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Scientific paper

Mechanical anisotropy of deep ice core samples by uniaxial compression tests

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***Abstract*:** Mechanical anisotropy of ice core samples has been observed in various uniaxial compression tests. The *c*-axis orientation distribution is the primary influence on the mechanical behavior of ice cores. A strong single-maximum fabric pattern is observed in the deep parts of the ice sheet. In this region, polycrystalline ice is very hard along the vertical axis; however, it easily shears along the horizontal plane. Thus, by acquiring the distribution of *c*-axis orientations throughout the ice sheet, the mechanical anisotropy of ice sheet flow behavior can be understood. Analysis of fabric measurements on the Dye 3, GRIP, and Dome F ice cores suggests that the *c*-axis orientation distribution depends primarily on vertical strain. Therefore, if the ice thickness at some point in the ice sheet is known, it should be possible to predict the distribution of *c*-axis orientations at that depth. Uniaxial compression tests were carried out along various directions of the Dye 3, GRIP, and Dome F ice cores. A contour map of mechanical anisotropy was then made to relate the compression direction to the vertical strain. This clarified the flow enhancement factor in every compression direction at a given vertical strain.

key words: ice core, crystal texture, mechanical property, anisotropy

1. Introduction

The ice sheet flow is determined by the temperature, geographical feature, and the physical and chemical properties of ice. Three factors, *c*-axis orientation, grain size and impurity content mainly influence mechanical properties of ice. The general distribution of *c*-axis orientation in the ice sheet is concentrated from random to single maximum with depth, except for the region of girdle (Vostok) type fabric. The order of grain size in most of the ice sheet is a few millimeters. The dust concentration is on the order of a few mg/kg. It is important whether these influence the mechanical properties of the ice core; however the result of many experiments and calculations showed that *c*-axis orientation distribution was the prime parameter for deformation of polycrystalline ice and ice cores (*e.g.* Shoji and Langway, 1988; Budd and Jacka, 1989; Azuma, 1995).

Shoji and Langway (1988) conducted a uniaxial compression test in various directions

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on the Dye 3 ice core. The enhancement factor is quite sensitive to the stress direction and varies by more than two orders of magnitude. We used the result of mechanical tests on three different ice cores (Dye 3, GRIP and Dome F) to discuss the mechanical anisotropy of deep ice core samples. The Dye 3 ice core and the GRIP ice core were recovered from Greenland ice sheet. The drilling site of the GRIP ice core was located at the dome summit. The Dome F ice core was recovered from the dome summit, Antarctica by the Japanese Antarctic Research Expedition.

2. Experiments

Uniaxial compression tests of the GRIP ice core were conducted under conditions of constant strain rate and constant load. The constant strain rate was adopted about $4.5 \times 10^{-8}\ s^{-1}$ and the constant stress was adjusted in the range 0.2 to 0.7 MPa. The experimental temperature was –11 to –17°C. Test specimens (approximately $25 \times 25 \times 90$ mm each) from the GRIP ice cores were prepared from core samples with the stress axis inclined 0°, 45° and 90° from the core axis. The detailed experimental conditions are described in Miyamoto *et al*. (1999). The result of the compression test of the Dye 3 core by Shoji and Langway (1988) was used directry. They conducted uniaxial compression tests with the stress axis inclined 0°, 15°, 26°, 30°, 45°, 60°, 70°, 75° and 90° from the core axis.

3. Mechanical test of the Dome F ice core

We also conducted uniaxial compression tests on the Dome F ice core from Antarctica. The Japanese Antarctic Research Expedition successfully drilled a 2503 m ice core of the Antarctic ice sheet at Dome Fuji Station from 1995 to 1997. The uniaxial compression test specimens were given from eleven different depth ranges from 175 m to 2176 m. Uniaxial compression tests were carried out under constant strain rate. All experiments were performed by using the MINEBEA Model TCM-5knb-S mechanical testing instrument which was especially modified for low speed testing. The stress was applied in parallel to the core axis in each test specimen (approximately $25 \times 25 \times 90$ mm each). A constant strain rate of

Table 1. Experimental conditions and results of compression tests of the Dome F ice core.

