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A COMPARISON OF ICE FABRICS AND TEXTURES AT CAMP CENTURY, GREENLAND AND BYRD STATION, ANTARCTICA

by

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ABSTRACT

A comparison of the crystalline texture and fabric of the two deep cores to bedrock from Camp Century, Greenland, and Byrd station, Antarctica, reveals striking similarities. Each core exhibits a fabric profile which progresses from depositional fabrics at shallow depths through multi-maxima transitional stages into single maximum distributions. The major difference between the two cores occurs near the base where the Camp Century fabrics maintain a high degree of orientation while the Byrd station fabrics break up into a diamond pattern. The most remarkable similarity between the two profiles occurs at the glacial-interglacial transition where crystal sizes decrease and crystal orientations strengthen significantly over a very short interval. Similar changes occur in other deep ice cores, thus indicating the possibility that the late Wisconsin ice has a unique crystallographic signature.

INTRODUCTION

The deep ice cores from Camp Century, Greenland, and Byrd station, Antarctica, are unique stratigraphic records. The 1 375 m of ice from Camp Century and the 2 164 m of ice from Byrd station represent the only surface-to-bedrock cores ever recovered from the interiors of the two existing ice sheets, and consequently they provide the only opportunity to investigate directly the internal structure and composition of these large ice masses (Hansen and Langway 1966, Gow and others 1968). In the past, isotopic, chemical, and microparticle studies on these two cores have provided a wealth of glaciological, climatic, and environmental data. Other investigations of physical and mechanical properties of polar ice have enhanced efforts to interpret flow histories and to predict ice properties and behavior. The analysis of textures and fabrics on the Byrd station core (Gow and Williamson 1976) has produced results which have been used extensively to aid in the classification of ice fabrics and the development of model fabric profiles for land-based ice (Budd 1972, Hooke and Hudleston 1980). The measurement and statistical treatment of the Camp Century ice-core textures and fabrics provide a new data base to compare with the observed Byrd station results and with the model predictions.

METHODS

Crystal size

Horizontal thin sections were prepared from 32 depths in the upper 240 m of the Camp Century core during the 1961 field season. Between 1978 and 1980, thin sections were prepared from the remainder of the 1 375 m core at approximately 100 m intervals between 400 and 800 m and at 50 m intervals below 800 m. Vertical sections covering at least 25 cm of core were made at the depths of 725, 1 028, 1 136, 1 231, 1 315, and 1 331 m. No samples were taken between 250 and 390 m due to the fractured condition of the core.

Cross-sectional crystal areas were measured from photographs using a semi-automatic Zeiss particle-size analyzer. For thin sections, in which crystal sizes were too large or crystal shapes too complex, this method was dropped in favor of counting crystals within a given area. Comparison of the two methods on eight thin sections revealed a variation of less than 15%. For each thin section, the area of the largest crystal or partial crystal was also recorded.

Fabrics

Crystal c-axis orientations were measured on a Rigsby universal stage and plotted on a lower hemisphere Schmidt net projection using standard techniques (Langway 1958, Kamb 1962). In order to describe the Camp Century fabric profile, the orientation data are treated in several ways. First, the results are presented as contoured fabric diagrams in order to facilitate comparison with published results from the Byrd station core (Gow and Williamson 1976). From these diagrams, it is possible to describe the shape of the distribution and to determine the maximum concentration of c-axes falling in 1% of the area.

Several statistical parameters are also calculated for each fabric analysis. One is the length of the resultant vector R, which is obtained by determining the unit vector equivalent to each measured c-axis orientation and summing all c-axis vectors from a given depth. If all c-axes are oriented in the same direction, the value of R will be equal to the number of c-axes. In this work, R is normalized, so the maximum possible value is unity. This statistic provides a measure of concentration about the mean direction and will be large for oriented samples (Mardia 1972).

