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ORIENTATION OF THE 700-M MIZUHO CORE AND ITS STRAIN HISTORY

Shuji FUJITA, Masayoshi NAKAWO and Shinji MAE

Department of Applied Physics, Faculty of Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060

Abstract: Structual analyses of the core revealed that the ice fabric pattern as well as the shape of individual ice grains and air bubbles exhibited strong anisotropies. They were correlated with the stress conditions of the ice sheet around the station. This became possible by an estimation of the geographical orientation of the core through measurements of the natural remanent magnetization formed accidentally. It was found that ice grains and air bubbles were elongated in the direction of flow, which was identical with the direction of the tensile strain. Also, *c*-axes of the ice grains tended to orient perpendicular to the tensile axis, forming a vertical great girdle pattern, which is considered to have resulted from by the gradual rotation of the ice grains toward a plane normal to the tensile axis. The rotation of the grains was calculated with respect to the total strain, simulating a formation of the great girdle fabric pattern. By comparing the simulated fabric pattern with the measured pattern of the Mizuho core, the accumulated strain in the core ice was estimated at various depths. The total strain the core ice has experienced increased almost linearly with depth at a rate of about 20% per 100 m.

1. Introduction

The ice fabrics of an ice core taken from an ice sheet are of great importance for studying the dynamic behavior of the ice sheet, since the mechanical properties of polycrystalline ice are known to be dependent on the fabrics (*e.g.* JACKA and MACCAGNAN, 1984; SHOJI and LANGWAY, 1984; AZUMA and HIGASHI, 1985). AZUMA and HIGASHI (1985) showed that the total compressive strain can be estimated from fabric patterns when the applied stress is simply compressive as usually encountered near a dome summit of an ice sheet. This idea is considered applicable at a site with different stress conditions when the formation of fabric patterns is mainly due to the rotation of the grains caused by the applied stress; *i.e.*, the temperature of the ice is as low as that the recrystallization mechanism can be excluded.

In 1983 and 1984, an ice core of 700 m long was recovered at Mizuho Station (70°42′S, 44°20′E), East Antarctica, by the 24th and 25th Japanese Antarctic Research Expedition. The geographical orientation of the core being succeeded to disclose, its core's fabrics were correlated with the stress/strain conditions near the station. This paper presents the accumulated strain in the core ice at various depths, which was estimated from the fabric data using a modified "ice grain rotation model" proposed by AZUMA (1986).

