Annals of Glaciology 10 1988

PRELIMINARY RESULTS OF ANALYSES OF 700 m ICE CORES RETRIEVED AT MIZUHO STATION, ANTARCTICA

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ABSTRACT

Preliminary results of the analyses on 700 m ice cores retrieved from Mizuho Station, Antarctica, in 1983 and 1984 are presented. The majority of the physical properties, density, grain-size and shape, and total gas content, were measured at the drilling site. Fabrics, microparticle concentration, electrical conductivity, and stable-isotope concentration $\delta^{18}O$ were measured in laboratories after the cores had been taken to Japan.

In spite of inaccuracy in measuring both density and total gas content in the ice, due to interlocking cracks in cores, several attempts were made to correct the data. The coincidence between the incremental peaks in the depth profile of the microparticle concentration, as well as in the electrical conductivity and the warm trend indicated by the $\delta^{18}O$ profile is discussed. The shape of the $\delta^{18}O$ profile is characterized by two inflection points and is compared with results obtained from the Byrd Station, Dome C and Vostok cores. From this comparison, it is tentatively concluded that the bottom of the Mizuho core may be an age of the order of 10 ka B.P.

1. INTRODUCTION

In 1983 and 1984, wintering parties (members of JARE-24 and 25) at Mizuho Station, Antarctica, successfully retrieved a 700.56 m ice core (Narita and others 1988, this volume). Unfortunately, the core quality was poor below 130 m, where there were many interlocking cracks. These may have resulted from the sudden change in temperature of the ice, associated with the thermal-drilling technique. Although the physical properties of the cores were affected by these cracks (described below), some of the chemical properties were not affected because the analyses were conducted on melt-water samples which were carefully prepared. Water samples were taken carefully from the central part of the cores by standard procedures.

The entire core was taken from Mizuho Station to Tokyo by the icebreaker *Shirase* at the end of each wintering period, and was stored at about −20 °C in a cold-room of the National Institute of Polar Research (NIPR). Several of the physical analyses were conducted at Mizuho Station immediately after retrieval of the cores. Additional physical and chemical analyses were carried out after 1986, when appropriate arrangements for the distribution of the cores had been made.

This paper summarizes the core analyses which have already been carried out to determine both physical and chemical properties. The depth profile of $\delta^{18}O$ in the cores shows characteristic features which are different from those in cores obtained previously from the east and west plateau areas in Antarctica. Preliminary interpretations of the

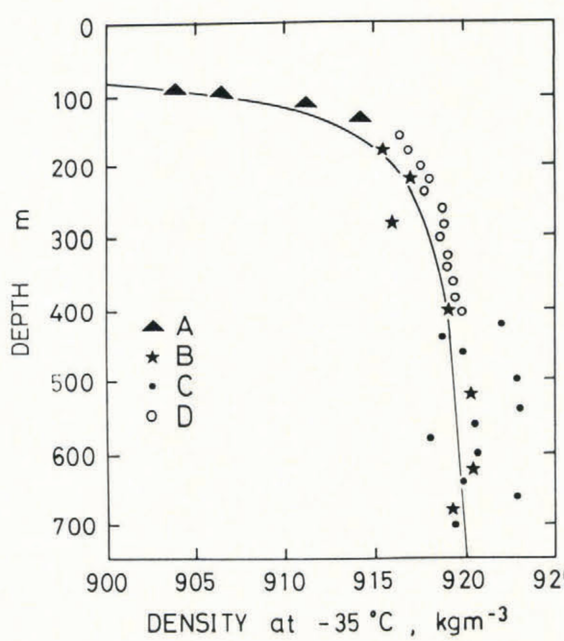

Fig.1. Depth profile of the density of ice measured at Mizuho Station immediately after retrieval of the core. A: 100–200 g samples without cracks (less than 130 m). B: 7–20 g small samples without cracks. C: 2–7 smaller samples without cracks. D: corrected density from the data of 100–200 cracked samples (Nakawo and Narita 1985).

https://doi.org/10.3189/S026030550000416X Published online by Cambridge University Press

differences were deduced from the preserved stratigraphic record, taking into account the effect of ice flow near Mizuho, and a chronology for the core is proposed. However, definitive interpretations will only be possible in the future, when sufficient data on the flow of the ice sheet in east Dronning Maud Land are available.