Core No.	Depth at top of specimen, m	Median inclination*, degree	Temp., ±0.5°C	Yield stress, MPa	Strain rate, $10^{-8}\ s^{-1}$	B, $10^{5}\ s^{-1}\ MPa^{-3}$
01-124	175.12	48	–15	0.66	4.46	2.13
03-150	374.96	43	–15	0.81	4.19	1.10
05-154	575.50	40	–15	1.11	4.23	0.43
07-155	776.85	35	–15	0.91	4.28	0.78
09-151	975.20	31	–15	1.04	4.11	0.51
11-147	1173.00	28	–15	0.99	4.22	0.59
13-152	1375.50	28	–15	1.05	4.32	0.52
15-152	1575.50	25	–15	1.19	4.14	0.34
17-152	1775.50	19	–15	0.97	4.42	0.67
19-152	1975.50	16	–15	1.18	4.46	0.37
21-152	2175.50	12	–15	1.42	4.14	0.20

*predicted from Azuma *et al.* (1999).

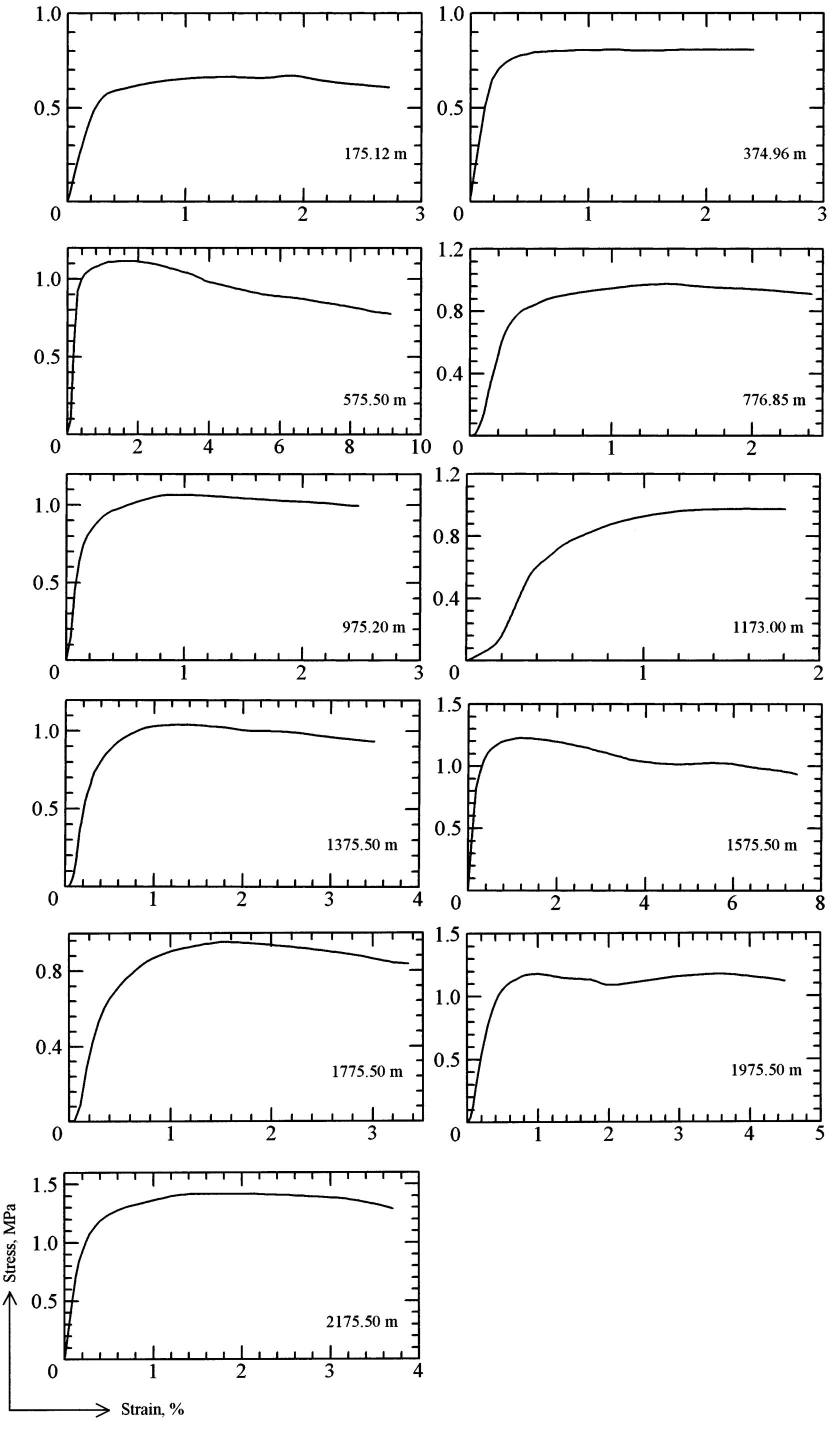

Fig. 1. Stress-strain curves of the Dome F ice core.

