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The Stress Pattern within the Law Dome Summit to Cape Folger Ice Flow Line, Inferred from Measurements of Crystal Fabric

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Abstract: Crystal fabric and texture data are presented from ten ice cores that have previously been drilled along an approximate flow line extending from the summit of Law Dome ice cap to Cape Folger, East Antarctica. Our interest in these data is their interpretation in terms of stress patterns within the ice cap, and in particular the detection of the depths at which the stress changes from predominantly near-vertical compression to predominantly near-horizontal simple shear zones. This transition potentially marks an increase in flow rate, from a factor of ~ 3 in the compression zone to ~ 10 in the shear zone, compared to deformation of the initially isotropic ice that accumulates at the surface. Determining the depth of this potentially large change in flow rate between compression flow and shear flow provides valuable information for computer models of the ice sheet. In the Law Dome ice cap the compression-shear transition is found at approximately one-third of the total depth.

Key words: ice crystal orientation fabrics, crystal size, ice sheet stress pattern, ice flow, Law Dome

1. Introduction

The size and remoteness of the Antarctic Ice Sheet require that remote sensing and modelling techniques are necessary to examine its mass budget. Both of these techniques depend upon an understanding of the crystal structure of ice. Crystal structure affects and is affected by the ice flow pattern. Knowledge of ice flow physics is therefore important for improving the ice sheet models.

We use the term crystal fabric or crystal orientation fabric pattern, to mean the bulk pattern of crystal orientations within the ice (indicated by measurements of crystal c-axis orientation within a thin section, i. e. the intersection of the orientation of each c-axis with the lower hemisphere of a sphere, projected onto a Schmidt equal area net). Note also that the c-axis is perpendicular to the basal (glide) plane of the crystal. We use the term 'crystal structure' to mean crystal fabric and mean crystal size (also measured from ice thin sections). A few different techniques have been used to indicate crystal size (e. g. the ratio of thin section area to the number of crystals within the section, the square of the mean linear crystal intercept length) however, we will not directly compare crystal sizes within one ice core with those of others; we will consider only the pattern of crystal size change through the cores.

Recrystallisation and crystal rotation are induced by the stress and strain regime within an ice mass [1, 2, 3]. The stress configuration and crystal orientation fabric coevolve as an ice mass deforms, so that there are relationships (although not necessarily unique) between ice crystallographic properties and flow in an ice mass. We propose here that c-axis orientation fabric and crystal size analyses along the flowline can be used as guides to estimate the strain regimes within the ice mass. Larger strains are associated with a strengthening of the fabric pattern. The crystal size provides some indication of the magnitude of the stress, provided the crystals have reached their equilibrium size for that stress [4]. We attempt to use crystal fabric data to generate a picture of the general large-scale deformation regimes within the flow line from Law Dome summit to Cape Folger.

Laboratory deformation tests have been performed in the past, on natural and laboratory prepared ice to generate the different crystal orientation fabric patterns found in the natural ice masses. Anisotropic c-axis orientation fabrics form in response to the stress configuration and total strain. Mechanisms of fabric development include crystal rotation, grain boundary deformation, grain growth and recrystallisation [5, 6, 7]. Effective strains of $>10\%$ can be required to change from an easy glide fabric in one stress pattern to another [2, 3]. This stability makes the fabric pattern a valuable indicator of the ice flow. In deformation experiments, initially isotropic ice continues to exhibit a random crystal orientation pattern until a strain of ~ 1 - 10% [3, 8] and at lower temperatures and stresses, at greater strains [9].

Experiments have been performed by several workers (e. g. [8, 10, 11, 12, 13]) to determine the effect of different stress patterns (e. g. uniaxial compression and extension, simple shear, combinations of shear and compression, etc.) on natural and laboratory prepared ice. These experiments were performed to high strains to determine the changes in the ice crystal structure.

Small circle girdle fabric patterns have been identified in ice from uniaxial compression deformation experiments conducted to large strains ($>10\%$) and in some field locations (e. g. Amery Ice Shelf [5, 10, 14], Law Dome [5, 14], Byrd [1] and Siple Dome [15]). In laboratory experiments this fabric pattern develops with strain and the progression from the isotopic minimum to tertiary (maximum) strain rate [8]. The colatitude of the small circle (i. e. the mean half angle of the cone formed by the orientations) is $\sim$ 25 - 30°. This results as a balance between the effects of crystal rotation (which alone would result in a colatitude near 0°, i. e. a single maximum fabric) and recrystallisation (which alone would result in a colatitude near 45°). In extension, a small circle fabric pattern results, with colatitude $>50°$ [8]. A single maximum fabric develops when simple shear is applied to an ice sample [11, 13]. Initially a two-maxima fabric develops in shear at lower total strain, with one maximum normal to the horizontal shear plane and the other in the direction of flow [6, 12]. A multi-maxima fabric develops in annealing low stress conditions at higher temperatures [10, 12, 16].

The crystal fabric orientation patterns described above may not be unique to the stress configuration. Some authors (e.g. [17, 18]) suggest that compression may be the dominant stress configuration throughout the depth of summit, near summit or ridge locations in ice sheets. Further, in the lower temperature and deviatoric stress regimes typical of the polar ice sheets, it is suggested that a single pole c-axis orientation fabric in such locations is likely to be the result of compression. In these regimes it is argued, dynamic recrystallization ceases and rotation alone drives the fabric development. This will be discussed further elsewhere [19].

