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Scientific paper

Dating of the Dome Fuji, Antarctica deep ice core

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Abstract: The Antarctic ice sheet preserves paleo-climate information in the form of physical and chemical stratigraphy. A deep ice core was continuously drilled down to a depth of 2503 m at Dome Fuji Station, East Dronning Maud Land, Antarctica, during the 1993–97 JARE inland operations. Oxygen isotope measurements were conducted on 7 to 50 cm-long ice core samples selected from the entire core depth. A time scale for the Dome Fuji core is calculated from past accumulation rates and an ice flow model. Past accumulation rates were converted from oxygen isotope values by using an empirical equation obtained in the Dome Fuji area. A steady-state flow model was preciously developed for a time scale calculation of the Summit ice core, Greenland. Using reference depth points from volcanic signals and annual layer thickness values measured on the Dome Fuji core allows for tuning of the calculated time scale. A depth-age profile was obtained for the past 320 kyr.

The obtained paleo-temperature profile shows the characteristics of the past three glacial and interglacial periods. The power spectrum of δ^{18}O change over an interval of 320 kyr reveals three dominant cycles. The paleo-temperature profile coincides quite well with the Vostok ice core data in general but not in detail, suggesting that further studies are needed both for chronological investigations and a multi-factor, cross-correlation analysis between deep ice cores for climatological understanding.

key words: dating, Dome Fuji core, oxygen isotope ratio, annual layer thickness, climatic change

1. Introduction

Japanese Antarctic Research Expedition (JARE) has planned and executed the Dome Fuji Program, a comprehensive glaciological research program focusing on deep ice coring and analysis for retrieving past environmental information recorded in the Antarctic ice sheet. A continuous deep ice core down to a depth of 2503 m was recovered at Dome Fuji Station (Fig.1), Dronning Maud Land, Antarctica (77°19′01″S, 39°42′12″E: elevation, 3810 m a.s.1.; ice thickness, 3028 m; mean surface temperature, –57.3°C; Fujita *et al.*, 1998) by using a JARE mechanical drill in a liquid-filled hole during the 1993–97 field operations (Dome-F Deep Coring Group, 1998). The core quality is excellent even in the slightly brit-

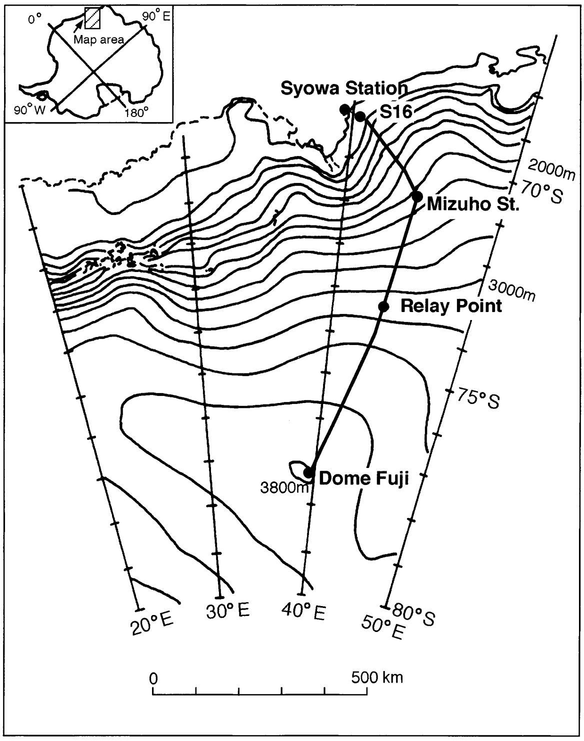

Fig. 1. Traverse route from Syowa Station to Dome Fuji Station.

tle zone ranging from 550 to 840 m depth.

Oxygen isotope measurements have been continuously made by Mat Delta E on 25 or 50 cm-long samples (so called half or full bag samples) so that the value for about every 50 years could be acquired from the whole core depth (Dome-F Ice Core Research Group, 1998). The $^{18}O/^{16}O$ ratio obtained from each sample is converted to $\delta^{18}O$, the relative deviation from that in standard mean ocean water. Consequently, the oxygen data value of 6158 pieces was acquired from the 2503 m deep core.