2. DENSITY

Ice density was measured by the hydrostatic method at Mizuho Station immediately after each core was brought to the surface. Cores from below 135 m have many interlocking cracks, so that the measurements of the density and total gas content are inaccurate. When a thin specimen is cut from the core in order to avoid cracks, it may have to be as small as 2–20 g, which makes it difficult to obtain a good degree of accuracy. Nakawo and Narita (1985) attempted to determine the "crack-free density" from the measurements of cracked specimens of 100–200 g, by taking account of measurements of typical total gas content. Details of the measurements are given in a paper by Nakawo and Narita (1985) which includes the methods of correcting the data obtained from cracked specimens.

Results of measurements are shown in Figure 1 as the depth profile of the corrected or "crack-free" density of ice. Data are classified according to the size of the samples. Data in category A are for the cores from a shallow depth (above 135 m), in which no cracks were found. Category B comprises data for small samples of 7–20 g, assumed to be crack-free. In the case of the upper half of the total depth (less than 413.5 m), these data were compared with corrected data from cracked samples as shown in category D. It was found that the category D values are a little higher than those for category B. However, in the case of the lower half, category B data depend on the extrapolation of the category D data in the upper half. Category C data, obtained by the 1985 party, using smaller samples of 2–7 g in order to avoid cracks completely, are rather scattered, although some of them follow the trend of category B data.

A solid-line curve in the figure shows a relationship between the density ρ and the depth z, expressed in the following equation:

$$z - z_c = \left(\frac{P_c}{g}\right)\left(\frac{1}{\rho} - \frac{1}{\gamma}\right)\left[\frac{\gamma(\rho - \rho_c)}{(\gamma - \rho)(\gamma - \rho_c)} - \right.$$
$$\left. - \ln\left\{\left[\left(\frac{\rho_c}{\rho}\right)\left(\frac{\gamma - \rho}{\gamma - \rho_c}\right)\right]\right\}\right] \qquad (1)$$

which was derived by Nakawo and Narita (1985) from the relationship between the total gas content and the density, and an assumption that the bubble pressure is equal to the overburden pressure in ice. In Equation 1, P_c and ρ_c are the bubble pressure and the density of ice at the depth of bubble close-off, γ is the density of pure ice, and g is the acceleration of gravity. The base data for Equation 1 on the bubble close-off at Mizuho Station were taken from Higashi and others (1983). As can be seen in Figure 1, the data obtained fit the curve of Equation 1 very well. This suggests that the densification of ice after bubble close-off may be attributed solely to the shrinkage of occluded air bubbles in response to overburden pressure.

3. STRUCTURAL FEATURES OF ICE GRAINS

The size and shape of ice grains were measured from thin-section photographs taken within a month of the recovery of the cores. Details on the preparation of thin sections are given by Narita and Nakawo (1985). The grain-size, expressed as the arithmetic mean S_a of 200–300 individual grain areas measured on photographs, increases very rapidly from the surface down to a depth of 70 m. However, below this depth S_a increases much more slowly with depth (Fig.2a).

Since the measured cross-sectional area of individual grains is generally smaller than their maximum cross-sections, the arithmetic mean thus obtained is smaller than the real mean size of the grains. The real mean value of the grain area S was obtained by using the size distribution curves of the measured areas on the thin section: S, shown in Figure 2b, is defined as the area corresponding to 76%

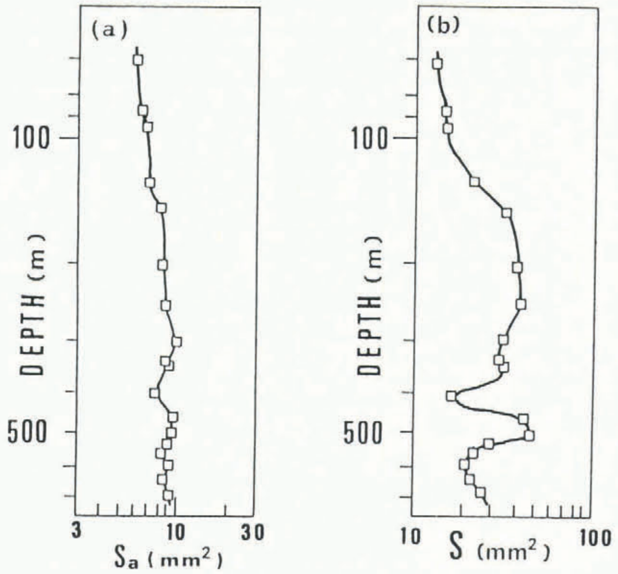

Fig.2. Depth profile of the average grain-size of ice: (a) arithmetic mean S_a of observed areas on thin-section photographs, (b) average area S corrected by Krumbein's method (Narita and Nakawo 1985).

on the cumulative distribution (Krumbein 1935). Note the increase in grain-size with depth below 100 m. We are not yet able to give a clear explanation of the abrupt decrease and increase at 400 and 500 m depth respectively.