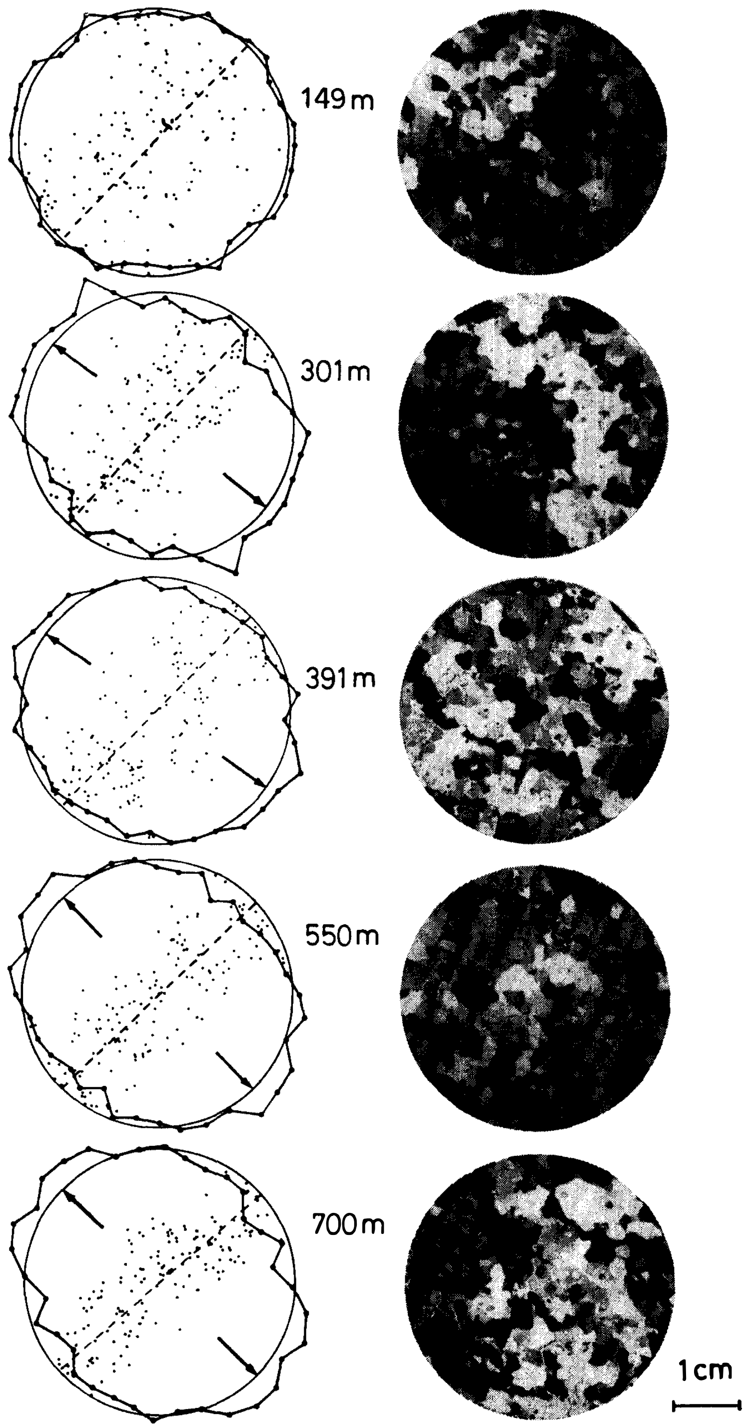

Fig. 1. *Horizontal thin sections and the fabric diagrams of the Mizuho core. The fabrics are great girdle pattens in general, and the girdles are on vertical planes (center of the fabric diagram represents the vertical direction). Broken line shows the least squares fit to the fabric data. Solid circles connected by the solid line segments indicate the average lengths of crystal grains for various orientations, obtained by the linear intercept method. Directions of elongation are indicated by arrows, all of which are roughly perpendicular to the vertical plane of great girdle given by the broken line.*

2. Structural Characteristics of the Core

C-axis distribution of about 150 ice grains was measured with a horizontal thin section sample prepared from the core at twelve depths using the Rigsby-Stage. Figure 1 shows examples of the obtained fabrics plotted on the Schmidt's equal-area net, in which the center of the circle represents the virtical direction. It can be seen that the *c*-axes tend to concentrate around a vertical plane shown by a broken line in each diagram, forming a so-called great girdle pattern. This feature is more pronounced as the depth increases. Similar patterns were reported by DUVAL and LLIBOUTRY (1985) with cores obtained at Vostok.

Figure 1 also shows photographs of the horizontal thin sections at the respective depths. In most of the pictures, except of 149 m, the crystal grains seem to elongate in a certain direction as shown by arrows in each fabric diagram (the photographs and the diagrams are placed so as to correspond in orientation with each other). To quantify the elongation of the grains, the linear intercept method was employed along radii of 10° interval from the center of the horizontal section of the core to see the orientation dependence of the grain length (OHTOMO and WAKAHAMA, 1982). The grain size at a certain orientation is plotted after normalized by the average length at each depth, *i.e.*, the outer circle of each diagram shows the average grain length for 360° orientations. Although hardly discernible at a depth of 149 m, we can see in Fig. 1 that the elongation of grains in the direction of arrows, on a horizontal plane, becomes stronger with increasing depth.