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An alternative method of determining the form of the distribution is also used. This method, determined by Bingham (unpublished) and summarized by Mardia (1972), is based on the interpretation of the eigenvectors and eigenvalues calculated from axial data at each depth. Using this approach, three eigenvalues are obtained. These represent the three principal axes of the normalized ellipsoid which best fit the c-axis orientation data. The lengths of the principal axes give the eigenvalues which can be used to interpret both the fabric distribution and strength. From the eigenvalues, certain types of axial distributions can be identified as follows: (1) for a uniform distribution, all the eigenvalues are approximately equal, (2) for a bimodal distribution, one of the three eigenvalues is large with respect to the other two, the remaining two are not equal, and R is not large, (3) for a unimodal or polar distribution, one eigenvalue is large compared to the others and R is large, and (4) for a girdle distribution, one eigenvalue is small compared to the other two.

The eigenvalues can be further used in the evaluation of fabrics by calculating the concentration statistic, $(E_3/N)^{0.5}$, where E_3 is the largest eigenvalue and N is the number of c-axes measured in the sample (Hudleston 1977). This statistic is similar to the maximum concentration and the length of the resultant vector in that it provides a measure of concentration about the mean directions.

RESULTS

Camp Century textures

The crystal size data from the upper 240 m of the Camp Century core are presented as a function of time in Figure 1. Ages for the samples above 130 m

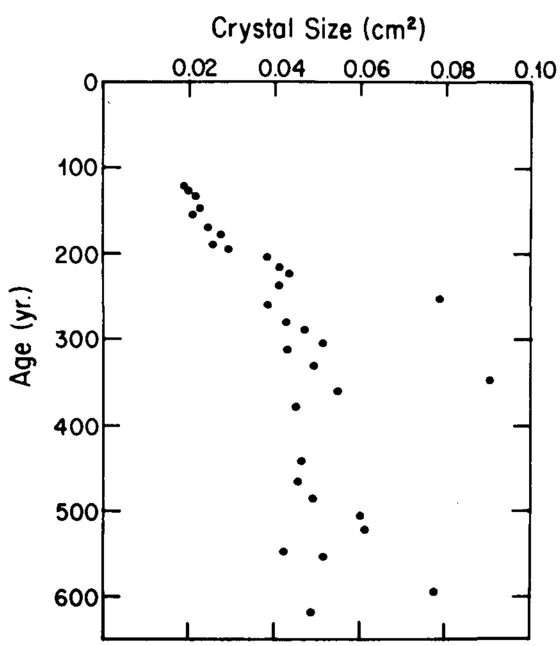

Fig.1. Crystal growth in the upper 240 m of the Camp Century core.

were determined from the firn densification model of Herron and Langway (1980), and ages for samples below 130 m were determined from the Camp Century time-scale of Hammer and others (1978). In each case, an accumulation rate of 0.382 m a^{-1} or 35 g a^{-1} was used (Hammer and others 1978). A linear regression of the crystal size data through the past 360 a yields a Camp Century growth rate of 1.7×10^{-4} cm^2 a^{-1} in close agreement with the value reported by Gow (1971, 1975). These rates are in accordance with the published temperature dependence of crystal growth (Gow 1971, 1975).

The results of the textural analysis over the entire depth interval are presented in Figure 2. In the upper 600 m, the average crystal size increases from 0.03 cm^2 at 100 m to about 0.4 cm^2. Over this same interval, the crystalline texture changes from tessalate to complex and interlocking, as may be seen in the thin-section photographs presented in