The elongation of grains was investigated with several samples at different depths, in conjunction with the pattern of the *c*-axis fabrics. The horizontal orientation distribution of the elongation of grains was obtained as follows. Draw radial straight lines from the center of a horizontal thin-section photograph at 10°C intervals, and then count numbers of grain boundaries between adjacent grains intercepting each straight line. The reciprocal of the number normalized by the mean diameter of grains in the photograph indicates the degree of elongation of grains in a specified direction. Directional variation in this quantity is given by a circular graph as shown in Figure 3. Although the distribution does not differ significantly from a circle for a sample from 149 m depth, those for other samples at 391 m and deeper certainly protrude in a specified direction, which indicates the direction of the elongation of grains.

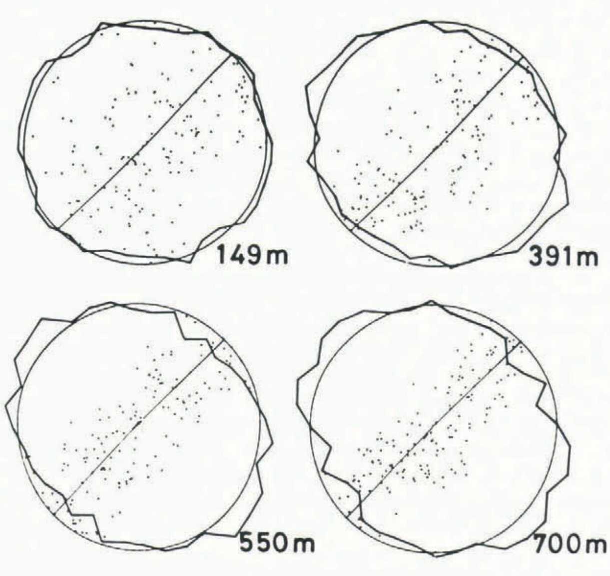

Fig.3. Diagrams to show the elongation of grains and fabric of ice crystals at different depths. An orthogonal relationship can be seen between the direction of elongation and the *c*-axis orientations.

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Ice fabrics, or the orientation distribution of the c-axes of individual grains, were measured on a Rigsby stage on the same specimens as used for the observation of grain elongations. The fabric diagram obtained from more than 150 grains in each thin-section specimen was superimposed on the plot of grain elongations in Figure 3. Although geographical direction on a horizontal thin-section specimen could not be determined, directions of the grain elongation and the normal to the plane of a large girdle coincided at each depth. All fabric diagrams in Figure 3 exhibit more or less the girdle type, in which plotted data are concentrated in a band near a great circle perpendicular to the elongation axis. The degree of concentration of data, or the band width, becomes narrower with depth. The orthogonal relationship between the direction of grain elongation and the direction of the c-axes indicates that the flow of the polycrystalline ice crystals is taking place in the direction of the elongation of the grains. Details are given in a paper by Fujita and others (1987).

4. AIR BUBBLES

Studies of air bubbles occluded in deep ice cores have been interrupted by the existence of many interlocking cracks, as in the case of the density described in section 2. Nominal bubble pressures measured by melting ice specimens even right after the core recovery were as low as 1.0 MPa throughout cores from below 100 m depth, much smaller than the overburden pressures at corresponding depths, presumably because of air loss through the cracks (Nakawo and Narita 1985). Therefore we cannot address the origin of the ice at different depths, nor can we use the bubble pressure to examine the climatic changes in this area of the Antarctic ice sheet.