To see the shape of grains on a vertical plane, vertical thin sections were cut from two samples (301 and 550 m) as they were perpendicular to the horizontal direction of

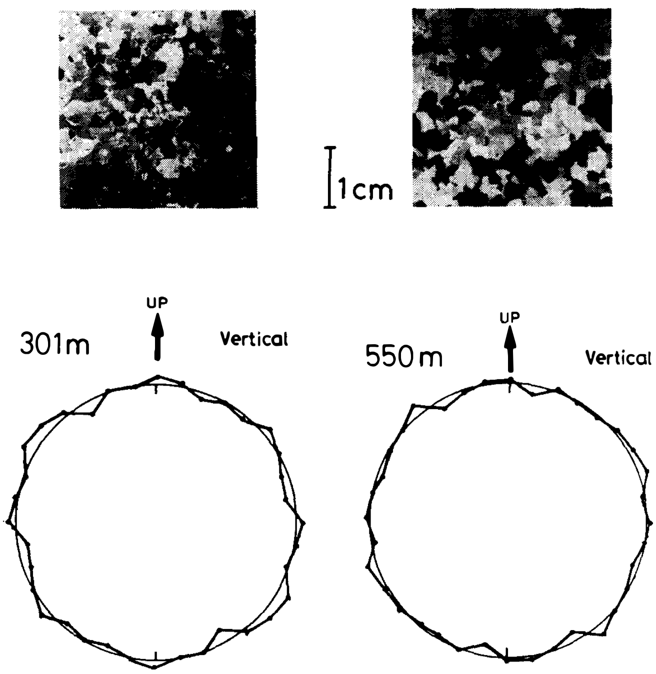

Fig. 2. Orientation dependence of the grain length on the vertical plane perpendicular to the direction of the grain elongation shown with the arrows in Fig. 1. No elongation of the grains was found on the vertical plane.

elongation shown by arrows in Fig. 1. These thin sections were analyzed by the same method as used with the horizontal sections. As can be seen in Fig. 2, no elongation was found for the ice crystal grains in the virtical sections. This fact indicates that the ice grains in deep cores were linearly elongated in a certain direction on a horizontal plane.

The direction of the grain elongation, shown by the arrow in Fig. 1, is almost orthogonal to the vertical plane (shown by the broken line) on which the *c*-axes of the crystals tend to concentrate. In other words, the crystal grains were elongated in a certain direction on a horizontal plane, and their *c*-axes were oriented perpendicular to it. This seems to suggest that a tensile stress has been applied in the same direction, which will be discussed later.

3. Orientation of the Core and Flow Direction of the Ice Sheet

Geographical orientation of the Mizuho core cannot be determined directly, because the drill used in the coring had no equipment to mark the orientation *in situ*. It is of importance, however, to identify the orientation, when the structural characteristics of the core are to be studied, in particular for cores with strong anisotropy. Recently it was found that the orientation could be determined by the use of remanent magnetization of fine iron particles accidentally included in a part of the core.

During the drilling operation, when a core sample was pulled up toward the surface, it occasionally happened that the cable suspending the drill was accidentally stretched for a moment, presumably owing to an instantaneous stacking of the drill on a small bump on the wall of the drill hole. Then vibration of the cable occurred which gave rise to the falling of ice particles from the wall with some dirts from the cable. In the subsequent drilling, several centimeters thick dirty "snow ice" was overlying the top of retrieved core sample. It is inferred that ice particles chipped off from the borehole wall by the vibration of the cable have accumulated at the bottom of the hole with dirt. This dirty snow layer might be melted by the next penetration of a thermal drill and refrozen to form a layer of "snow ice". Magnetized iron particles mixed with the "snow" should be aligned in the direction of earth's magnetic field during melting and fixed in the ice when the "snow ice" was formed. Such a formation of the "snow ice" acquiring remanent magnetism took place several times during the drilling of the 700 m long core. SAKAI and FUNAKI (1987) found experimentally that the artificial snow samples with rock dust acquire the remanent magnetization almost parallel to the geomagnetic field.