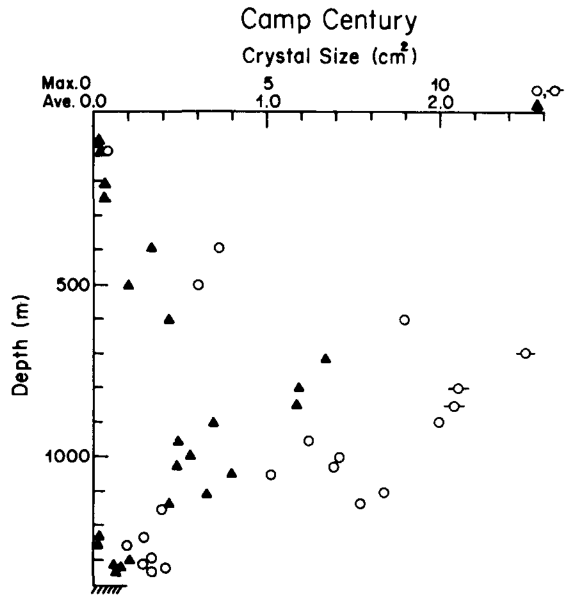

Fig.2. Crystal size in the Camp Century ice core. Triangles represent average size as indicated on the lower scale. Circles represent maximum size observed as indicated on the upper scale; a horizontal line through the circle indicates that the largest crystal was truncated at the edge of the thin section.

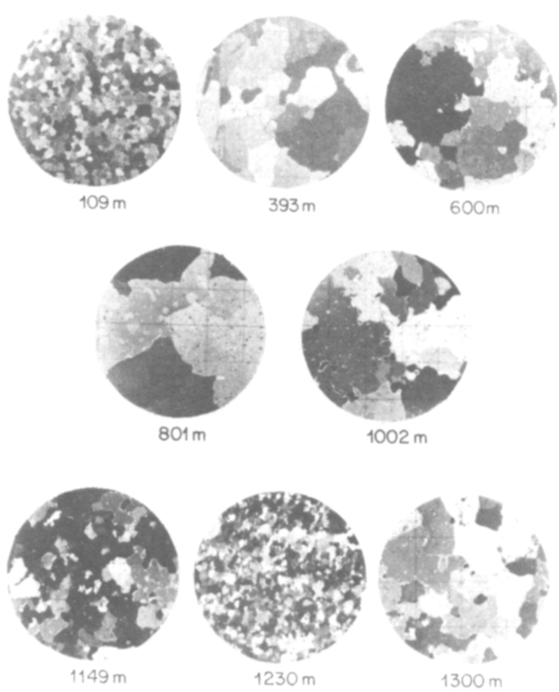

Fig.3. Textural development in thin sections from the Camp Century ice core. All photographs are at approximately the same magnification; the grid spacing is 1 cm.

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Figure 3. In this zone of the core, some of the deviation of observed crystal sizes from the expected growth curve can be attributed to the natural variability of crystal size. In a study conducted on the new Dye 3, Greenland, core it was found that crystal size varies seasonally and may change by a factor of four or more over short core intervals. This effect may be minimized by continuously sampling over multi-year increments (Herron and Langway to be published).

In the next 100 m of core, the average crystal size triples, and the largest observed crystals have cross-sectional areas which exceed 12 cm^2. These large crystal sizes persist until at least 850 m. Between 850 and 950 m, the average size decreases to about 0.5 cm^2, a size which is maintained for nearly 200 m. Then, between 1 136 and 1 149 m, the ice undergoes a drastic transformation to a very fine-grained texture with average crystal sizes as low as 0.02 cm^2 and maximum sizes of less than 0.4 cm^2. This reduction in crystal size occurs in the zone which has been identified as the glacial-interglacial transition by stable oxygen isotope analysis (Dansgaard and others 1969). By a depth of 1 300 m, the crystal sizes have increased back to 0.2 cm^2, and they do not exceed this size in the remaining 75 m of core, including the 16 m of debris-laden ice at the base (Herron and Langway 1979).