5. MICROPARTICLES AND ELECTRICAL CONDUCTIVITY

Samples for the measurements of microparticle concentrations, electrical conductivity and stable oxygen-isotope composition were prepared in a cold-room laboratory in the NIPR. Ten semi-circular disks, approximately 5 cm thick, were cut out from a 50 cm long core; they were selected at intervals of 5 m along the length of the core from depths of approximately 60 to 700 m. These samples were melted in a clean-room of class 1000, taking care to avoid contamination from both intrinsic and extrinsic sources. The final melt water of approximately 150 cm^3 from each 5 cm thick sample was divided into three: 15 cm^3 for the microparticle counting, 30 cm^3 for the electrical conductivity, and the remainder (about 100 cm^3) for major chemical-composition analyses.

Procedures for the microparticle analysis, using the Coulter model TA II counter, are as described in detail by Fujii (1981) and Fujii and Ohata 1982). The number of microparticles with diameter exceeding 0.63 μm was counted, using 0.05 cm^3 of each melt-water sample. In the present study, when two or three consistent values were obtained, their mean value was considered as the microparticle concentration of the sample. Then the data for ten samples in a 0.5 m core were averaged to obtain the representative value for the core.

Figure 4 illustrates the concentration (number of particles per 0.05 cm^3 water) for each 0.5 m long core at its specific depth. The maximum and minimum values of the concentration from ten samples in a 0.5 m core are designated at each depth by crosses on a horizontal line. The median value (the fifth from the maximum), designated by a small circle on the line, is considered as a representative value for the concentration at a specific depth. Although the maximum value exceeds 7000/0.05 cm^3 at some depths, as indicated by numbers to the right of the horizontal lines, the arithmetic mean of the median values through the total depth is 1070/0.05 cm^3, which is shown as the vertical straight line in the figure. Lack of data at depths between 140 and 230 m may affect the mean value to some extent, but the effect is expected to be small.

Thick solid lines connecting circles of the median value indicate general trends in the depth variation of the microparticle concentration. A remarkable feature of the trend is that the concentration exceeds the mean value 1070/0.05 cm^3

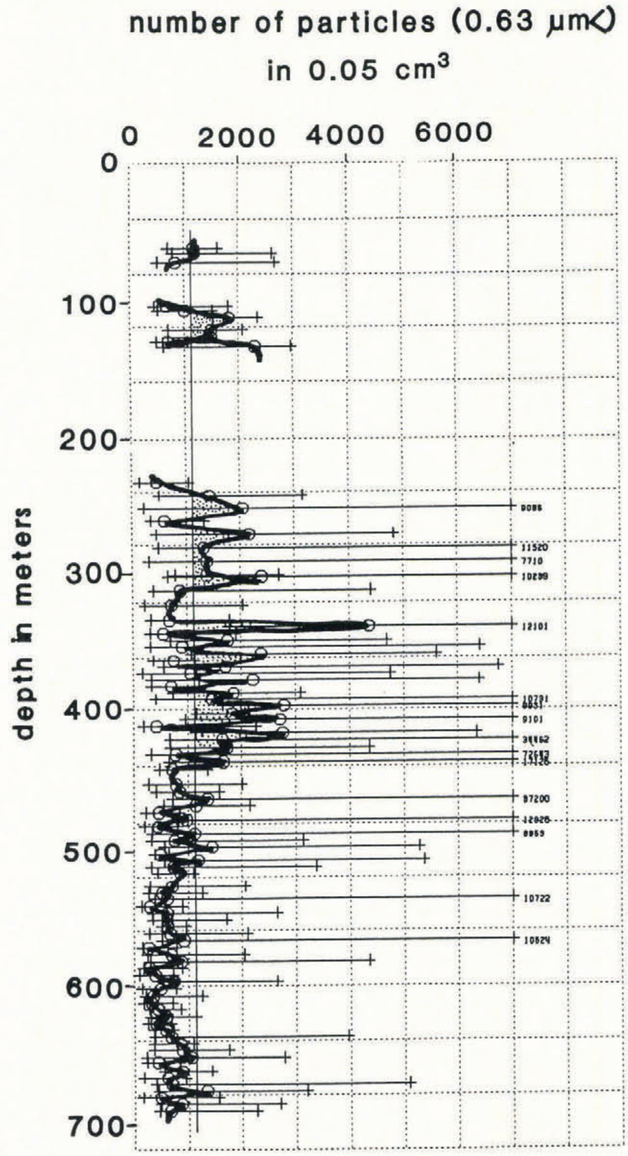

Fig.4. Depth profile of the microparticle concentration in the ice core. (See figure 4 in Fujii and Watanabe 1988, this volume, p.).

very often in the depth range between 230 and 440 m, whereas it rarely does below 440 m.