2. Meteo-glaciological conditions around Dome Fuji

The Japanese Antarctic Research Expedition parties have carried out a large number of inland traverses on the Antarctic ice sheet including the Syowa–South Pole round trip traverse in 1968–1969, and collected valuable meteorological and glaciological data. Analyses of these data, such as the temperature distribution on the ice sheet, the distribution of the amount of snow accumulation, and of the chemistry of snow, have often provided new knowledge about the environmental conditions of the snow surface in this area. The 2nd East Queen Maud Land project started in 1989. Glaciological data have been collected along the traverse route from Syowa Station to Dome Fuji Station in East Dronning Maud Land by a JARE field survey (Fig. 1). Systematic surface traverse research has revealed a characteristic relationship of 10 m-depth snow temperature (T; °C), and $\delta^{18}O$ value (denoted by δ, per mil) (Fig. 2) as related to elevation above sea level (E; m). They are described as follows (Satow *et al.*, 1999)

$$\delta = -0.01188\ (E-3810) - 56.30, \quad (1)$$
$$\delta = 0.852\ (T+57.3) - 56.74. \quad (2)$$

The $\delta^{18}O$ value is a function of the condensation temperature of vapor in the atmosphere,

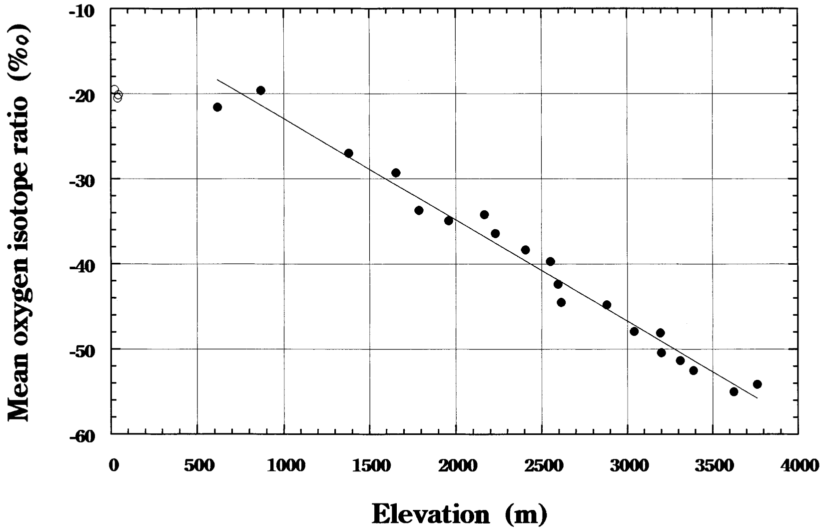

Fig. 2. Mean $\delta^{18}O$ value of near-surface snow plotted against elevation (after Satow et al., 1999). The straight line represents eq. (1).

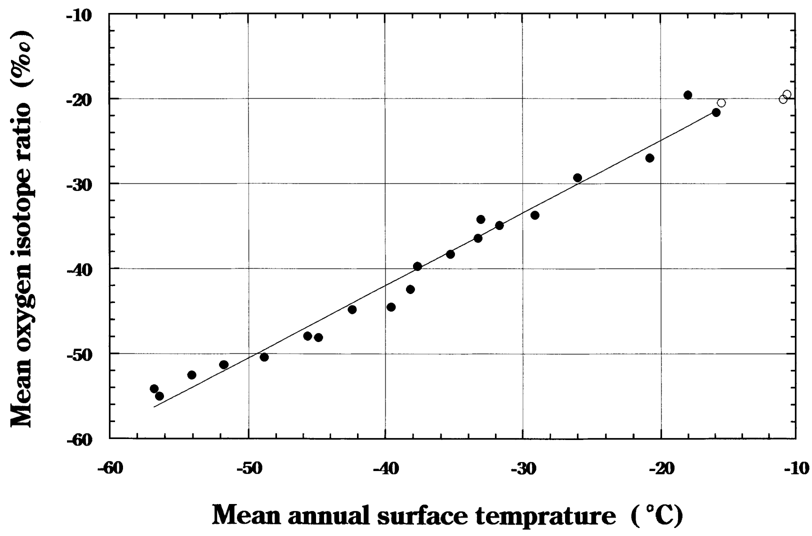

Fig. 3. Mean $\delta^{18}O$ value of near-surface snow plotted against mean annual surface temperature (10 m-depth snow temperature) (after Satow et al., 1999). The straight line is given by eq. (2). Three points on the coast marked by open circles are excluded from the regression equation.

and the average δ^{18}O of the snow pit or surface snow core can be expressed in terms of the annual mean air temperature which is approximately equal to the 10 m-depth snow temperature (Fig. 3). An empirical equation was obtained for the relationship between accumulation rate (λ_0; cm of ice equivalent/year) and δ^{18}O value in the area with $\delta \leqq -51$‰ (Fig. 4):

$$\lambda_0 = 3.876 \exp (0.1462 (\delta + 55)). \tag{3}$$

Equations (1), (2) and (3) characterize a wide range around the Dome Fuji region, without any fixed points for data regression. Hence, none of these equations exactly fit present day values observed at Dome Fuji Station.