We restrict our study here to Law Dome in which, even in the colder summit area (annual surface temperature, $-21.8°$C), strong and clear small circle crystal fabric patterns are found at depth. The rate at which crystal orientation fabrics develop is strain dependent. By the time sufficient strain has accumulated in compression to have developed a clear small circle pattern, shear may have taken over, favouring a single pole fabric. Thus, to interpret what the stress regime might be, it is not always a distinct fabric pattern that we should be looking for, but rather, indications of a trend towards particular patterns.

Crystal size increases with age (and thus depth) in low stress conditions in the upper layers of an ice sheet, due to grain growth at a temperature dependent rate [20]. This crystal growth is usually termed 'normal grain growth'. For deeper ice, once several percent strain has accumulated, deformation processes also come into play [1, 3], and the grain growth rate from here down is determined by a balance of the two processes (i.e. crystal growth and ice flow).

By the time steady state flow has been established in laboratory tests, typically by about 10 to 20% strain, an equilibrium crystal size will have developed, i.e. the normal grain growth process is balanced by the deformation process [4]. In the polar ice sheets, while it needs to be recognised that steady state flow will never actually be attained (because the stresses and temperature change with depth) the crystal size will always trend towards the (changing) equilibrium size. The resulting crystal size profile with depth in the ice sheet typically shows a size increase in the top layers (normal grain growth), followed by a trend (decreasing or increasing; see [19]) towards an equilibrium size determined by the current stress magnitude [4], with deviations due to impurities, flow and other effects. In the basal layers of the ice mass temperatures are higher than above, and local stress relaxation can lead to the growth of very large crystals.

2. Law Dome

Law Dome, an ice cap at the edge of the East Antarctic Ice Sheet between 110° E and 115° E, is an ideal location to examine the flow of ice. This small, approximately circular ice cap $\sim$ 200 km diameter is an isolated glacial system. Over several decades, the Australian Antarctic Program ice core drilling project on Law Dome has acquired a series of ice cores and associated boreholes following the path of an approximate flow line from the summit to the coast. Furthermore, the measurement density of ice crystal fabric and size in the cores is sufficient to provide a preliminary assessment of the ice flow and stress patterns through the flow line.

Thirty ice cores have been drilled on Law Dome. Of these, eight (A001, BHQ, BHP, BHB, BHF, BHA, BHC1 and BHC2) lie on the approximate flow line from the summit to Cape Folger (CF) (Figure 1). A001 is at the summit. Roughly halfway between the summit and Cape Folger is BHQ. Nearer the coast are two shallower cores, BHB and BHP. Close to Cape Folger there are four cores grouped together, BHF, BHA, BHC1 and BHC2. All four of these cores extend to near bedrock. In addition to these eight cores, this study includes samples from the DSS and BHD cores, which are located in the summit region and display properties that make them valuable additions to an analysis of the flow regime of Law Dome. A comparison of the crystal fabrics from A001 and BHD [21] has illustrated the variability that can occur over only a few kilometres. DSS, drilled 4.6 km south-southwest of the summit, is the only near summit core that reaches bedrock [22]. DSS is not located on the flow line described above. However, the results from the core and borehole analysis can be used to provide an excellent indication of the deep ice structure (to $\sim$ 1200 m depth) of the general region of the ice cap, provided the flow regime is roughly radially symmetric about the summit.

We present analyses of measurements of crystal fabric from the Law Dome summit to Cape Folger flow line ice cores. Crystal orientation statistics are used to infer the stress patterns along the flow line. In particular we are concerned with the depth in the ice sheet at which the ice shifts from a compression to a shear regime. With this transition depth determined, profiles of stress configuration can be used to more precisely model the ice cap [23].

3. Availability of ice crystal fabric data

The crystal structure properties of some of the cores included in this study have been measured previously. Li [24] examined c-axis orientation and crystal size for the