Electrical conductivity of the melt water was measured by a calibrated commercial conductivity cell, AOC-10. It varied between 1.34 and 4.99 $\mu S\,cm^{-1}$, although values more than 4 $\mu S\,cm^{-1}$ were rare: only 2 out of 80 measurements. As was the case with microparticle concentration, the median value from the ten successive samples from a 0.5 m core was taken as representative for a specific depth. The depth variation in the electrical conductivity is given in figure 4 of a paper by Fujii and Watanabe (1988, this volume). The trend of the variation is quite similar to that of the microparticle concentration; median values often exceed the mean value 2.16 $\mu S\,cm^{-1}$ at the depth range above 400 m, but are generally lower than the mean below 400 m. The similarity of the trend is discussed in the paper by Fujii and Watanabe (1988, this volume).

6. STABLE OXYGEN ISOTOPES $\delta^{18}O$

The concentration of the stable oxygen isotope, or $\delta^{18}O$, for a specific depth was measured in a mixed sample, prepared by mixing ten samples of 3 cm^3, each taken from a 0.5 m core in the manner described in section 5. For the depth range from 5 to 150 m, however, a different method of sampling was used. Nearly continuous samples were cut from the cores (5–6 samples of 3–5 cm thick per 1 m core).

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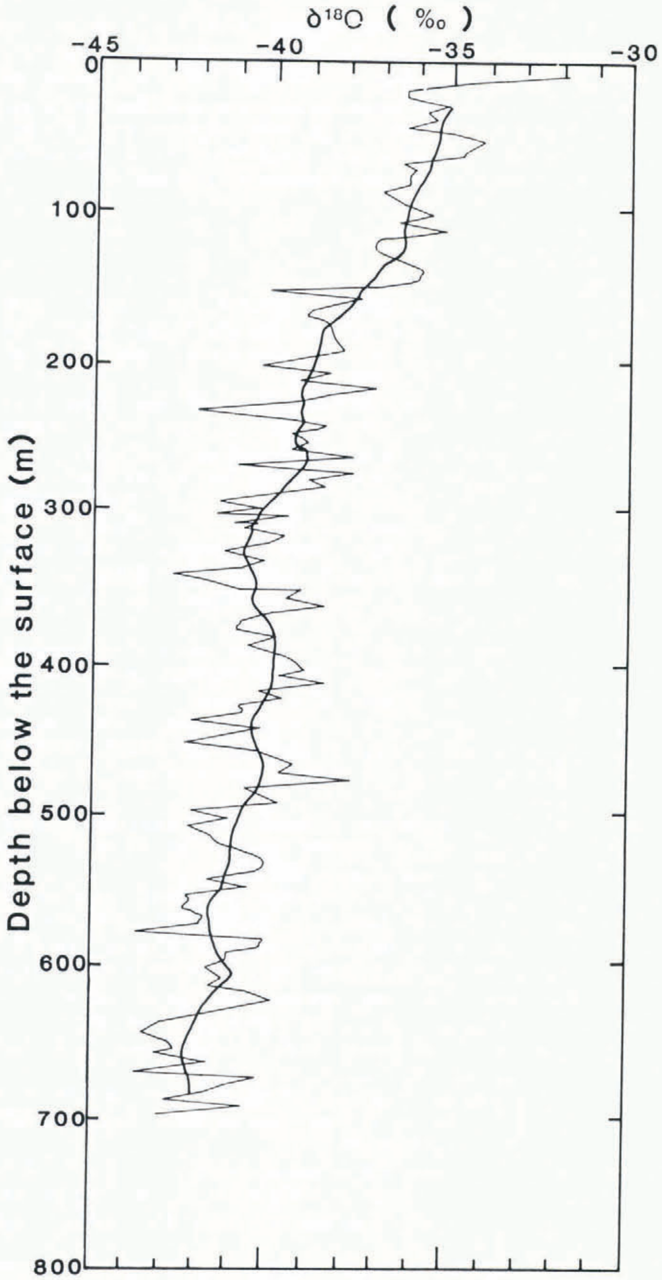

Fig.5. Depth profile of $\delta^{18}O$ in the ice core. Observed values at every 5 m (thin zig-zag line) are smoothed to give the thick solid line by taking running averages of every ten successive values.