about 4.5×10^{-8} s^{-1} was adopted and the experimental temperature was kept at –15±0.5°C during each test run. The experimental conditions and results of each test run are shown in Table 1. The stress-strain curves are shown in Fig. 1. The maximum stress value after about 1% strain was adopted as the yield stress value. The total strain was about 2 to 8%. The median inclination of each specimen on Table 1 was predicted from Azuma *et al.* (1999).

4. Results and discussion

The enhancement factor defines the ratio of measured minimum strain rate to the strain rate of isotropic ice. Figure 2 shows the result of uniaxial compression tests with various directions on the Dye 3 ice core with a strong single maximum fabric (Shoji and Langway, 1988). They found that the enhancement factor is quite sensitive to the stress direction and varies by more than two orders of magnitude.

Figure 3 shows the result of a mechanical test on the GRIP ice core. All test specimens were prepared from core samples with the uniaxial stress axis inclined 45° from the core axis. The flow law parameter, B, can be calculated by Glen's flow law.

$$B = \frac{\dot{\varepsilon}}{\sigma^n \exp\left(-\frac{Q}{\kappa T}\right)},$$

where Q is the activation energy for creep, n is a nonlinear exponent, κ is the Boltzmann con-

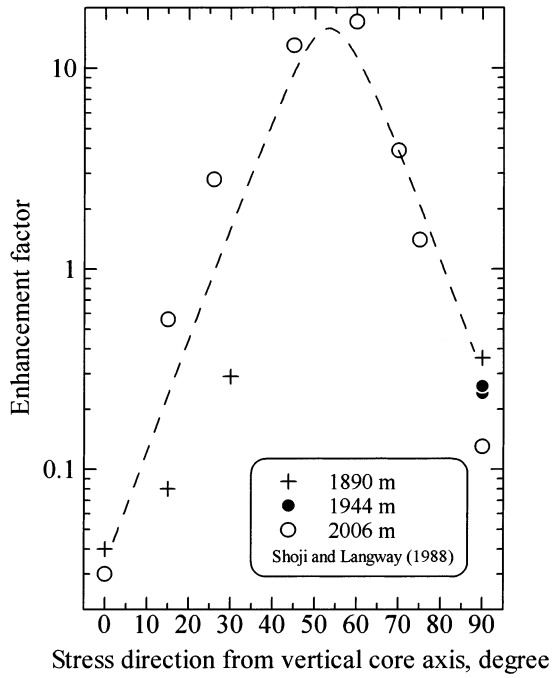

Fig. 2. Enhancement factor versus stress direction of the Dye 3 ice core (Shoji and Langway, 1988).

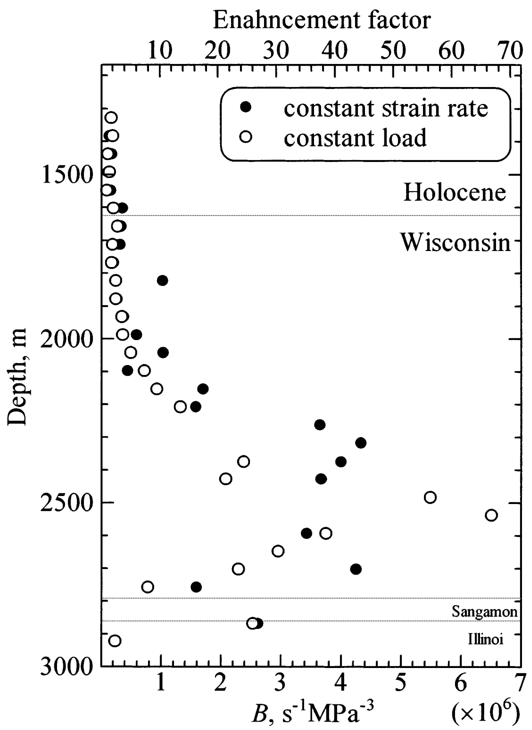

Fig. 3. The result of uniaxial compression tests of the GRIP ice cores, which were prepared from core samples with the stress axis inclined 45° from the core axis.

