times as large and larger than those at 140 m were not uncommon in ice from below 150 m. The gradual disappearance of undulose extinction from crystals from below 150 m can probably be attributed to the elimination of strains within the crystals, which may have occurred during the period when crystals were undergoing exaggerated growth. Exaggerated growth of crystals can probably be correlated with the onset of warmer temperatures in the deeper parts of the Ross Ice Shelf. Alternatively, the abrupt change in the structure of the ice between 140 and 150 m may reflect a change in the origin of the ice from above and below this zone. Schytt (1958), for example, has attributed a similar sharp increase in crystal size between 70- and 75-m depth in the Maudheim Is-Shelf to a change in ice type, ice from below 75 m having been derived from the inland ice sheet and that above 75 m having originated as shelf accumulation.

Except for a slight indication of a multiple-maxima fabric pattern at 100-m depth, Schytt did not detect any significant trend of c-axis orientation in the ice shelf at Maudheim. At Little America V, however, the inland ice component of the Ross Ice Shelf may have been eliminated almost entirely by bottom melting. According to estimates made by Crary *et al.* (1962) all but the bottom 20 m or so of the ice column at Little America V should be composed of shelf accumulation. If so, elevated temperatures near the bottom of the ice shelf should have obliterated any differences in the original structure of the ice.

Most of the features of the texture and fabrics of ice at Little America V can be reconciled with some process of deformational recrystallization, particularly the kind of deformation that could be expected from the simple spreading action of a broad ice sheet floating on water. Weertman (1957) has likened this situation to that of a weightless material being compressed between frictionless plates. However, the question arises: To what extent does the structure observed in cores from Little America V reflect current conditions in the ice shelf and to what extent is it inherited? For example, areas of grounded ice and obstructed flow are known to exist upstream from Little America V, e.g. Roosevelt Island. Such obstruction to flow would introduce an additional element of deformation, which, if intense enough, could be expected to leave some imprint in the structure of the ice. One particular element of the structure which may have originated in this way is the bubble lineation observed in cores from between 95- and 130-m depth.

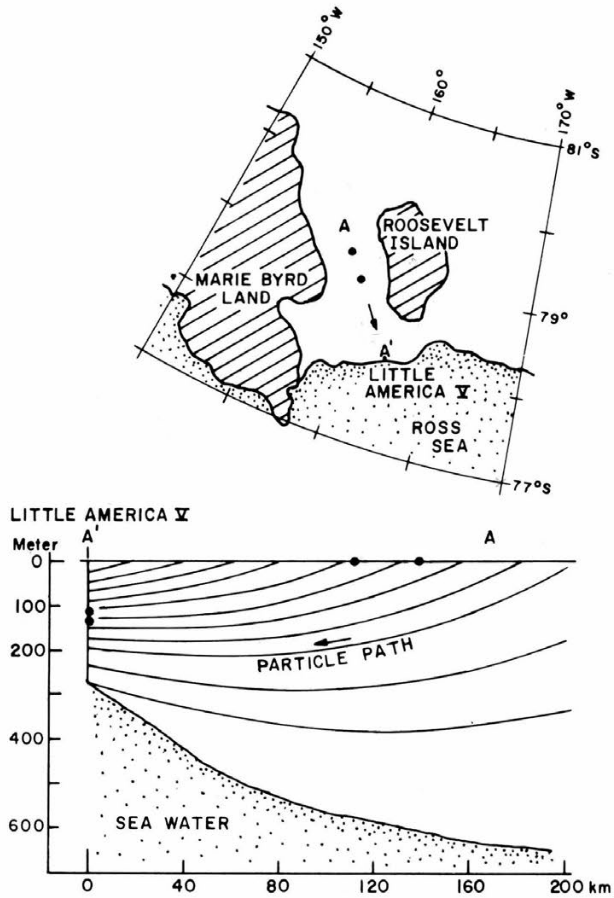

Figure 10. Sketch map indicating the direction of ice flow east of Roosevelt Island towards Little America V. The region between the two solid circles represents the probable deposition site of cores containing oriented elongate air bubbles from a depth of 95-130 m at Little America V. The cross section is adapted from Crary et al. *(1962).*

A generally north to northwest motion has been established for the direction of ice flow in the vicinity of Little America V (Crary and Chapman, 1963; Zumberge, 1964), and it is apparent from Fig. 10 that most of the material of the cores at Little America V must have been subjected at one time or another to strongly directed flow as it made its way past the eastern edge of Roosevelt Island. Roosevelt Island is aligned in a north-south direction and its northern tip is located approximately 60 km from Little America V. It is approximately 120 km long and so could be expected to influence the movement of that part of the ice shelf located 60 to 180 km upstream from Little America V.