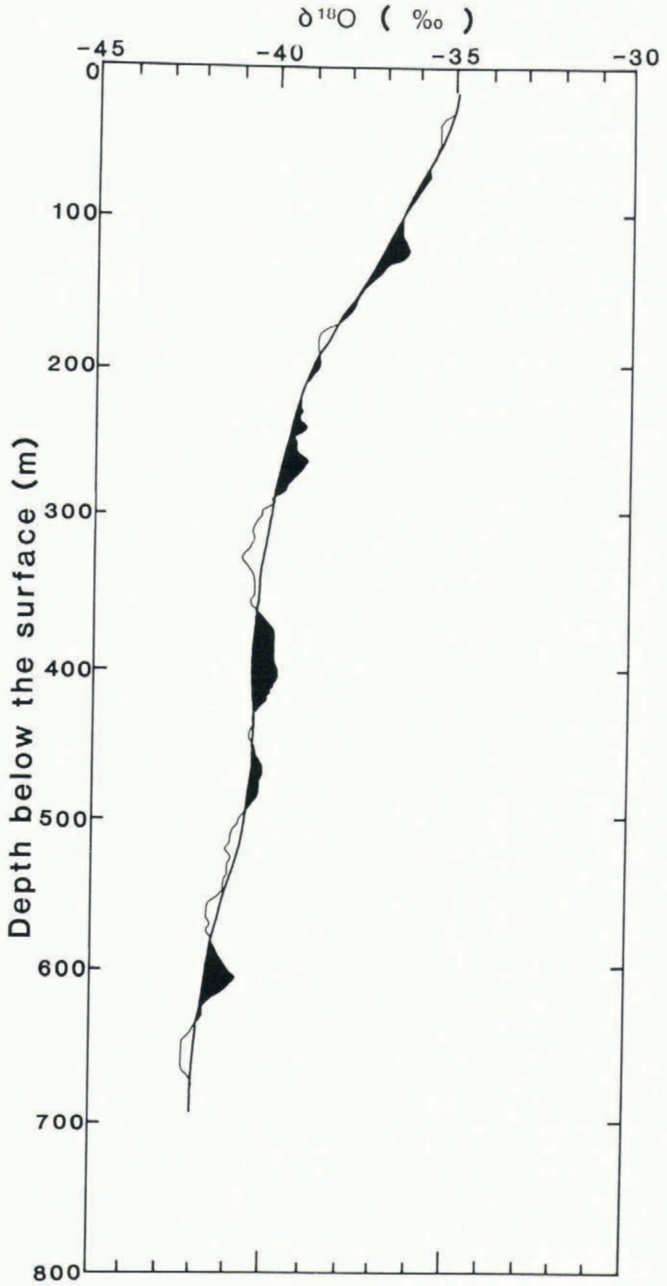

Fig.6. A regression line of the fifth order, expressing the relationship between $\delta^{18}O$ and the ice depth. The smoothed curve from Figure 5 is superimposed. Note two inflection points at 220 and 500 m depths. Shadowed areas formed by plus deviations of the smoothed curve from the regression line indicate periods of warm climate.

Therefore $\delta^{18}O$ data down to 150 m (Fig.5) are the mean of all measured $\delta^{18}O$ values in every 5 m depth, whereas below 150 m there is only one sample for each depth interval of 5 m.

The thin line in Figure 5 connects each measured value at 5 m intervals and a smooth curve (the thick line in the figure) is obtained by taking the running average of every ten succesive measured values from the top. A regression line of the fifth order was derived for $\delta^{18}O$ as a function of the depth, using the original data given in Figure 5. In Figure 6, this regression line is shown with the smooth curve of the running average. The regions of positive deviation of the smoothed curve from the regression line are shaded, whereas those of negative deviation are unshaded. The implications of Figure 6 are given in the next section.

7. DISCUSSION

Correspondence between the microparticle concentration and electrical conductivity

The general trends in the depth profile of the microparticle concentration and of the electrical conductivity are similar. Two depth ranges, 240–300 m and 340–440 m, in which remarkable incremental peaks appeared in Figure 4, could possibly correspond to those of warm climate as indicated by shading in Figure 6. Therefore it is suggested that the increase in microparticles in ice might be attributed to dust advected from bare rocks in Antarctica, which expanded in a warm climate (Thompson and others 1975). An increase in electrical conductivity accompanying that in microparticles may be explained either as the dust containing soluble impurities or as increased sea salts

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transported inland from open waters of the Indian Ocean, which might have expanded in the period of a warmer climate. To determine which was the case, chemical analyses of principal ions in the sample water are under way.