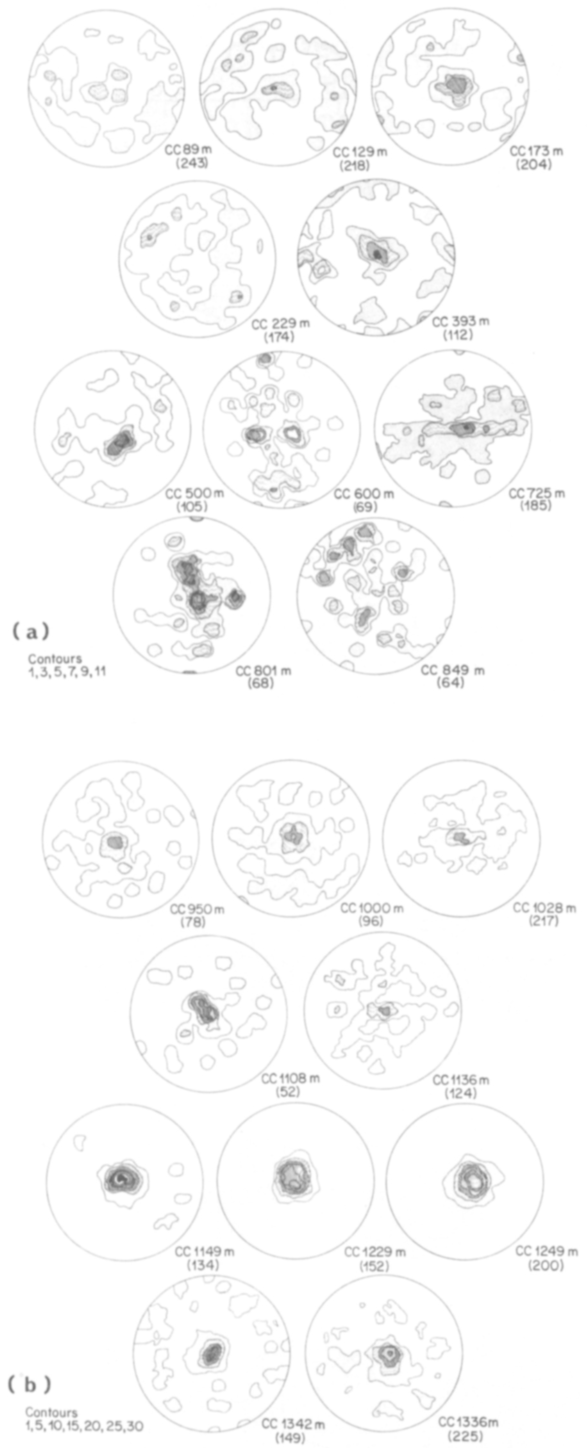

Fig.4. Contoured fabric diagrams for the Camp Century ice core. The number following CC on the upper line indicates the depth in meters; the number in parentheses is the number of c-axes measured. The contour intervals from 89 to 850 m (Fig.4(a)) are 1,3,5,7,9, and 11% per 1% area, and from 950 to 1 336 m (Fig.4(b)) they are 1, 5, 10, 15, 20, 25, and 30% per 1% area.

Camp Century fabrics

The fabric profile of the Camp Century ice core is shown in Figure 4 and the results of data treatment are presented in Figure 5. The average values

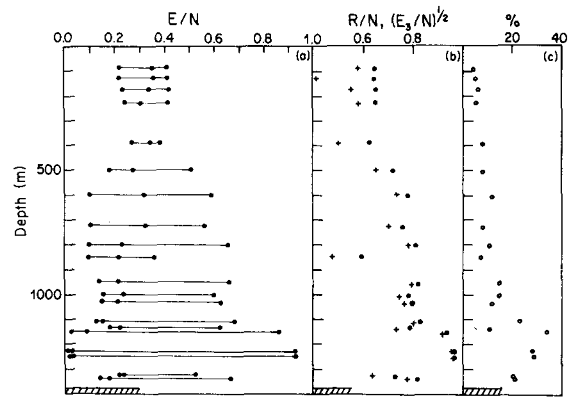

Fig.5. Orientation parameters calculated for Camp Century. (a) Normalized eigenvalue distribution. (b) Normalized resultant length (+) and concentration statistic (•). (c) Maximum concentration (%).

of the concentration maximum, normalized resultant, and concentration statistic are also summarized in Table I.