Several cubes of about a few centimeters length were cut out from the dirty "snow ice" layer formed at depths of 413 and 543 m, and the measurements of their natural remanent magnetization were carried out with a Super Conducting Rock Magnetometer (SQUID). Obtained horizontal components of the magnetization of the cubes were concentrated in a particular direction with a scatter within 20 degrees. From this direction of magnetization and the geomagnetic direction at Mizuho Station, we determined the geographical orientation of the core just attached to the snow ice, although the inclination of the magnetic field was not compatible with that of the geomagnetic field at Mizuho Station as suggested by an experiment by FUNAKI and

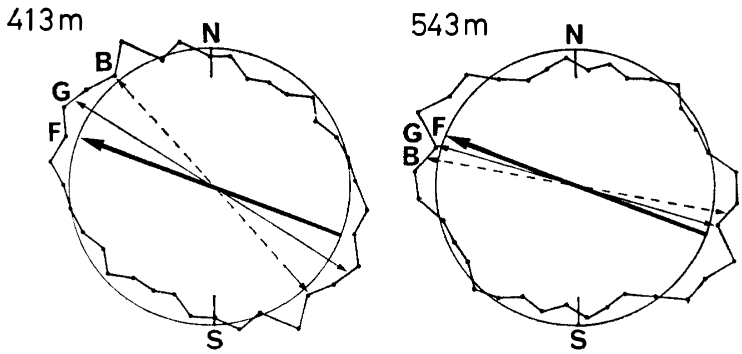

Fig. 3. Orientation of the core denoted by N and S and the surface flow direction (F) of the ice sheet at Mizuho Station. Elongation of the air bubbles and crystal grains is indicated by B and G respectively.

SAKAI (private communication).

Thin section analyses were carried out with core samples taken at depths of 413 and 543 m, both were just below the "snow ice" with which the orientation was determined. Figure 3 shows the results analysed in the same manner as in Fig. 1. The core orientation is marked by N (geographical north) and S (south). The direction of elongation for the both crystal grains and air bubbles, denoted by G and B respectively, is roughly NW for the 413 m core and WNW for the 550 m core. They roughly coincide with the direction of the flow and that of the tensile strain of surface ice at Mizuho (indicated by an arrow F), as can be seen in Fig. 3. It is now recognized that *c*-axes of the crystal grains are distributed around the vertical plane normal to the tensile axis, since the *c*-axes of the ice grains were almost normal to their elongation direction (Fig. 1). Such a pattern of ice fabric formed under tensile strain can be interpreted in the next section.

4. Formation Processes of Ice Fabric Pattern Under Tension

AZUMA and HIGASHI (1985) reported that the random fabric of polycrystalline ice was transformed into the single maximum fabric when the ice was subjected to uniaxial compression at low temperature. Physical process of this transformation is that the *c*-axis of each ice grain rotates, when the sample is compressed uniaxially, so as to become parallel to the compression axis (SCHMID and BOAS, 1935). Similar process may take place in the core under uniaxial tension.

Suppose a polycrystalline ice sample is subjected to an uniaxial tensile stress, the *c*-axis of each ice grain tends to rotate away from the tensile axis as the strain increases (SCHMID and BOAS, 1935). The resultant fabric, hence, would be a great girdle which is perpendicular to the tensile axis. With increacing strain, the girdle pattern would become more pronounced as was found in the Mizuho core (Fig. 1).

Figure 4 schematically shows the deformation process of a single crystal of ice under uniaxial tension. Angle between the *c*-axis and the tensile axis, χ, increaces from the initial value χ_0 with time as the deformation proceeds, if the deformation is solely attributed to the basal sliding in the crystal.