stant, and T is the absolute temperature. To calculate the value of B the power-law creep exponent, n, and the activation energy, Q, are taken to be 3 and 60 kJ/mol, respectively, under the temperature conditions of this study (Weertman, 1983). It is known that the value of B depends on impurity content, grain size and c-axis orientation distribution. The value of B shows a gradual increase with depth down to approximately 2000 m. Below a depth of 2000 m, the value of B increases to about 2 to 5×10^6 s^{-1} MPa^{-3}. It depends on c-axis orientation distribution. A strong single-maximum fabric pattern of the GRIP ice core was observed in the deep parts. Polycrystalline ice in this region is very resistant to compression along the horizontal direction; however, it easily shears along the horizontal plane. The flow law parameter, B, of the Dome F ice core was calculated using the same method as for the GRIP ice core as mentioned above.

In order to compare the result of a mechanical test conducted by the same method, we quote the result by Castelnau *et al.* (1998) for the GRIP ice core. They conducted uniaxial compression tests on the GRIP ice core with the stress axis applied in parallel to the core axis in each test specimen. We also conducted a compression test on only one specimen of the GRIP ice core by using the same method. The relationship between flow law parameter, B, and average Schmid factor is shown in Fig. 4. The resolved shear stress is given by the Schmid factor calculated from the angle between the stress axis and the direction of the c-axis. The value of the average Schmid factor becomes small when the c-axis orientation

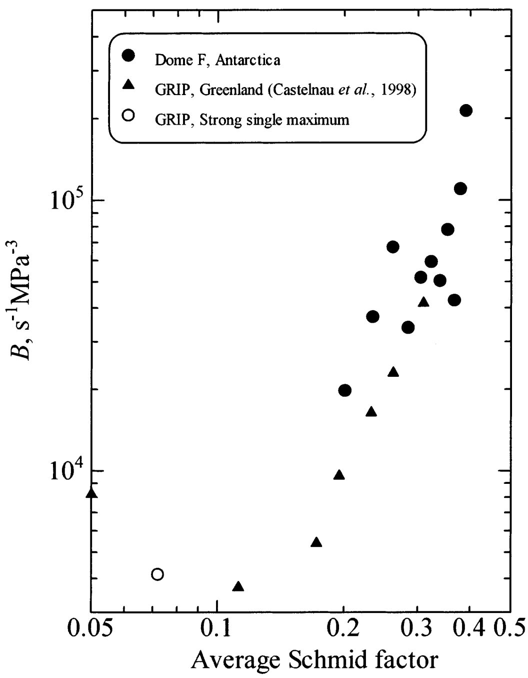

Fig. 4. Flow law parameter versus average Schmid factor of the GRIP and Dome F ice cores.

produces a strong single maximum type fabric. The decrease of values of B correlates closely with decrease of the average Schmid factor for both ice cores, from Greenland and Antarctica (Fig. 4). This result means that the c-axis orientation distribution is the principal parameter for deformation of ice core ice. It is suggested that the influence of impurity content and grain size on mechanical behavior of the ice sheet ice is small in this mechanical test method.

Figure 5 shows vertical strain versus median inclination for the GRIP, Dye 3 and Dome F ice cores. The general distribution of c-axis orientation of the GRIP ice core was measured by Thorsteinsson *et al.* (1997). These data also appear in Fig. 5. The c-axis orientation of the Dye 3 ice core was estimated from Azuma and Higashi (1985) and Herron *et al.* (1985). The fabric development with depth of the Dome F ice core was reported by Azuma *et al.* (1999, 2000). There are some weak clustering fabrics in high-impurity-concentration layers (Azuma *et al.*, 2000); however, the c-axis orientation distribution of the Dome F ice core is generally concentrated to the direction of the core axis with depth. The median inclination defines the half apex angle within which half of the measured axes lie from the average direction. The vertical strain (ε) is defined by:

$$\varepsilon = -\ln\left(\frac{H-h}{H}\right),$$

where H is ice thickness and h is depth. This equation is based on the assumption that vertical strain rate along the depth is uniform. C-axis orientation distribution is similar for the same amount of vertical strain at every location in the ice sheet. Therefore, if the ice thick-