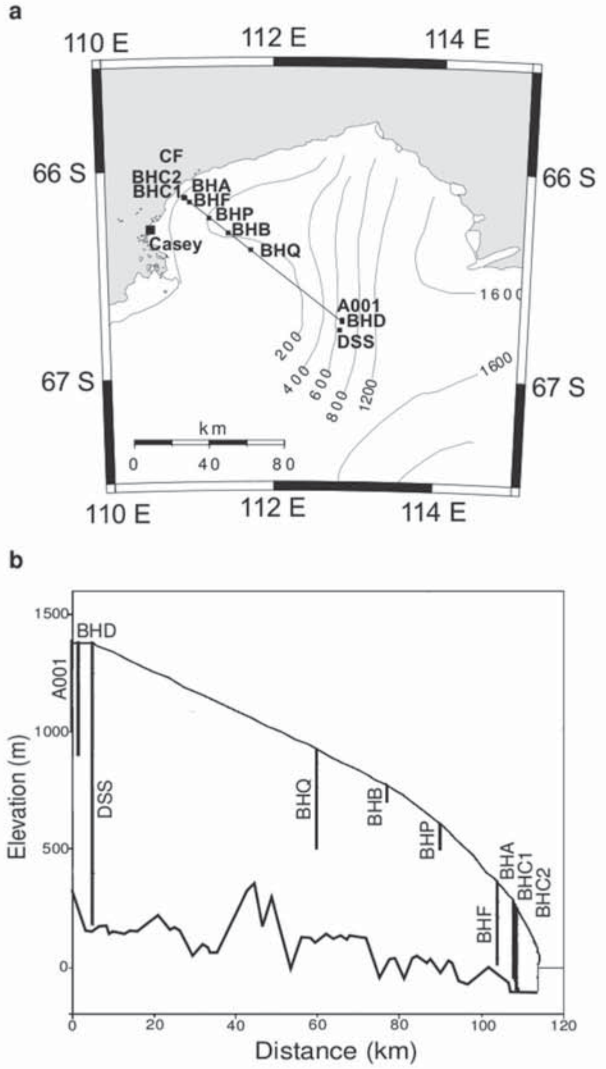


Figure 1: (a) Map of Law Dome showing position of ice coring sites along an approximate flow line (straight line). A001 is at the summit. Contours indicate accumulation (kg m^2 a^{-1}). Note the high (for Antarctica) accumulation values and the high east-west accumulation gradient across the summit. (b) Profile of the flow line from Law Dome summit to Cape Folger, showing the location and depth of ten ice core-drilling sites.

DSS and BHQ cores. For DSS, these measurements were at $\sim$ 6 m intervals throughout the 1200 m depth of the core [25], while BHQ was measured at 10-20 m intervals [26]. Other cores previously measured for fabric and crystal size include: A001 [19, 21, 27]; BHD [19, 25]; BHF [28]; BHC1 [29, 30, 31]; and BHC2 [29, 31]. In order to pinpoint the depth at which the dominant stress configuration changes, more detail is required than so far reported for some of these cores. In addition, no crystal fabric data have been reported for the BHB, BHP, or BHA ice cores. New measurements, using an automatic ice crystal fabric analyser (an early prototype, circa 1985-1990, of the Russell-Head machine) have therefore been made on these cores. Detailed crystal orientation fabric diagrams (Schmidt equal area nets) and statistics for all the ice cores along the Law Dome summit to Cape Folger flow line have been tabulated by Donoghue [32]. Figure 2 shows some examples of typical crystal orientation fabrics from the Law Dome cores.

4. Statistical analyses of crystal fabric data

Several different statistical parameters are often used to indicate the degree to which crystal c-axes within a measured thin section are clustered. Here, we utilize three measures of central tendency: the colatitude mean, Φ_m, colatitude median, $\Phi_{1/2}$, and the angle that encompasses 25% of the colatitudes, $\Phi_{1/4}$. We also utilize one measure of approach to 45°, the mean Schmid factor, S_f, where

$$S_f = \frac{1}{N}\sum_{N} \sin\theta_N \cos\theta_{\mathrm{N}} \qquad (1)$$

and θ_N are the N colatitudes measured from the thin section [7]. Note that $0 \leq S_f \leq \frac{1}{2}$, and that for a random distribution of crystal orientations, $S_f = \frac{1}{3}$.

To utilise these measures, it is important to first identify the nature of the crystal orientation fabric pattern. That is, to classify it as random, indicating isotropic ice, as a small circle indicating compressive flow, as a single pole indicating shear flow, as a multi-maxima fabric indicating annealing, or as some transition fabric indicating a change from one flow regime to another. Once a single pole fabric pattern has been identified, the above measures of central tendency provide an indicator of fabric strength.

Our main aim in this study is to identify the transition zones within the ice mass between different stress patterns. We need to establish the depth at which the flow is predominantly near-vertical compression, then the boundary zone between this and predominantly near-horizontal shear flow. We identify unconfined compression by a trend towards development of a small circle fabric pattern. Our concern therefore is to determine whether the trend with depth in the ice mass is towards a small circle fabric pattern. Accordingly, we require a technique for determining whether the number of crystal colatitudes in the range 20 to 35° is increasing with depth. We must also be aware that development of a single pole fabric would initially produce an increase in the proportion of colatitudes in the 20 to 35° range (i.e. as c-axes in the range >35° rotate inwards). We interpret a trend towards the development of a single maximum pattern as indicative of simple shear. An increase in the proportion of crystal colatitudes in the range 0 to 15° is expected if the trend with depth is towards a single pole fabric, while a decrease is expected if the trend is towards a small circle. We do not need to establish that strong characteristic fabrics have developed. It is more important to identify the trends in fabric development, as they point to the dominant stress configuration within the region of interest.