Between 65 and 229 m, fabrics were measured on 13 thin sections, four of which are shown here. From the contoured diagrams, the fabric patterns appear random in the upper sections changing to a small-circle distribution by 190 m with maximum c-axis concentrations between 4% and 6%. The average normalized length of the resultant over this interval is 0.53, and the concentration statistic is 0.64. For the upper three diagrams (Fig.4), the eigenvalues generally describe a weak girdle distribution, but for the small-circle they indicate a weak polar concentration. By 400 m depth, the maximum, concentration has increased slightly to 8%, but the statistics describe a pattern which is similar to those in the upper 200 m.

Between 500 and 850 m, the c-axes begin to cluster into smaller areas and the maximum concentrations have increased to between 8% and 12%. The normalized resultant length and the concentration statistic both show increases over this interval. The nature of the eigenvalues has also changed; they now spread over a larger range with one being slightly larger than the other two. Over this 350 m interval, there are actually several changes in the axial distribution. The pattern at 500 m is quite similar to the one over-

TABLE I. SUMMARY OF CAMP CENTURY FABRIC PROFILE

Depth interval (m)	Form of distribution	Average maximum concentration	Average normalized resultant	Average concentration statistic
90-400	Random, small circle	6%	0.52	0.64
500-850	Transition, multiple maximum	9%	0.67	0.73
950-1 135	Broad single maximum	15%	0.76	0.80
1 150-1 250	Strong single maximum	30%	0.95	0.96
1 325-bottom	Single maximum	21%	0.71	0.77

lying it, with the exception of the low-lying c-axes, but, by 600 m, the pattern has converted to a multi-maxima distribution. The 600 m depth also marks the beginning of the textural change to coarse-grained ice; although the average crystal size here is 0.44 cm^2, the largest crystal is 9 cm^2. By 725 m, where the average crystal size is over 1 cm^2, the fabric develops into an elongated central maximum, which is again broken up into a multi-maxima distribution by 800 m.

Below 850 m, the fabrics undergo a re-orientation which is concurrent with the first decrease in crystal size. Between 950 and 1 136 m, the fabrics display a near-vertical, broad single maximum with c-axis concentrations ranging from 11% to 23%. The normalized resultant length and the concentration statistic increase to 0.76 and 0.80, respectively.

Only 13 m below this depth interval, there is another significant re-orientation which produces the strongest single maximum fabrics observed in the entire Camp Century core. This strong vertical fabric persists between 1 149 and 1 249 m in the fine-grained ice from the Wisconsin glaciation. Here the c-axis concentrations range from 28% to 34% and the concentration statistic reaches its highest value of 0.96.

The fabrics from 1 324 and 1 336 m retain the vertical single maximum, but their strength is somewhat diminished from those directly above. Although the axial clustering appears compact, the statistics calculated for this zone are quite similar to those for the broad single maximum distributions.

Comparison with Byrd station

It is now possible to compare the texture and fabric profiles of the Camp Century ice core with those of the Byrd station ice core. In the following discussion all data from Byrd station are taken from the work of Gow and Williamson (1976). A schematic drawing representing the major trends in crystal size and fabric in the two cores is presented in Figure 6.

In the upper 600 m of ice, there are striking similarities between the two cores. In both cases, crystal size increases at a growth rate which can be closely predicted by the mean annual temperature at the site (Gow 1975). As in Camp Century, the upper several hundred meters of core display c-axis distributions with concentrations generally below 5%. In both cores, the patterns belong to what Matsuda (1979) has termed the depositional fabric phase, which is expected to predominate at shallow depths and is generally characterized by very small (0.01 to 0.1cm^2) polygonal crystals. By 400 m in the Byrd core, there are fewer low-angle c-axes and the distributions more closely approximate the two-maxima phase of the Matsuda (1979) classification; this is also expected at relatively shallow depths for small to medium crystal sizes.