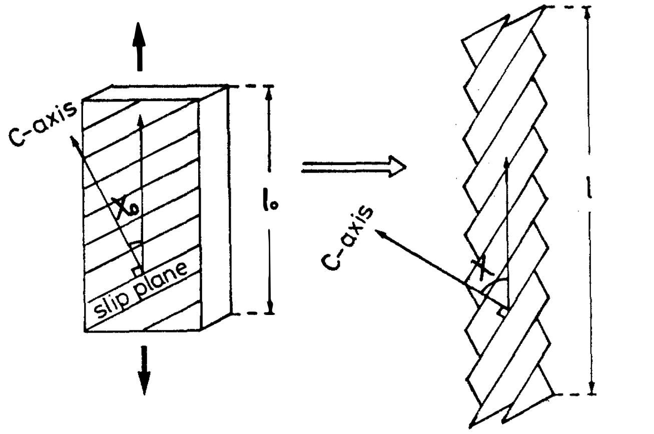

Fig. 4. Schematic diagram for an elongation of a single crystal of ice.

SCHMID and BOAS (1935) derived the following equation for the elongation of single crystal:

$$1+d\varepsilon=l/l_0=\cos\chi_0/\cos\chi\ , \tag{1}$$

where $d\varepsilon$ is a small increment of strain, l_0 and l are the lengths of the sample before and after the elongation respectively. With $d\chi$, a small increment of χ,

$$(1+d\varepsilon)\cos(\chi+d\chi)=\cos\chi\ , \tag{2}$$

and hence,

$$d\varepsilon=(\sin\chi/\cos\chi)d\chi\ , \tag{3}$$

This can be integrated to have

$$\varepsilon=\ln(\cos\chi_0/\cos\chi)\ . \tag{4}$$

With a polycrystalline ice sample, individual ice grains are bounded by adjacent grains. Hence,

$$d\varepsilon_i=(\sin\chi_i/\cos\chi_i)d\chi_i\ , \tag{5}$$

where χ_i is the misorientation angle between the tensile axis and the orientation of the c-axis of i-th crystal, and ε_i is its tensile strain.

For a compression test with polycrystalline ice, AZUMA (1986) found a relationship between ε_i and the average compressive strain of grains surrounding the i-th grain, $\bar{\varepsilon}_l$, as follows:

$$\varepsilon_i/\bar{\varepsilon}_l=S_i/\bar{S}_l\ , \tag{6}$$

where S_i is the Schmid factor for the i-th grain and $\bar{S}_l$ is the average Schmid factor for the grains surrounding it. Both Schmidt factors are given by