The problem of estimating the ages of cores, and determining just where they originated on the ice shelf, has been attempted already by Crary *et al.* (1962). An examination of Crary's section depicting ice particle paths along the flow line inland of Little America V (see Fig. 10) shows that cores from between 95 and 130 m (those with elongated bubbles) would have been deposited and buried to a depth of 40 to 80 m during the time this ice was moving by Roosevelt Island some 115 to

140 km to the rear of Little America V. The particular interest in this ice stems from the fact that any flow-induced alignment of bubbles in the ice as it made its way past Roosevelt Island is more likely to occur in the firn-ice transition zone, with its abundance of tubular bubbles, than in deeper ice where bubbles tend to be spherical. This could explain why oriented elongate air bubbles are confined to cores from between 95 and 130 m. The most severely "strained" crystals were also observed in this zone and dimensional orientation of crystals was best developed at these depths, too.

Composition of Ross Ice Shelf at Little America V. Results based on the structure and fabrics of cores at Little America V definitely confirm earlier conclusions, based on temperature measurements and electrolytic conductivity data, that the Ross Ice Shelf at Little America V is composed entirely of glacial ice. Conductivity tests of the bottom cores by Gow (1968) failed to reveal any accretion of sea ice, and according to Crary (1961) and Jenssen and Radok (1961) the temperature gradient near the bottom of the Ross Ice Shelf at Little America V can be reconciled only on the basis of very substantial bottom melting.

CONCLUSIONS

Radical differences in the crystal structure and petrofabrics of ice in deep drill cores from Byrd Station and Little America V probably reflect major differences in the thermal and deformational history of the Antarctic Ice Sheet at these two locations. At Byrd Station, situated on the thick (2400-m) grounded ice sheet of West Antarctica, the mean crystal cross section increased from 3.1 mm^2 at 65-m depth to nearly 20 mm^2 at 307-m depth. The largest crystals seldom exceeded 1.5 cm^2 in a cross-sectional area. Crystal size was found to increase linearly with the age of the ice. Since temperatures in the ice are essentially constant between 65 m and 307 m this lineal growth of crystals with time can be considered analogous to the process of isothermal grain growth in metals and ceramics. However, the sixfold increase in mean crystal size between 65 m and 307 m was not accompanied by (1) any gross changes in the distribution of entrapped air bubbles, (2) any dimensional orientation of bubbles or crystals and (3) any significant increase in the degree of preferred orientation of crystallographic c-axes. These data, in conjunction with the observation that the bore hole itself has undergone no significant bending since it was drilled, would indicate that negligible shear deformation is occurring in the top 300 m of the ice sheet at Byrd Station.

At Little America V, situated near the seaward edge of the large free-floating Ross Ice Shelf, the mean size of crystals increased from 7.0 mm^2 at 52 m to nearly 40 mm^2 at 140-m depth. A very abrupt increase in crystal size occurred below 140 m (crystal cross sections in excess of 10 cm^2 are not uncommon) and this is attributed to the effects of increasing temperatures in the ice shelf. "Strained" crystals were much in evidence below 65 m, dimensional orientation of crystals and air bubbles was particularly well developed between 95 m and 130 m, and a thoroughly interpenetrated texture had evolved by 150-m depth. All these elements of the ice structure at Little America V are compatible with the existence in the ice shelf of considerable shearing that has also produced drastic changes in crystal orientation.

A clustering of c-axes into two maxima about the normal to the horizontal plane of the ice shelf occurred initially, but this pattern was replaced in deeper ice by multiple-maxima fabrics composed of three or four symmetrically oriented maxima. This discovery of multiple-maxima fabrics in deformed ice considerably below its melting point further refutes the idea that such fabrics are confined to temperate glacier ice that has recrystallized under near stress-free conditions at the surface. The major fabric elements can probably all be correlated with current conditions of deformation and temperature in the immediate vicinity of Little America V. However, the occurrence of elongate oriented bubbles between 95-m and 130-m depth may be related to a period of more intensive deformation when the ice was moving past Roosevelt Island. It is established also that the Ross Ice Shelf at Little America V is composed entirely of glacial ice.

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13. ABSTRACT

Radical differences in the crystal structure and fabrics of glacier ice cores at Byrd Station and Little America V, Antarctica, are attributed to gross differences in the thermal and deformational histories of the ice at these two locations. At Byrd Station the mean size of crystals increased more than sixfold between 65 m and the bottom of the drill hole at 309 m. Crystal size was also found to increase linearly with the age of the ice, thus simulating isothermal grain growth in metals. However, this growth was not accompanied by any dimensional orientation of crystals or entrapped bubbles, or by any significant increase in the degree of preferred orientation of crystallographic c-axes. These observations imply that negligible shearing is occurring in the top 300 m of the thick grounded ice sheet at Byrd Station. By contrast very considerable deformation is indicated for the floating 258-m-thick Ross Ice Shelf at Little America. This deformation is characterized by the widespread occurrence of "strained" crystals below 65 m, the existence of elongated oriented bubbles between 95 m and 130 m and the attainment of pronounced crystal orientation (multiple-maxima fabrics) by 100-m depth. Exaggerated growth of crystals below 150 m is attributed to increasing temperatures in the ice shelf. The crystal structure of these cores clearly demonstrates that glacial ice only is present in the Ross Ice Shelf at Little America V.

14. Key Words

Antarctica--Byrd Station	Ice cores	Ice deformation
Antarctica--Little America V	Ice crystal growth	Ice fabrics
Glacier ice	Ice crystal structure	

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