The Byrd station fabrics continue to maintain a broad central clustering with two, or sometimes three, maxima through 900 m, all the while maintaining a constant crystal size near 0.6 cm^2. Between 600 and 900 m, the comparison of fabrics between the two cores is difficult because large crystal sizes and fractured core limited the number of measurements on the Camp Century core. Although there appear to be some similarities, the Camp Century development is difficult to interpret. This depth interval does, however, contain the first significant difference in the textural profiles of the two cores. Whereas the Byrd crystal sizes are constant, the Camp Century crystal sizes increase rapidly.

Around 950 m, the similarities between the two cores resume. By this depth, both cores display crystal sizes in the 0.3 to 0.6 cm^2 size range and both

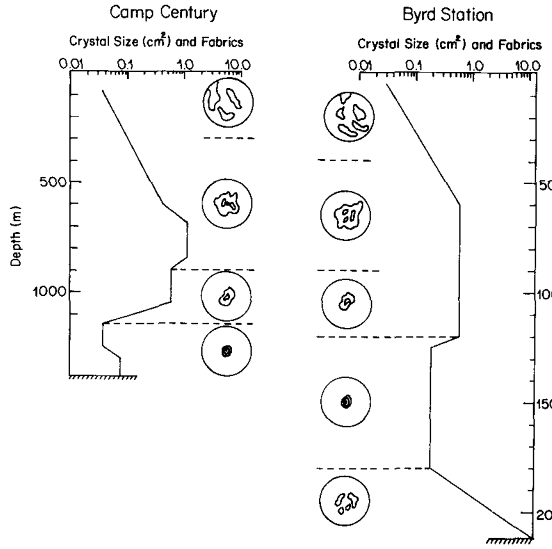

Fig.6. Comparison of crystal sizes and fabrics from Camp Century and Byrd station.

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cores have broad single maximum fabrics with c-axes oriented vertically and maximum concentrations over 10%. While the Camp Century fabrics remain fairly constant between 950 and 1 136 m, the Byrd station fabrics split into two closely-spaced maxima at 1 067 and 1 137 m before returning to a constant single maximum.

The next significant changes in the Byrd core occur around 1 200 m, and they bear a remarkable resemblance to those changes that are observed at 1 149 m in the Camp Century core. In both cores, crystal sizes decrease abruptly (0.02 cm^2 at Camp Century, 0.2 cm^2 at Byrd station) and c-axes are reoriented into strong, vertical single maximum fabrics. In both cores, these changes occur simultaneously with the isotopic shift marking the glacial-interglacial transition.

The remaining feature in the bottom 350 m of the Byrd station core constitutes the major difference between the fabric and texture profiles of the two cores. Below 1 810 m, Byrd station crystal sizes increase rapidly, reaching an average size of over 9 cm^2 by the bottom of the core. At the same time, the single-pole fabric breaks up and reorients into a diamond fabric. The features in this zone conform well to the diamond-fabric phase of Matsuda (1979) which is characterized by very large, interlocking crystals, and which occurs at bottom depths and high temperatures. The similarities and differences between these two deep cores can be explained more fully by a consideration of the parameters which determine texture and fabric in ice sheets.

Comparison with a model profile

Many factors have been postulated as important in the development of crystalline texture and fabric. These include stress level and stress state, total strain and strain-rate, microparticle and impurity content, time, temperature, deformation history, and deformation mechanism (Budd 1972, Kamb 1972, Gow and Williamson 1976, Matsuda 1979, Hooke and Hudleston 1980). Based on a combination of experimental studies and observations of crystal fabrics, Budd (1972) has described a fabric sequence which might be expected in a large land-based ice mass. Building on previous work, Hooke and Hudleston (1980) have isolated three parameters: stress, cumulative strain, and temperature, in order to predict stability fields for the commonly observed glacier fabrics. The Byrd station fabrics were taken into account in the construction of these models, and, in a general sense, the Camp Century fabric profile lends support.