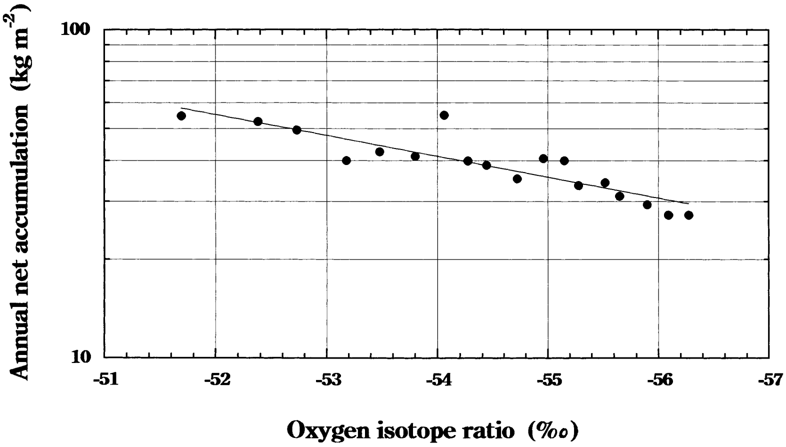

Fig. 4. The relationship between accumulation rate and mean δ^{18}O value of near-surface snow (after Satow et al., 1999). The straight line is given by eq. (3).

3. Dating of the Dome Fuji deep ice core

The δ^{18}O value measured on the shallow core from Dome Fuji is about –55‰ on an average (Watanabe *et al.*, 1997a). Equation (3) gives an accumulation rate value of 3.876 cm of ice equivalent/year at Dome Fuji Station, which is about 25% higher than the range of 2.8 to 3.3 cm of ice equivalent/year obtained from the shallow core study. The following equation is assumed for the past accumulation rate at Dome Fuji.

$$\lambda_0 = B \exp (0.1462\ \delta), \tag{4}$$

where B is a constant to be determined later.

A time scale of the Dome Fuji deep ice core can be calculated by using eq. (4) and a modified Dansgaard-Johnsen model (Dansgaard *et al.*, 1993) with flow model parameters as shown in Fig. 5; the ice thickness, H, intermediate shear layer thickness, h, sliding layer thickness at bedrock, s, and ratio between the strain rates at the top of the sliding layer (silty ice) and at the surface, f_b. Two reference depth points are selected from volcanic signals at true depths of 97.80 m (2.338 kyr BP; Watanabe *et al.*, 1997b) and 1849.55 m (141 kyr BP; Fujii (unpublished); Fujii *et al.*, 1999).

It was discovered that the number density of air hydrate particles seemingly varies sea-

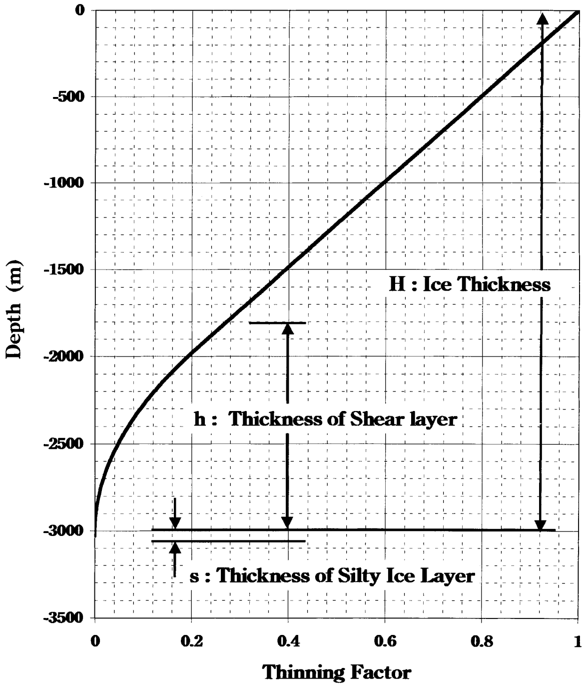

Fig. 5. Thinning factor for annual layer thickness calculated by the Dansgaard-Johnson model.