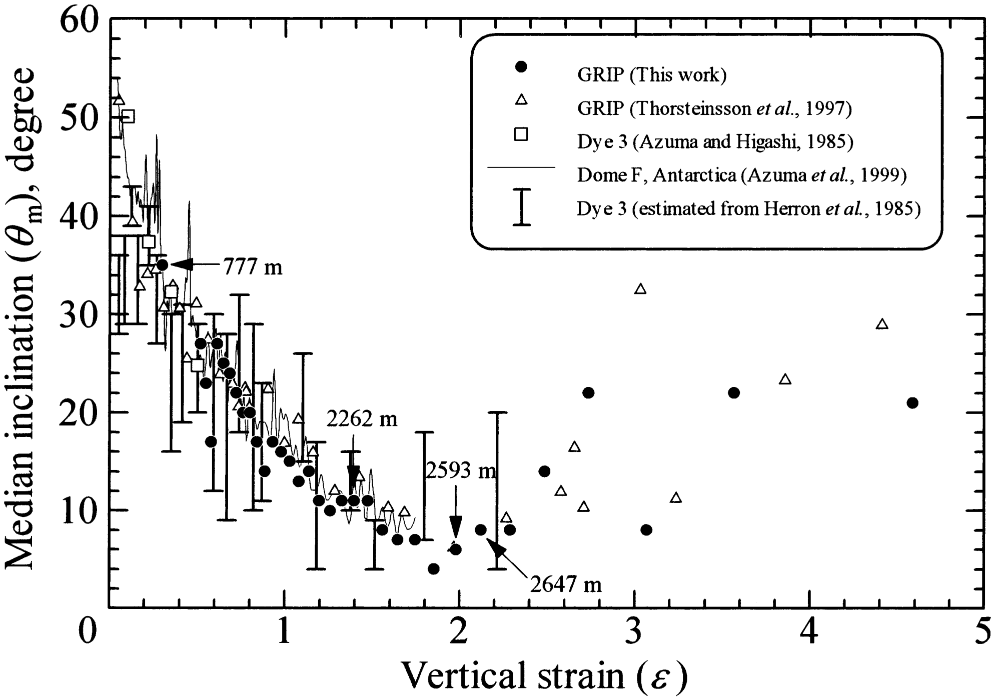

Fig. 5. Median inclination versus vertical strain.

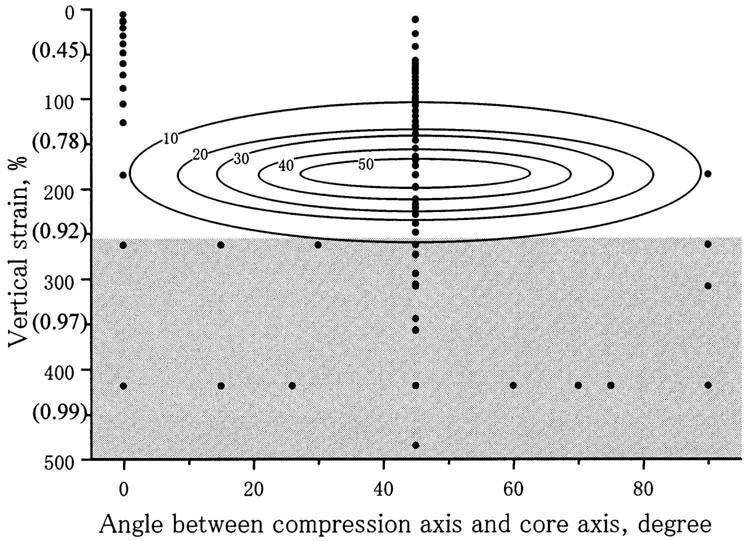

Fig. 6. Contour map of the enhancement factor. The black dots show the results of uniaxial compression tests. Numerals in parentheses show normalized depths on the vertical axis.

ness at some point in the ice sheet is known, it should be possible to predict the distribution of *c*-axis orientation distribution at that depth. The preference for vertical *c*-axis orientations can be explained by the rotation of the *c*-axis of each grain with vertical strain. The *c*-axis of each grain rotates toward the direction of the uniaxial compression axis with an increase of bulk strain, which means the gross strain of the test specimen. The strain in individual grains is proportional to the gross strain of the test specimen (Azuma, 1994). The relationship between bulk strain (ε) and the angle between the compression axis and *c*-axis of each grain is calculated using the following equation:

$$\varepsilon = \frac{l - l_0}{l_0} = \frac{\sin\phi}{\sin\phi_0} - 1,$$

where l_0 and l indicate initial length and deformed length of test specimen respectively. ϕ_0 and ϕ indicate the initial angle between the direction of uniaxial compression axis and *c*-axis of each grain, and the rotated angle, respectively.