$$S_i=\sin\chi_i\cos\chi_i\ , \tag{7}$$

and

$$\bar{S}_l=1/N_i\left(\sum_{j=1}^{N_i}\sin\chi_j\cos\chi_j\right)\ , \tag{8}$$

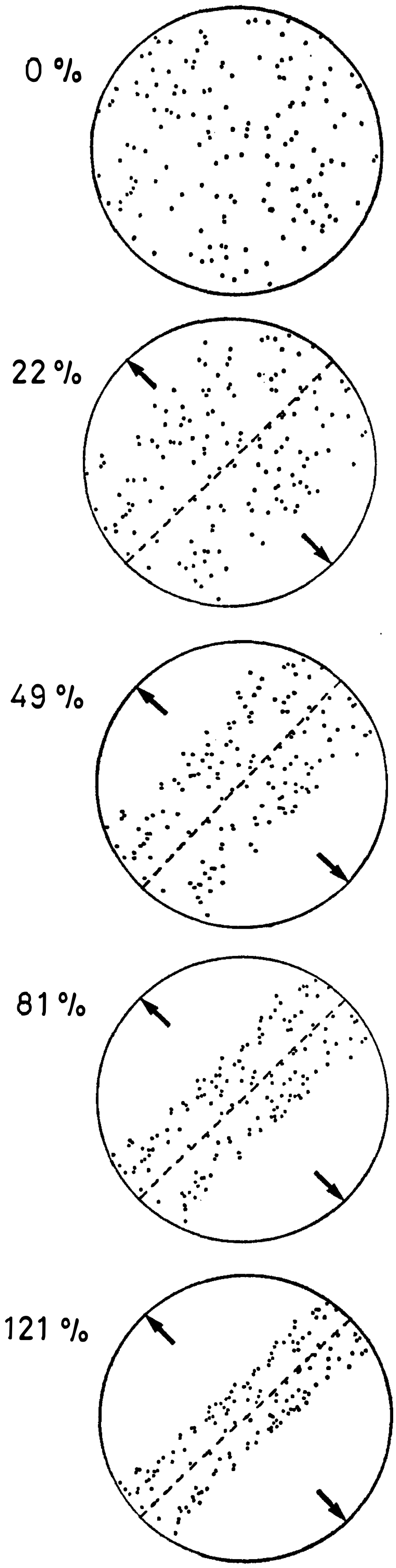

Fig. 5. Simulated fabric patterns under tension. Artificial fabric pattern (0% strain) changed to great girdle patterns as the tensile strain increased in the direction given by arrows.

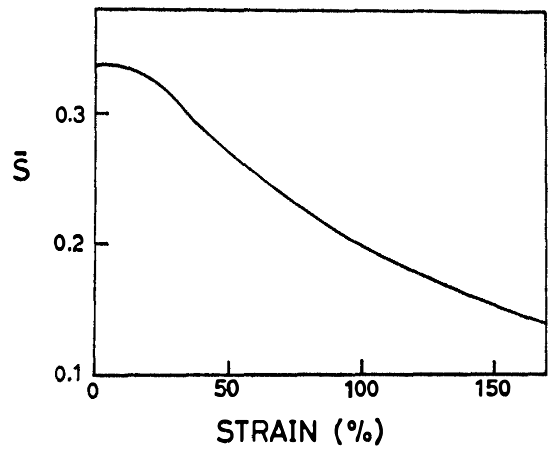

Fig. 6. Change of average Schmid factor $\bar{S}$ as the tensile strain increases. $\bar{S}$ decreases uniformly except at an earlier stage, where a small increase is found below 8% strain. $\bar{S}$ for the random fabric is 1/3.

Here N_i is the number of the grains surrounding the i-th grain. It is assumed here that eq. (6) holds for the elongation of the specimen under a tensile stress condition as well, when the deformation is due only to the basal slidings in each crystal grain. Equation (7) is then substituted into eq. (6) to have

$$d\varepsilon_i=(1/\bar{S}_l) \sin \chi_i \cos \chi_i d\varepsilon_l \ , \qquad (9)$$

which gives, combined with eq. (5),

$$d\chi_i=(1/\bar{S}_l) \cos^2 \chi_i d\varepsilon_l \ , \qquad (10)$$

When the deformation is uniform, or independent of the location over the whole specimen, $\bar{S}_l$ being independent on i, becomes compatible approximately with $\bar{S}$ the average Schmid factor of all the grains of the polycrystalline specimen. $\bar{S}$ is given by

$$\bar{S}=1/N(\sum_{i=1}^{N} \sin \chi_i \cos \chi_i) \ , \qquad (11)$$

where N is the number of the grains in the specimen. Average Schmid factor $\bar{S}$ can be calculated with this equation from ice fabric data for a specimen. A small increment of χ_i, $d\chi_i$ is, hence, correlated with a small increase in tensile strain of the sample, $d\varepsilon_t$ as follows.

$$d\chi_i=(1/\bar{S}) \cos^2 \chi_i d\varepsilon_t \ , \qquad (12)$$

which is reduced from eq. (10).

Suppose a polycrystalline ice sample with random fabric subjected to a tensile stress, $\bar{S}$ for the sample is calculated by eq. (11), and $d\chi_i$ for each crystal grain can be obtained by eq. (12) for a given $d\varepsilon_t$, a small increment of the sample strain. Owing to the rotation of the crystal grains by an amount of $d\chi_i$, the fabric pattern and hence $\bar{S}$ are subjected to a slight change. Using this modified value of $\bar{S}$, further rotation of each grain can be calculated by eq. (12). The calculation was repeated with a step of $d\varepsilon_t=1\%$ until a given total strain was achieved for the sample. Figure 5 shows fabric patterns for various tensile strain, thus estimated from a random fabric. It is seen that the orientation of *c*-axes rotates toward a plane normal to the tensile axis, forming a great girdle pattern with increasing tensile strain. In association with the change in fabric pattern, average Schmid factor $\bar{S}$ changes also with increasing strain, as shown in Fig. 6. $\bar{S}$, having a value of 1/3 for a random fabric, increases slightly at first with increasing tensile strain reaching a maximum at around 8% strain and then decreases uniformly for further deformation.