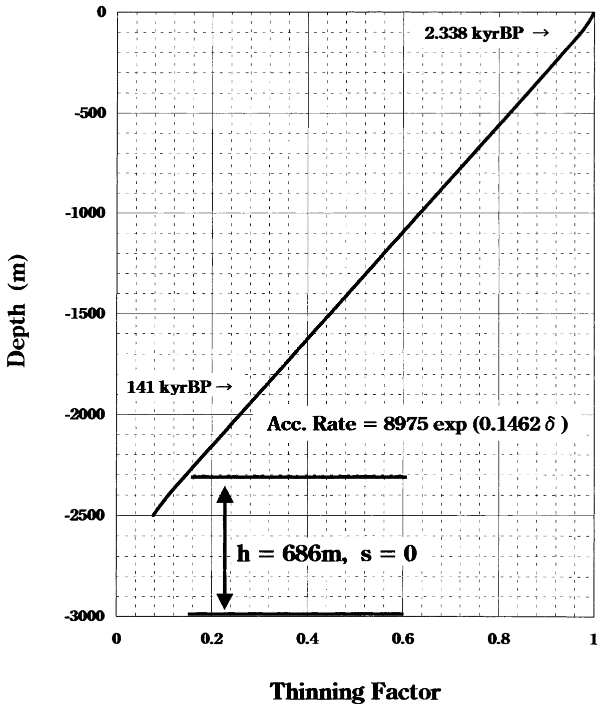

Fig. 6. Thinning factor profile obtained for the Dome Fuji core.

sonally between the depths of 1100 and 2500 m of the Dome Fuji core (Narita *et al.*, 2003). The annual layer thickness can be estimated from the width of this seasonal variation.

True ice thickness measured by radar echo sounding is 3028±15 m (Watanabe *et al.*, 1999), and air amount near the surface is about 33.4 m at Dome Fuji. The air amount was calculated as follows. Density as a function of depth was obtained from the density profile of surface layers (Watanabe *et al.*, 1997c). The depth where firn becomes ice was set to 147.5 m and the thickness of the ice from the surface to the depth was calculated, and thus the thickness of air amount was obtained.

Therefore, H=3000 m is assumed for simplicity in the age calculation. The flow law parameters h, s and f_b, and B in eq. (4), were determined so as to have calculated ice ages at two reference depths fit the volcanic event ages, and calculated annual layer thickness values fit the above estimated values obtained by air hydrate counting. Ice thickness is assumed to be constant for this calculation. This means that vertical strain rate is changing with time so that ice thickness is kept constant, although accumulation rate changes. The best fit with volcanic event ages and number density of air hydrate resulted in h=686 m, s=0 m, f_b=0, and B=8975 cm of ice equivalent/year. With this B value, 2.89 cm of ice equivalent/year is obtained for the present day value of accumulation rate at Dome Fuji, which agrees quite well with the measured value within about 10%. The result of the thinning factor for annual layer calculation is shown in Fig. 6.

4. The features of accumulation and δ profile

The accumulation rate and δ profile with the time scale obtained are shown in Fig. 7 (upper figures). The accumulation rate correlates well with the δ profile, being small in a glacial period, and large in an interglacial period. The δ profile clearly shows three glacial-interglacial cycles in a quite similar way to the Vostok δD profile (Jouzel *et al.*, 1996) (bottom figure in Fig. 7). All major features on the two profiles can be easily compared. The three glacial-interglacial changes strongly resemble each other in 100 to 120 thousand-year cycles with approximately 10-thousand-year overlap. Significant fluctuations can be seen both in the Dome Fuji and Vostok profiles even in the Holocene period. The durations of Marine Isotope Stages (MIS) 1, 6, 7 on the two profiles match almost exactly. However, MIS 6 through 9 is about 7 kyr shorter; especially, MIS 6 through 7 seems much shorter in the Dome Fuji core as compared with the Vostok core.

Equation (2) was modified to calculate the temperature difference ΔT between the present day value (δ=–55‰ at T=–57.3°C) and the past temperature, as follows.

$$\Delta T = (\delta+55)\ /\ 0.852. \tag{5}$$

The paleo-temperature profile obtained (Fig. 8) shows a variation of approximately 10°C between glacial and interglacial periods, which seems to be close to but a few degrees larger than the T-variation at Vostok. The difference in temperature of 10°C between glacial and interglacial periods is similar to the temperature difference obtained from the summit ice core of Greenland in the Arctic region (*e.g.*, Grootes *et al.*, 1993).