We can predict that a contour map flow enhancement factor can be derived from available results of uniaxial compression tests (Fig. 6), although further data will be required in the future. The flow enhancement factors of the Dye 3 and the Dome F ice cores were calculated by using a flow law parameter for a randomly oriented fabric ice obtained by Barnes *et al*. (1971). For the GRIP ice core, the flow law parameter (=9.7×10^4 s^{-1} MPa^{-3}) was estimated from the relation between the value of *B* and the Schmid factor. This relation was extrapolated to a random distribution. It is possible for the flow enhancement factor in every compression direction at a given vertical strain to be estimated from this map. Contour lines of flow enhancement factor were drawn as concentric elongated ellipses around the angle between the compression axis and the core axis of 45°, with vertical strain of about 200%. Especially, when the angle between the compression axis and the core axis is near parallel (0–30°) or perpendicular (70–90°), the enhancement factor is sensitive to a slight difference of angle between compression axis and core axis for single maximum fabric ice which appears at about 200% strain. Though this had previously been shown by the model calculation of Castelnau *et al.* (1998), it was shown experimentally for the first time by this study. This means that the compression method with the stress axis inclined 45° from the core axis provides a good result when we discuss horizontal shear deformation using a uniaxial compression method. This is because it is expected that the result of the compression test has a greatly different value when the specimen cutting angle deviates a few degrees from the target angle when the stress axis is nearby parallel or perpendicular to the core axis.

In the bottom part (larger than 250% vertical strain), recrystalized grains were observed in the GRIP ice core. The fabric pattern was multiple single maximum. This is a high temperature (near pressure melting point) region. In this region (hatched area of Fig. 6), prediction of development of a *c*-axis is difficult; the enhancement factor will have various values. However, by using this contour map, if we acquire data on ice thickness throughout the ice sheet, we can estimate the mechanical anisotropy of the ice sheet flow. Moreover, the layering in the bottom 10% region has much more inclined strata than the upper 90% (Dansgaard *et al.*, 1993; Taylor *et al.*, 1993; Grootes *et al.*, 1993; Alley *et al.*, 1995) (Fig. 7). Thus, if fabric information (*C* axis orientation distribution and concentration axis direction of mean *C* axis orientation) and the inclination of strata are known, and the contour map of mechanical anisotropy is adapted for inclined strata corresponding to the angle between the compres-

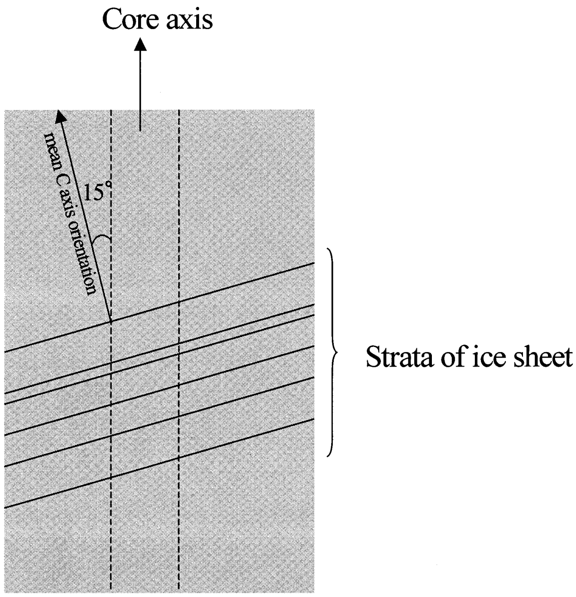

Fig. 7. Schematic diagram of inclined strata in the bottom part of the ice sheet.

sion axis and core axis in Fig. 7, we can also predict the deformation behavior of inclined strata under uniaxial compression. This contour map also explains that ice flow behavior changes by the layer structures. This makes it possible for the general flow behavior inside the ice sheet to be estimated from information on the fabric and layer structure of ice radar measurements. Furthermore, the flow parameter based on the actual internal structure of the ice sheet is provided for the ice sheet flow model.

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