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DATING THE MIZUHO 700-m CORE FROM CORE ICE FABRIC DATA

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Abstract: The vertical strain rate of the ice sheet has been estimated from the longitudinal total strain derived from Mizuho core fabric data. The vertical strain rate is considered to be the average value in the past while the ice sheet has experienced a significant thinning. With use of the obtained vertical strain rate, the age of ice in the Mizuho core has been dated. It was shown that the 700-m core corresponds with the time period of the past 9400 years.

1. Introduction

For dating ice cores, various methods have been employed, *e.g.* counting the seasonal variations of quantities such as $\delta\,^{18}O$, dust content, nitrate content etc. in the core, and measuring the activity of radioisotopes such as ^{10}Be, ^{14}C, and ^{210}Pb etc. which give absolute values. Flow model calculation is often used to date an ice core, but it is usually used under an assumption of stationary state. However, on the Mizuho Plateau, Antarctica, where the present 700 m core was retrieved, this condition is not satisfied, because significant thinning of the ice sheet has been reported (MAE and NARUSE, 1978; NARUSE, 1978; NAKAWO *et al.*, 1988). We propose here a new method to estimate the age of ice in the ice core based on a relationship between accumulated tensile strain and fabric data for the core ice.

FUJITA *et al.* (1987) estimated the total tensile strain in the flow direction, exerted in ice at various depths of the Mizuho core during its travel along the particle path, from a location where the snow particles were deposited on the ice sheet surface to their present position (depth). The estimate was based on core fabric data *per se*; hence, the obtained strain is considered plausible whether the ice sheet is in the steady state or not.

This paper aims at presenting a depth-age curve for the Mizuho core, derived

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from the data on a relationship between depth and total tensile strain, thus derived from the fabric data.

2. Longitudinal Strain

Figure 1 shows a typical fabric pattern of the Mizuho core plotted on Schmidt's equal-area net, in which the center of the outer circle represents the vertical direction of the core (y-axis), and the x-axis coincides with the flow direction at Mizuho Station. The origin of the coordinate system is taken at the ice sheet surface. This pattern is a so called great girdle, whose pole coincides with the flow direction. FUJITA *et al.* (1987) considered the girdle pattern as a result of the accumulated tensile strain in the flow direction, since the c-axes of ice crystals tend to rotate away from the tensile axis to be in a plane perpendicular to the direction of flow of the ice sheet at the station. This consideration is based on the grain rotation model in establishing ice fabrics, proposed by AZUMA (1986), which is considered applicable to ice masses at low temperatures such as a shallow portion over a high plateau on the Antarctic ice sheet.

The concentration of the c-axes on the girdle increased with depth. In other words, the girdle width decreased with depth. The degree of concentration of the c-axes is expressed by the average Schmid factor $\bar{S}$ of each crystal grain in the core

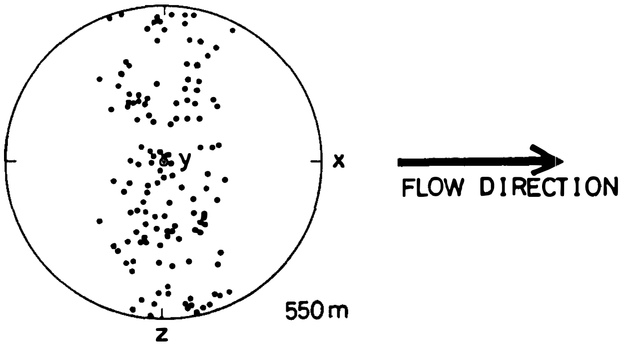

Fig. 1. A typical fabric pattern found in the 700 m Mizuho core. The c-axes of ice crystals were concentrated nearly in a vertical plane normal to the flow direction (arrow) of the ice sheet at Mizuho Station.

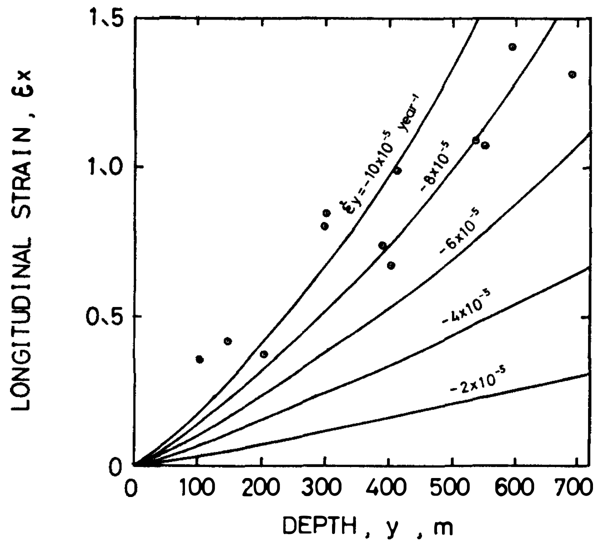

Fig. 2. Cummulative longitudinal strain vs. depth. Open circles were derived from fabric data (FUJITA et al., 1987). Solid lines are from eq. (5) for various values of the vertical strain rate.

ice. From an empirical relation between $\bar{S}$ and the total strain (AZUMA, 1986), FUJITA *et al.* (1987) estimated the total longitudinal strain ε_x exterted in ice at various depths of the Mizuho core, assuming the initial fabric to be random. Their results are presented in Fig. 2 with open circles, which show an increasing trend of ε_x with depth.