Depth profile of $\delta^{18}O$

The regression curve for the depth profile of $\delta^{18}O$ shown in Figure 6 is quite different from those of other deep cores obtained in Antarctica (e.g. from Byrd Station, Dome C, and Vostok). The depth profile of $\delta^{18}O$ at Dome C (Lorius and others 1981) should be a standard form unaffected by the lateral flow of ice, if the ice divide remained constant. The profile is characterized by a vertical straight line down to 380 m depth, which exhibits an almost constant value of $\delta^{18}O$ in the Holocene period. Then the value of $\delta^{18}O$ decreases by approximately 5‰ in the depth range between 380 and 510 m, and its low value remains constant down to 650 m, corresponding to the last ice age. Similar profiles were observed in the Vostok and Byrd Station cores.

The different shape of the $\delta^{18}O$ profile (Fig.6) is attributed to the flow of the ice beneath Mizuho Station. There are two notable inflection points on the curve in Figure 6, at approximately 220 and 500 m. The large decrease in $\delta^{18}O$ between the surface and 220 m depth probably results from the comparatively rapid flow of ice near Mizuho Station (surface velocity approximately 20 km/a). The decrease of 4.5‰ in $\delta^{18}O$ in this depth range corresponds to the decrease in $\delta^{18}O$ in the surface snow up-stream over approximately 100 km (see Figure 8 in a paper by Watanabe and others 1988, this volume). Since the area 100 km up-stream from Mizuho Station is near the boundary of the Shirase basin, the nearly vertical profile below 220 m depth may correspond to the profile in the Holocene ice originating within a local area near the boundary.

Similar characteristics of the depth-profile curve for $\delta^{18}O$, corresponding to the above two inflection points, are also found in the curve for Byrd Station (Johnsen and others 1972). The upper point of inflection, concave downward, is not as prominent as in the case of Mizuho Station, probably because the lateral flow rate beneath Byrd Station is much less than that beneath Mizuho Station.

The second inflection point, at a depth of 500 m, where the regression curve is concave upward, cannot be understood to correspond to a sharp bend at 380 m depth on the curve for Dome C, because the rate of decrease in $\delta^{18}O$ with depth is much slower than that for Dome C. Since a dirt band was found in the core near 500 m (Fujii and Watanabe 1988, this volume), this depth must correspond to the 799 m depth of the Byrd Station core, in which a prominent topmost ash band was found (Gow and Williamson 1971), if both dirt bands have the same origin.

Although the equation for determining the age of ice in ice sheets deduced by Lorius and others (1979), based on Nye's flow law for an ice sheet (Nye 1957), cannot be applied properly in the case of Mizuho Station, beneath which the lateral flow is taking place, an approximate calculation of the time-scale by this equation gives 7000 years B.P. for the 500 m depth and 10.5 ka B.P. for the 700 m depth, assuming 70 kg m^{-2} for the mean annual accumulation. This accumulation rate is that observed in the area up-stream of Mizuho Station in recent years (Watanabe and others 1988, this volume). The age obtained for the 500 m depth is therefore the same as that for the dirt band at a similar depth in the Byrd Station core: 7500 years B.P. according to Gow and Williamson (1971) and 6500–8800 years B.P. according to Thompson and others (1975).

The increase in negative $\delta^{18}O$ with increasing depth below 500 m may correspond to a significant isotope event designated by "I" in the Dome C profile (Lorius and others 1981). However, it is too early to discuss the details of the age of cores, isotopic events and related climatic changes, until there is a better determination of the depth–age relationship.

Determination of the age of cores which were subjected to lateral flow, as in the Mizuho region, is interesting, and it can be accomplished with a better characterization of the vertical profile of flow in the ice sheet. The collection of the necessary information is under way, as a study of the dynamics of the ice sheet in this region has been undertaken.

ACKNOWLEDGEMENTS

This paper is a contribution from the Glaciological Research Program in east Dronning Maud Land, Antarctica. We are grateful to members of the wintering parties of JARE-24 and 25 at Mizuho Station, for providing assistance in retrieving deep cores and in field measurements. We are also indebted to anonymous reviewers, whose comments resulted in considerable improvement of this paper.

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