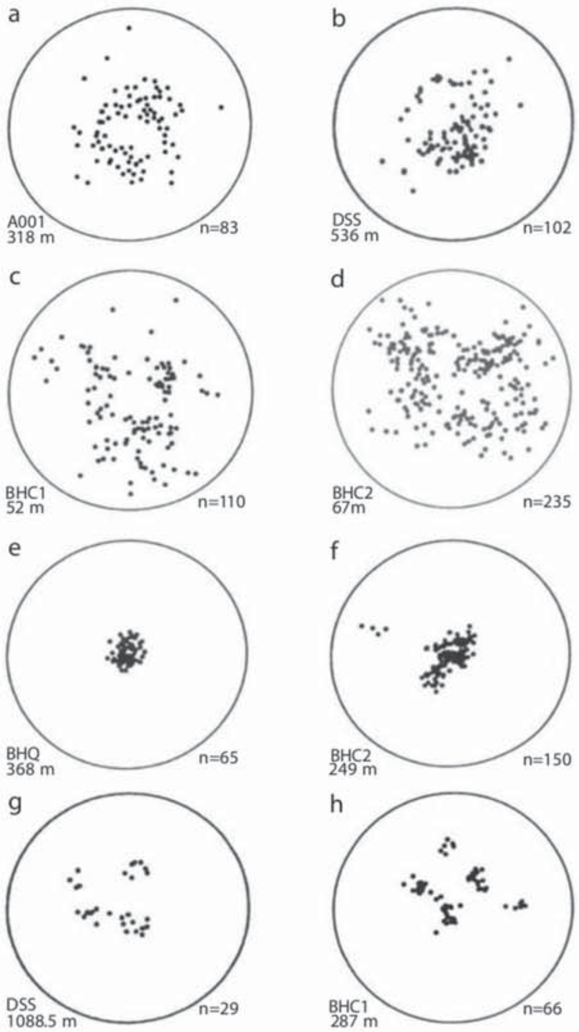


Figure 2: Examples of ice crystal orientation fabric plots showing (i) small circle fabric patterns from (a, b) two cores drilled in the summit region [21, 24] and (c, d) two cores drilled near Cape Folger [30, 31], (ii) single pole fabric patterns indicating strong shear from (e) the middle layers of the ice sheet about half way along the flow line [24] and (f) near Cape Folger [31], and (iii) two plots indicating multiple-maxima fabrics from deeper layers within the ice sheet near (g) the summit [24] and (h) Cape Folger [29].

Li and Jacka [25] (see also [23]) propose that to facilitate comparison of these counts of crystals with different orientations from one thin section to another, normalised ratios are calculated :

$$R_{0-15} = \frac{N_{0-15}}{N_{0-90}} \times \frac{100}{3.41} \tag{2}$$

$$R_{20-35} = \frac{N_{20-35}}{N_{0-90}} \times \frac{100}{12.05} \tag{3}$$

where N_{0-15} and N_{20-35} are the numbers of crystals in the range 0 to 15° and 20 to 35° respectively and N_{0-90} is the total number of crystals in the thin section, and where 3.41% and 12.05% are the expected values of N_{0-15} and N_{20-35} for an isotropic distribution of c-axes.

R_{0-15} and R_{20-35} can be measured for each crystal thin section from an ice core to provide an indication of the trend of the fabric pattern development. R_{0-15} increasing with ice core depth indicates a trend towards development of a single maximum fabric, implying crystal rotation, or shear recrystallisation. R_{20-35} increasing with depth (while R_{0-15} decreases) indicates a trend towards development of a small circle pattern, implying compression.

Under little or no stress the normal grain growth of crystals continues. Stress and crystal size are related by an inverse relationship once steady state flow has been established [4]. For low stress, there is a tendency for increased crystal size and a weaker crystal orientation fabric to develop. A high stress will result in smaller crystals and a stronger crystal orientation fabric. Therefore, the regions of high and low stresses in the flow of the ice, to some degree, can be observed through changes in crystal size.