According to the model profile of Budd (1972), shallow-depth fabrics could be expected to reflect a stress regime of uniaxial compression by forming a small-circle distribution about the vertical. Two opposite maxima would form and strengthen as depth and horizontal shear increase. As this occurs, the small-circle would break up into transition fabrics with several apparent maxima, and eventually two maxima would predominate. This description can be favorably compared to the Camp Century fabric distribution, which displays a small-circle fabric by around 200 m and multi-maxima patterns below 500 m. Although an easily identifiable pattern does not dominate between 500 and 850 m, the statistical parameters shown in Figure 5 indicate that a transition from one type of distribution to another does occur between 400 and 500 m. In terms of Budd's model, the 350 m interval below 500 m could be considered a large zone of transition fabrics representing the increasing horizontal shear. The fabrics in the Byrd station core are quite similar through this interval.

The expected two maxima fabric is never observed in the Camp Century core. Instead, the multiple maxima distribution transforms into a broad single maximum near 950 m. Again, the statistical parameters and the eigenvalue distribution are useful in delineating the fabric domain. An identical development takes place in the Byrd station core, but here the single maximum reverts briefly to a pattern with two closely-spaced maxima. In either case, the fabrics represent the dominance of horizontal shear.

The Camp Century fabric profile seems to deviate somewhat from the expected profile in its formation of the strong single maximum beginning at 1 149 m. Although single-pole fabrics are expected, it is observed here that a drastic transformation occurs over a very short depth interval. In the Byrd station core, the transition is a bit more gradual, but nevertheless distinct. Such a discontinuity in crystallographic development is not predicted by any of the existing models.

A second discrepancy between the observed Camp Century results on the one hand, and the Byrd station and model fabric profiles on the other hand, occurs in the lowermost section of the ice cores. The Camp Century core continues to display a fairly strong single maximum fabric within 40 m of the bottom, while the model predicts, and the Byrd station core exhibits, a multi-maxima distribution. Gow and Williamson (1976) attribute the loss of highly preferred orientations and the rapid growth of crystals to annealing in the bottom 350 m where the temperature increases rapidly to the pressure-melting point. However, the temperature of -15°C at 1 810 m seems too low to explain adequately the sudden textural changes. Russell-Head and Budd (1979) suggest that, in some cases, basal ice may constitute an immobile layer, in which horizontal shear is decreased due to interference from bedrock irregularities. This could explain the differences in basal fabrics and textures between Camp Century and Byrd station, because, while the up-stream bedrock topography is fairly smooth in the vicinity of Camp Century, it is quite irregular at Byrd station (Johnsen and others 1972).

Quantification of fabrics and relationship to ice flow

It is generally recognized that crystal anisotropy must have an effect on the flow of polycrystalline ice, but until the work of Lile (1978) and Russell-Head and Budd (1979), the effect of preferred crystal orientations had not been directly incorporated into a flow law. In this work, fabrics have been illustrated as contoured diagrams (Fig.4) and described in terms of their eigenvalue distributions, resultant vectors, and maximum concentrations. The forms of the distributions are determined predominantly from the contoured diagrams, but it is shown here that the eigenvalue distribution can be a valuable aid in identifying changes in the a fabric profile.

A comparison of the eigenvalue distribution portrayed in Figure 5 with the Camp Century fabric summary provided in Table I shows that, for each depth interval described, the eigenvalue distribution changes: where fabrics are random or weak, the eigenvalues are relatively low and closely spaced; in the transition fabrics, the eigenvalues are equally spaced over a wider range of values; in the broad single maximum fabrics, the range of eigenvalues does not change but the spacing changes to one high and two low values; and in the strong single maximum fabric zone, the distribution spreads out to one very high and two very low values.

Combined with the description of form, there must be a measure of fabric strength. The normalized resultant and concentration statistic show very good agreement with one another, and they generally reflect the fabric trends identified from the contoured diagrams and the eigenvalue distributions. The results (Fig.5, Table I) show that, where orientation distributions are non-preferred, the statistical parameters have relatively low values; in the transition zone, where low-lying c-axes are eliminated, the values increase; they increase further for the broad single-maximum fabrics; and, in the zone of strong orientations, the values are very high. It can also be noted that, although the maximum c-axis concentrations show greater variability, they provide a fair approximation to the fabric development observed.