5. Strain History of the Mizuho Core

Results of computer simulation shown in Fig. 5 are similar to the fabric patterns found with the Mizuho core. Since the temperature of the ice above the 700-m depth under Mizuho Station is well below −30°C (OKUHIRA, private communication), recrystallization is not expected to be associated with the fabric formation in the Mizuho core. As was stated in Section 3, directions of grain elongation coincided well with the normal of the plane of large girdle and they also roughly coincided with both the directions of the flow and the tensile strain of surface ice at Mizuho. If we assume that the ice under Mizuho Station all through the depth at least down to 700 m is subjected to the tensile strain condition approximately in the same direction of the grain elongation, even increasing with depth, the fabric pattern of the core at various depths could be understood as resulting from the formation process as described in Section 4.

Average Schmid factor $\bar{S}$ for each fabric diagram of the Mizuho core was calculated, and it was transformed to the accumulated strain of the core ice at corresponding depth using the diagram of Fig. 6. The total strain thus obtained is plotted against depth as shown in Fig. 7. Corresponding value of $\bar{S}$ is also shown in the figure for reference.

The figure seems to indicate a linear relationship between the strain and the depth. A linear regression analysis has resulted in a strain gradient of 18%/100 m, as shown

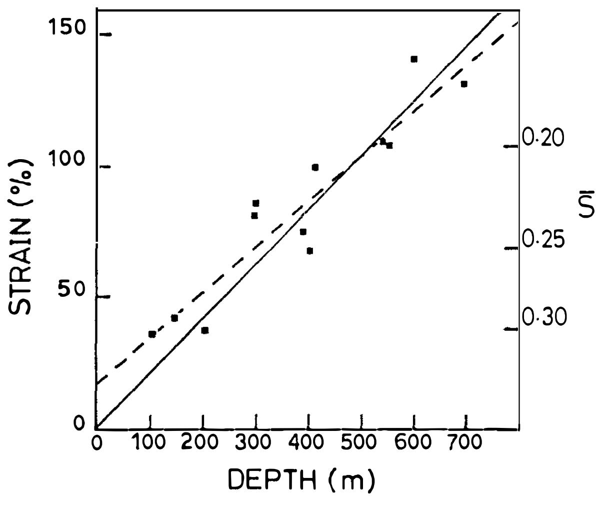

Fig. 7. Accumulated strain versus depth for the Mizuho core. The strain was estimated from the value of $\bar{S}$ calculated form the fabric data at each depth.

with a broken line in Fig. 7. With an assumption of random fabric ($\bar{S}$ is 1/3) at the surface, *i.e.*, zero strain at the surface, the strain gradient of 21%/100 m was obtained as shown by a solid line in the figure. Since the core samples were of snow/firm above 100 m, the relation between $\bar{S}$ and the strain as shown in Fig. 6 will not hold there, because the fabric patterns are affected not only by the stress conditions but also by metamorphisms of snow particles such as formation of depth hoar, *etc.*, in the snow/firn layers (NAKAWO, 1974, 1975). It would be concluded, none the less, that the tensile strain accumulates in the core ice with increasing depth at a rate of about 20%/100 m.

The cummulative strain thus estimated is the tensile strain in the direction of flow, which the ice has experienced during its travel along the particle path after the snow particles were deposited on the ice sheet surface. Such a strain history estimated with the core at different depths would be useful for ice sheet dynamics. Further discussion will be published elsewhere.

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