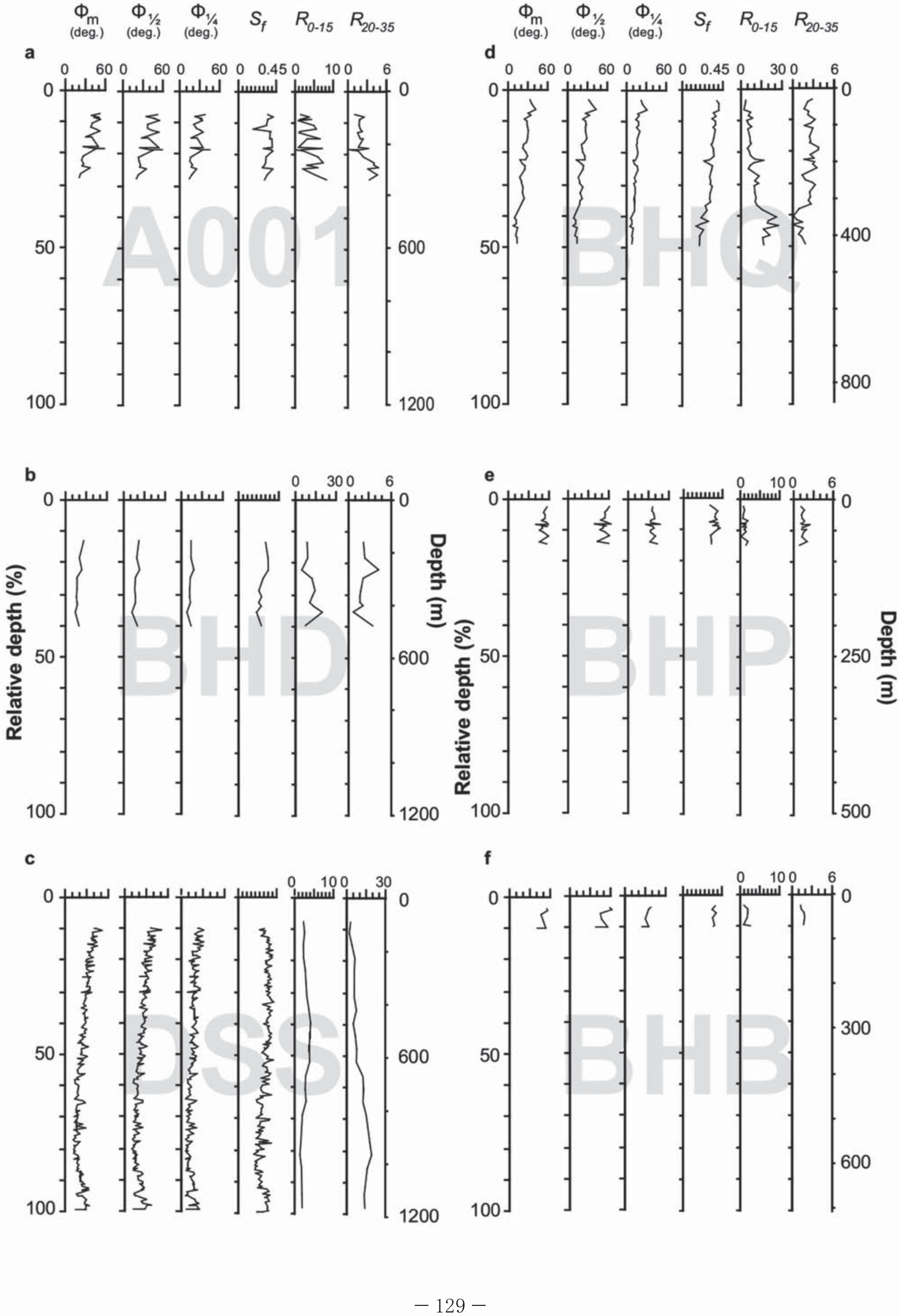
5. Results

Figure 3 shows plots against relative depth (depth / total ice depth at the site) of Φ_m, $\Phi_{1/2}$, $\Phi_{1/4}$, S_f, R_{0-15} and R_{20-35}, for each of the cores along the Law Dome summit to Cape Folger flow line. From the plots of Φ_m, $\Phi_{1/2}$, and $\Phi_{1/4}$ a steady decrease (i.e. an increase in central tendency) with depth is observed in all ice cores for the upper two-thirds of the ice cap. Within the lower one-third (for those cores extending to sufficient depths) an increase in the above parameters (i.e. a decrease in central tendency) is evident. The strongest fabrics appear to be located at about 60 to 80% of the depth.

In general S_f exhibits a small increase in the top 20% of the ice, followed by near constant or slightly decreasing values until about the same depth as the strongest fabrics. Finally S_f increases near the bedrock, closely following the fluctuations evident in the measures of central tendency.

For those cores in which we have measurements in the top 100 m, the plots of R_{0-15} and R_{20-35} are similar, indicating isotropic ice. Below this depth in most cores, there is a small increase in R_{20-35}, accompanied by near constant values of R_{0-15} (indicating compression recrystallisation) down to approximately a third of the total depth. Beyond this point there is a clear increase in R_{0-15} while R_{20-35} decreases, indicating the development of a single pole fabric and the onset of simple shear. Note in particular the sites BHD at $\sim$ 20% depth, DSS at $\sim$50%, BHQ at $\sim$ 30%, BHF at $\sim$ 40% and BHC1 and BHC2 at $\sim$ 30%. Finally, for all those cores containing ice from near bedrock, the R_{0-15} values decrease, associated with higher variability. There is also higher variability in the central tendency measures and the crystal size values.

Figure 4 shows plots of crystal size for each of the cores (except BHD). The plots indicate a gradual increase


Φm (deg.)
Φ½ (deg.)
Φ¼ (deg.)
Sf
R0-15
R20-35
a
A001
0 60
0 60
0 60
0 0.45
0 10
0 6
0, 50, 100
0, 600, 1200
b
BHD
0 30
0 6
Relative depth (%)
Depth (m)
c
DSS
0 10
0 30
d
BHQ
0 60
0 60
0 60
0 0.45
0 30
0 6
0, 400, 800
e
BHP
0 10
0 6
0, 250, 500
f
BHB
0 10
0 6
0, 300, 600