Crystalline signature of Wisconsin ice

The greatest discrepancy between the model profile considered and the observed profiles occurs at 1 149 m in the Camp Century core and 1 200 m in the Byrd station core. At these boundaries, crystal sizes decrease suddenly and fabrics are markedly enhanced over a very short depth interval. In both ice cores, these discontinuities mark the glacial-interglacial boundary (Dansgaard and others 1969, Epstein and others 1970). Similar developments have been reported for the texture and fabric in the Vostok, Antarctica, ice core (Korotkevitch and others 1978) and for the texture in the Dome C, Antarctica, ice core (Duval and Lorius 1980). The coincidence of these developments in the four ice cores recovered from the interiors of continental ice sheets indicates that the Wisconsin ice may bear a unique textural and fabric signature.

As in the other ice cores, the textural changes at the Wisconsin boundary are accompanied by other changes as well. These included increased impurities derived from continental dust and high sulfate concentrations, particularly during the late Wisconsin (Cragin and others 1977, Herron unpublished), increased microparticle concentrations (Thompson 1977), and decreased air content (Raynaud and Lorius 1973). Although explanations for most of these associated changes have been provided, the reasons for the unique texture and fabric in the glacial-period ice is not known. Koerner and Fisher (1979) attributed the Devon Island fine-grained texture to inhibition of crystal growth by high microparticle concentrations. However, Duval and Lorius (1980) rejected this explanation because, in the Dome C core, the small crystals and high concentrations are not concurrent. In the same study, Duval and Lorius considered and rejected the ideas that initial crystal size or changes in crystal growth rate could be responsible.

Although the causes and interrelationships of these many parameters have not yet been clarified, they appear to be inherent properties of late Wisconsin ice. If highly anisotropic fabrics and fine-grained textures are indeed characteristic of ice-age ice, then, due to enhanced flow, the glacial-interglacial transition also constitutes a rheological boundary which must be taken into account in the development of flow laws for ice sheets.

SUMMARY AND CONCLUSIONS

The Camp Century, Greenland, and Byrd station, Antarctica, ice cores display nearly parallel trends in ice texture and fabric development down to a depth of about 1 300 m. This is true, in spite of the differences in their total lengths (1 375 m at Camp Century, 2 164 m at Byrd station). The fabric profiles generally match the predictions by Budd that, with increasing depth in land-based ice, the following sequence might be expected: weak or random surface orientations, shallow small-circle patterns, intermediate transition fabrics, mid-depth double maxima patterns, deep single maximum orientations, and basal diamond fabrics. The absence of the basal diamond pattern at Camp Century probably reflects a combination of the relatively smooth bedrock topography and the relatively cold basal temperature of -13°C.

The fabric development in the Camp Century core can be fairly accurately monitored by examining the changing eigenvalue distribution with depth in conjunction with at least one of the statistical indicators of fabric strength. The usefulness of these statistical parameters will increase as more efforts are made to relate quantitatively ice flow and crystal anisotropy.

The identification of the single maximum fabrics beginning near 950 m in the Camp Century core is important. This depth corresponds to the suggested transition from uniform to non-uniform vertical strain-rate (Dansgaard and Johnsen 1969, Hammer and others 1978). In the light of recent work relating ice deformation and fabrics (Lile 1978, Russell-Head and Budd 1979), it seems likely that the highly oriented fabrics will provide a physical basis for the empirical Camp Century flow law (Dansgaard and Johnsen 1969, Hammer and others 1978).

Finally, the coincident development of a fine-grained texture and a highly preferred crystal fabric at the glacial-interglacial transition in cores from Greenland and West and East Antarctica suggests that ice-age ice may have unique characteristics. If this is true, then a fairly sharp discontinuity in crystalline fabric, and consequently in ice flow, will occur at depths marking the climatic transition within the cores. Whether these unique characteristics persist through to early Wisconsin ice or whether they are concentrated only in the later stages is yet to be determined.

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