3. Vertical Strain Rate

The nearly homogeneous distribution of dots (*c*-axis distributions) in the girdle band shown in Fig. 1, indicates that the strain components along the *y*-axis and *z*-axis are nearly equal to each other. To confirm this equivalence, average Schmid factors with reference to *y*- and *z*-axes were calculated with fabric data at various core depths. Results of the calculation showed that the differences in the factors for *y*- and *z*-axes are less than a few per cent at any depth. It was assumed, hence, that the average strain rates along the *y*- and *z*-axes are equal, *i.e.*,

$$\dot{\varepsilon}_y = \dot{\varepsilon}_z \ . \tag{1}$$

Assuming the incompressibility of ice,

$$\dot{\varepsilon}_x = -2\dot{\varepsilon}_y \ . \tag{2}$$

The vertical strain rate of an ice sheet is considered constant, in particular near the surface of the ice sheet. Hence, the vertical velocity decreases linearly near the surface. This assumption would hold even for an ice sheet in non-steady state. Assuming further that the vertical velocity v equals the accumulation rate c at the surface,

$$v = c + y\dot{\varepsilon}_y \ . \tag{3}$$

Since y is taken downward from the surface. From eqs. (2) and (3),

$$\frac{\partial \varepsilon_x}{\partial y} = \frac{-2\dot{\varepsilon}_y}{c + y\dot{\varepsilon}_y} \tag{4}$$

which is integrated to give

$$\varepsilon_x = -2[\ln (c + y\dot{\varepsilon}_y) - \ln (c)] \tag{5}$$

with a boundary condition that $\varepsilon_x = 0$ at the surface. Relationships between ε_x and y (depth from the surface) in eq. (5) are drawn as several curves in Fig. 2 for various vertical strain rates $\dot{\varepsilon}_y$. Here, the value of c was taken to be 99 mm year^{-1} (ice equivalent), an average value of measured accumulation rates on Route NY, which extended for 85 km upstream from Mizuho Station (measured for about 5 years from 1981 to 1986). The longitudinal strain obtained from core fabric data (FUJITA *et al.*, 1987) is plotted as open circles in the figure. Curves for the strain rate of either -10×10^{-5} or -8×10^{-5} year^{-1} seem to fit the longitudinal strain data. It is considered, however, the neither curves is the best fit: the $\dot{\varepsilon}_y = -10 \times 10^{-5}$ curve predicts greater strain than deep data, and the $\dot{\varepsilon}_y = -8 \times 10^{-5}$ curve predicts smaller values at shallow depths.

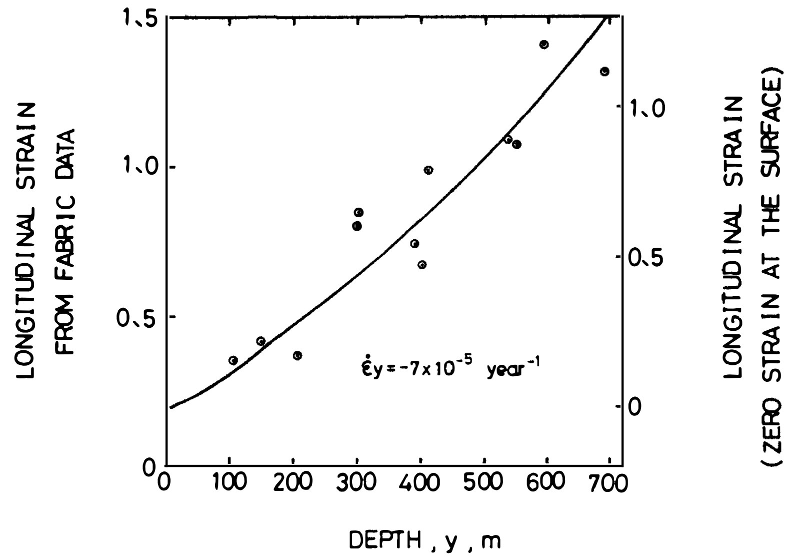

Fig. 3. Cummulative longitudinal strain vs. depth. Open circles are the same as in Fig. 2. A theoretical curve derived by a least square fit to the data gives the vertical strain rate of -7×10^{-5} *year*$^{-1}$ *in a modified form of eq. (5). A corrected scale for the curve is given on the right ordinate, considering that the longitudinal strain should be zero at the surface.*

Such discrepancies between the theoretical curves and strain data seem to require modification of the boundary condition adopted for obtaining eq. (5): the longitudinal strain is zero at the surface. When the ice fabric is not random at the surface, the estimated strain from the fabric data should apparently acquire a certain value even though the actual strain is zero at the surface. This would be the case, since NAKAWO (1974, 1975) observed several concentrated fabric patterns, at the surface snow layers near Mizuho Station. They were attributed mainly to depth hoar formation.