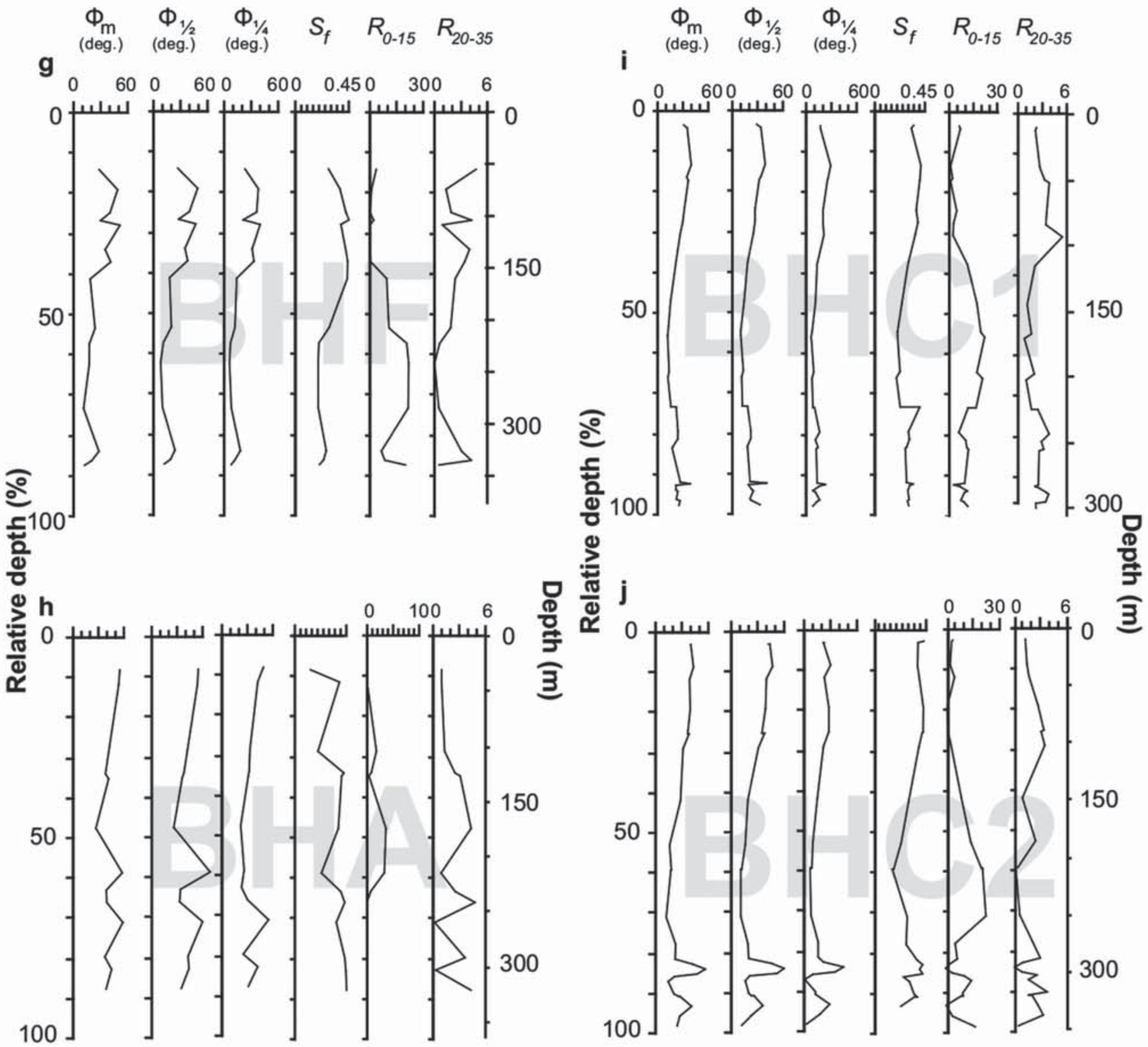


Figure 3: (previous page and this) Plots aganist relative depth (with depth scales also shown) for the cores (a) A001, (b) BHD, (c) DSS, (d) BHQ, (e) BHP, (f) BHB, (g) BHF, (h) BHA, (i) BHC1 and (j) BHC2 of the colatitude mean, Φ_m*, colatitude median,* $\Phi_{1/2}$*, the angle that encompasses 25% of the colatitudes,* $\Phi_{1/4}$*, the Schmid factor,* S_f*, and the normalised ratio of colatitudes that range from 0 to 15°,* R_{0-15}*, and 20 to 35°,* R_{20-35}*. Note the different scales for the* R *plots.*

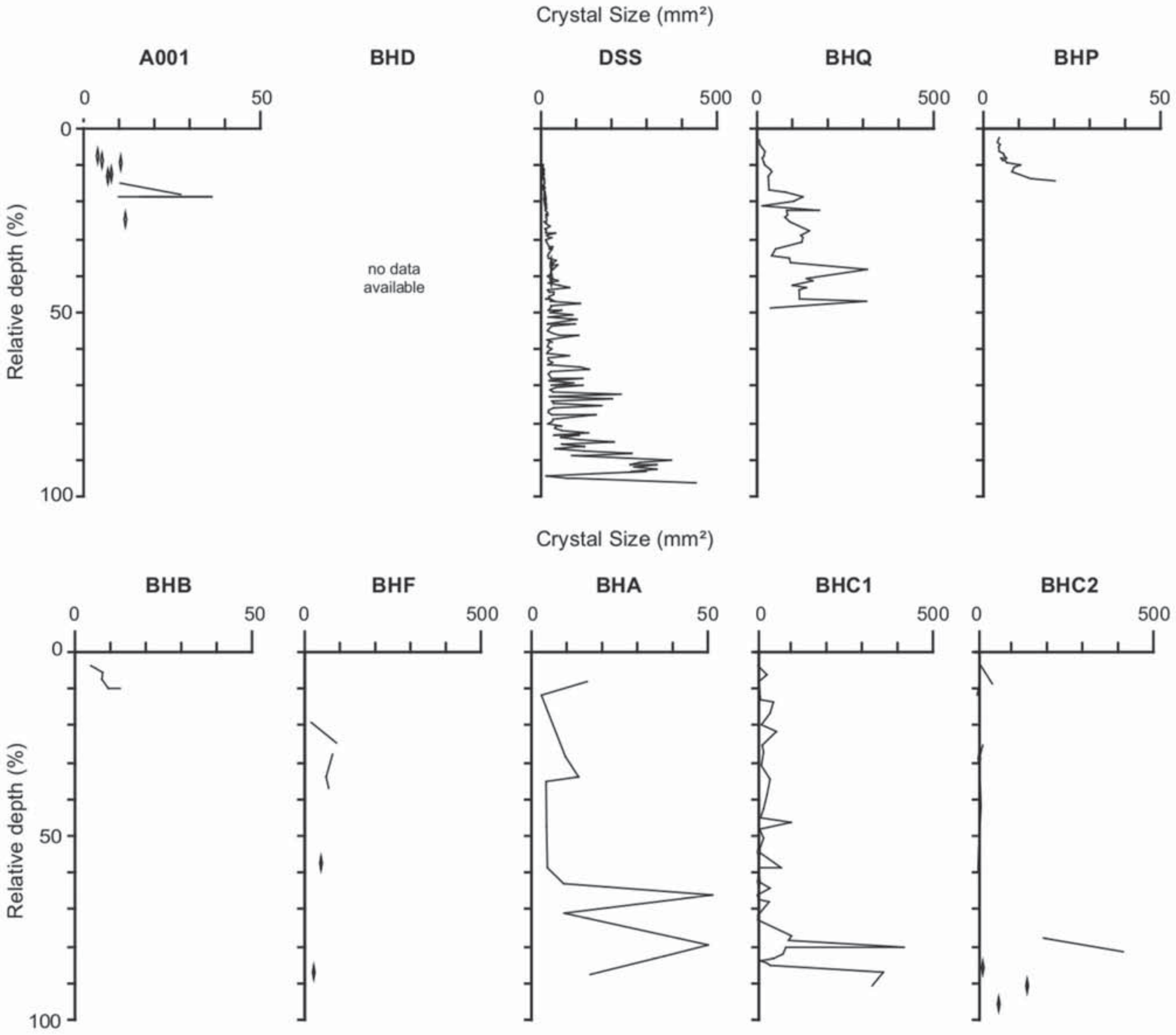


Figure 4: Plots of ice crystal size against relative depth for each of the ice cores. Note there are no crystal size data available for BHD. Note the different crystal size scales.

in size with depth for the top two-thirds of the ice thickness. In the bottom one third, there is greater variability in crystal size, which in some cases, increases to greater than 500 mm^2 (off-scale in Figure 4). Even in the upper layers, where there is greater variability in the fabric strength parameters, this seems to be matched by higher variability in crystal size. In general the crystal size is smaller for strong fabrics, larger for weak fabrics.

6. The stress pattern within the flow line

Based on our observations of fabric strength, crystal size and the R factors outlined above, we are able to estimate depths within each ice core at which the dominant stress patterns change. On this basis, stress regimes are mapped in Figure 5 on a profile of the approximate flow line from the summit of Law Dome to Cape Folger. The contours are based on a very limited distribution of cores along the flow line and they are not intended to indicate sharp boundaries but rather, transition regions from one stress pattern to another. Between the summit and BHQ and between BHQ and the coast they have been estimated based on projected particle paths and modelling outputs [23].

A consistent picture of four dominant stress regions is evident from the different crystal fabric patterns within the flow line:

1. A random crystal fabric pattern in the upper layers indicating isotropic ice unaffected by flow, i.e. a low stress region near the surface. Normal grain growth is evident in all cases.

2. A small circle crystal fabric pattern indicating a compression regime is evident throughout the length of the flow line. The strength of the small circle fabrics indicates high compression strains ($\sim 30\%$) [8] are reached at the summit.

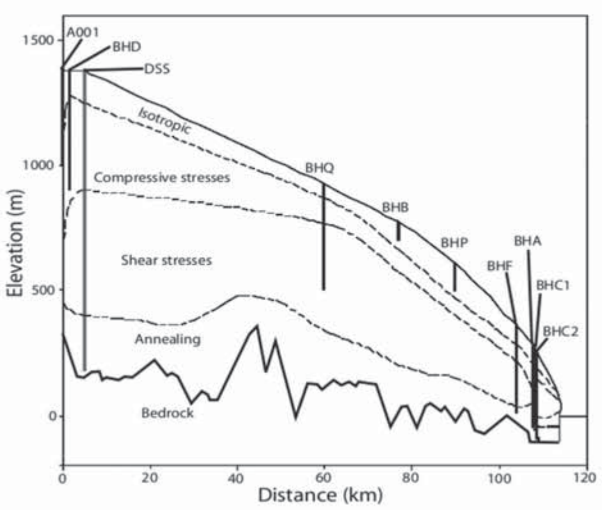


Figure 5: Stress regimes contoured on a profile of the approximate flow line from the summit of Law Dome to Cape Folger, based on observations of fabric pattern and crystal size. The contours are not intended to indicate sharp boundaries from one regime to another, rather they indicate the approximate positions of stress regime transition zones.

3. A single maximum fabric pattern indicating simple shear is the dominant flow regime through most of the flow line length and thickness. From the DSS core at greater depths, shear is evident from single pole fabrics. DSS borehole inclination measurements [33] also confirm the existence of a shear layer at greater depth with a maximum in the shear rate ~ 180 m above the bed.

4. The coastal cores are indicative of a more complex flow regime than those inland. There is high variability in the plots of Figure 3 (h) and (i). Here near the coast there is a relatively large compression region and a smaller isotropic region than at BHQ.