It is considered, therefore, the theoretical curves do not necessarily pass the origin of Fig. 2, but pass at a certain value of ε_x at zero depth. In other words, eq. (5) should be used without the condition of zero strain at the surface. Regression analysis gave the best fit to the strain data when the vertical strain rate was taken as -7×10^{-5} year^{-1}. This resulted in $\varepsilon_x=0.2$ for $y=0$ as shown in Fig. 3.

The longitudinal strain on the right ordinate of Fig. 3 is the value accumulated in ice at various depths during the flow along a particle path in a period from the deposition of the snow particles to the time when the core was retrieved. The obtained vertical strain rate, -7×10^{-5} year^{-1}, therefore, would be the average value for a certain period in the past and for a certain area upstream from Mizuho Station, which ice particles consisting the Mizuho core have passed through.

4. Determination of the Age of Ice

The age t for ice at a given depth y of the core is expressed by

$$t=\int_0^y \frac{1}{v}\mathrm{d}y\,. \tag{6}$$

Since v is given by eq. (3), eq. (6) can be integrated:

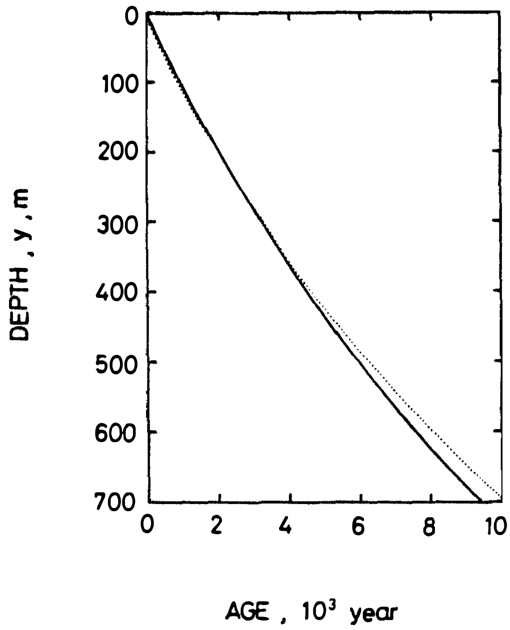

Fig. 4. Relationship between true depth and age of ice in the Mizuho core. The solid line is derived from fabric data, and dotted line from a steady flow model.

Table 1. Time scale for the Mizuho core from fabric data.

Depth (m)	Age (year)	Age (year)	Depth (m)
100	864	1000	112.5
200	1980	2000	202
300	3190	3000	285
400	4512	4000	362.5
500	5969	5000	435
600	7592	6000	502
700	9423	7000	565
		8000	623.5
		9000	678

$$t=\frac{1}{\dot{\varepsilon}_y}\ln\left(\frac{c+y\dot{\varepsilon}_y}{c}\right). \tag{7}$$

Using this equation with the values c=99 mm year^{-1} and $\dot{\varepsilon}_y=-7\times10^{-5}$ year^{-1} as given above, the age of ice was calculated for various depths. In the calculation, y is the depth for ice equivalent; hence, the true depth was estimated taking into account the density profile of the Mizuho core (NARITA and MAENO, 1978; NAKAWO and NARITA, 1985). The relationship between the true depth and the age of ice is presented in Fig. 4 and Table 1. It is indicated that the 700 m long Mizuho core covers a time period of about 9400 years in the past.

The dotted line in Fig. 4 indicates a depth-age curve given, for comparison, by a flow model calculation with an assumption of steady state. The calculation was done based on the steady model of TAKAHASHI and NAKAWO (1982). It predicts an older age, except at shallow depths, than the estimate from fabric data. The difference is about 600 years at the core bottom (700 m). This would be due to the steady state assumption of the model despite the recent thinning of the ice sheet on the Mizuho

Plateau.

The obtained depth-age curve from fabric data is certainly rough, since the vertical strain rate and the accumulation rate used were average values for a long period and for a large area upstream from Mizuho Station. An advantage of the calculation is that the estimate is based on accumulated strain data for a long period in which the ice sheet has evolved, and hence, it is considered applicable to an ice sheet in a non-steady state, such as on the Mizuho Plateau. Re-interpretation of vertical profiles of various core data such as $\delta^{18}O$, microparticle content, total gas content etc. (*e.g.*, FUJII and WATANABE, 1988), with this time scale, will be published elsewhere.

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