The shear zone, which dominates cores, was detected ~ 170 m above the bed at BHF from borehole inclination measurements [28]. Between BHF and the coast, the shear zone is composed of two bands of high shear separated by a weakening of fabric [32]. These two high shear bands have also been detected by measurements of borehole inclination at BHC1 and BHC2 [34]. In the BHC1 and BHC2 cores the weakening of the fabric is indicated by a small circle pattern between the two shear maxima, indicative of compression. Between BHF and BHA the bands are separated by a weakening of the single maximum fabrics. The multi-maxima fabrics at the base are found in a relatively thin section of the cores. The annealing zone has two bands of multi-maxima fabrics, separated by a layer of weak single maximum fabric and small crystals. This layer correlates with the depth of the Last Glacial Maximum (LGM) as determined from $\delta\,^{18}O$ dating [35]. This is interesting since there is debate on the causes of the small crystals and strong fabrics. Experiments show that while particle concentrations may be sufficient to have a pinning effect on crystal growth [36] this size decrease should not affect the fabric strength or flow. It is more likely in our opinion that high shear in the envelope just above the local bedrock maximum causes the development of strong fabrics and small crystals (i.e. crystal size is a result of the high shear [4]). It may be chance that it coincides with the LGM. Alternatively, the high shear may be enhanced by soluble (e. g. H_2SO_4 or HF) impurities (not particulates), which may have been in higher concentrations during the LGM.

The compression-shear transition is determined from the crystal fabric statistical analyses to be located at roughly a third of the depth, but this varies as the ice flows over the bedrock topography. Due to the lack of core measurements between DSS and BHQ, and the shallow depths of the BHB and BHP cores, the compression-shear transition was based on the modelled particle path distribution along the flow line. This estimation was confirmed by comparison with model outputs of the stress configurations [23, 37] presented in Figure 6. Also, the modelling indicates the same high shear layer near the base and smaller compression layer near the surface as indicated by the fabric data.

7. Conclusions

With each of the main stress regimes identified, the characteristics of the ice flow within the Law Dome flow line

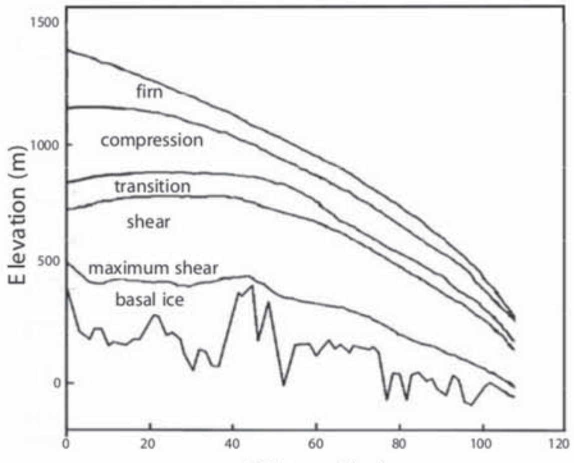


Figure 6: Model estimated ice flow regimes within the flow line [37]: firn zone (surface 10% compression strain), compression zone (compression strain rate > shear strain rate), transition zone (compression strain rate ~ shear strain rate), shear zone (shear strain rate > compression strain rate) and the basal ice (below the region of maximum shear).

have been estimated. In the upper 100 m of the ice cap the stress level is low, indicated by a random crystal c-axis orientation pattern and normal grain growth. The normal grain growth with time in this region reflects the growth rate characteristics of the in situ temperature until the strain becomes sufficient to generate fabric development and changes in crystal size.

Below this region of low stress lies one of predominantly vertically compressive stress with increasing vertical strain. A trend towards development of a small circle crystal fabric pattern is evident. Between one-third and two-thirds of the depth, the ice flow is predominantly in horizontal shear. It is here that a single maximum fabric develops, strongest at about two-thirds of the depth and coinciding with a smooth band of maximum shear following the large scale smoothed topography in the form of the orography envelope. The ice crystal growth in this region is retarded by the increase in the stress, which has balanced the expected growth due to temperature [4].

As the ice approaches the bedrock, and the stress is reduced (sometimes cyclically due to bedrock undulations), it can lead to annealing at higher temperatures. The crystal size is able to increase and a multi-maxima fabric generally develops [21]. In this basal region of the ice cap the ice continues to move, more slowly, laterally parallel and close to the bedrock where it can also be blocked and diverted around bed obstacles as well as shearing over hollows.

These main regions of stress are not uniform throughout the ice cap. They are affected by various parameters. The large and small scale bedrock topography are both found to have a large effect on the ice flow.

The most important stress transition is between the compression and shear zones. At the bottom of the compression zone where the small circle fabric is most strongly developed, the flow rate is expected to be a factor of ~ 3 higher than that for isotropic ice [3]. This small circle fabric pattern ice is the starting point as the shear flow begins to set in. In shear, this fabric enhances the flow initially by a factor of ~ 2.5 [38], but after an additional strain to $\sim 20\%$ (within a relatively small depth increment), the fabric is changed by further shear to a strong single pole pattern for which the flow will be enhanced by a factor of up to ~ 10 over that of isotropic ice [13, 38]. The strong vertical tendency of fabrics associated with shear causes the crystal lattices to be oriented with their basal planes nearly parallel (c-axis perpendicular) to the horizontal shear plane, allowing the crystals to deform more readily. This strain rate difference between the compression and shear layers is important for understanding flow differences in the ice sheet. Determining the depth of this large change in the flow rate between compressive flow and shear flow is essential for improved modelling of ice sheet dynamics.

Clearly, this study can be improved by further deep drilling (i.e. to near the bed so that each of the different stress regimes is penetrated) at several locations along the Law Dome flow line. To fully understand the flow dynamics of the polar ice sheets and other glacier systems, we require crystallographic studies from core collections from many major flow lines. For the high density measurement of ice core crystal properties, the recent introduction of automatic crystal fabric analysers is revolutionary. In addition the introduction to the glaciological armoury of 'fast drills' makes it possible to collect the cores in the density required to properly carry out these studies.

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