Also, in a long glacial period, the big change of 4 to 6°C in the temperature difference is also seen. Moreover, the tendency to which the situation of the temperature change was very similar is shown among the glacial periods, especially in the Wisconsin age period and

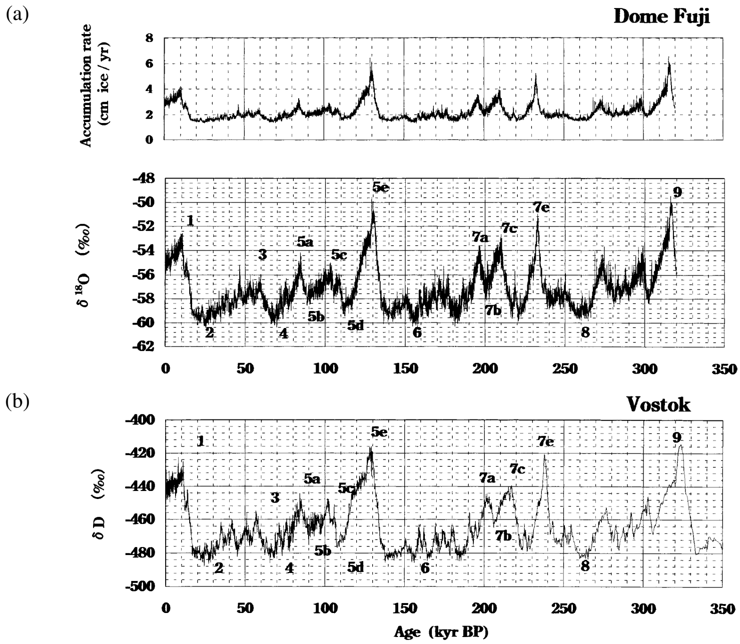

Fig. 7. *(a) $\delta^{18}O$ profile obtained at Dome Fuji. Accumulation rate, λ_0 is calculated from eq. (4). (b) δD profile obtained at Vostok (after Jouzel et al., 1996; Petit et al., 1999). MIS numbers are estimated and shown in both (a) and (b).*

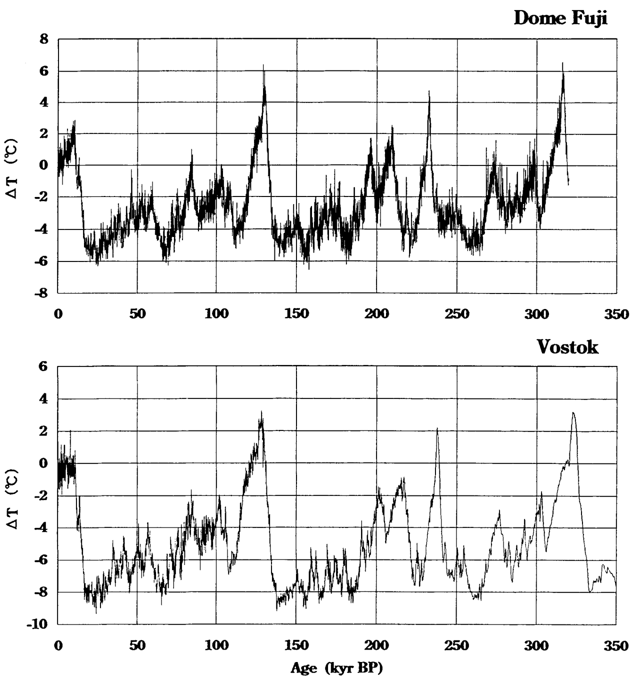

Fig. 8. *Surface temperature variations at Dome Fuji and Vostok. Temperature difference ΔT at Dome Fuji is calculated from eq. (5). ΔT at Vostok is after Jouzel at el. (1996) and Petit et al. (1999).*

the Illinois age period. Noteworthy is the fact that the highest temperature of the Holocene is 2 to 3°C lower than those of the interglacial periods. Each glacial period finishes with a sudden rise in temperature. Although the minimum temperature starts just before the end of a glacial period in the Wisconsin age, this is not the case in the other two glacial periods.

5. Spectral analysis

In order to detect prevailing periodicities of $\delta^{18}O$ variation of the Dome Fuji core covering a period of about 320 kyr, spectral analysis by the maximum entropy method (MEM) was applied. The upper figure of Fig. 9 shows the spectral power versus the frequency, and the lower figure the spectral power versus the period. Three dominant periodicities are seen at 102 kyr, 40 kyr, and 21 kyr. These peaks are associated with three cycles of the astronomical theory of Milankovitch, *i.e.*, the cycle of eccentricity of the earth's orbit (100 kyr), the cycle of obliquity of the earth's axis (41 kyr), and the precession cycle of the earth's axis (23 kyr and 19 kyr), respectively. The δD (or isotopic temperature) variation in the 420 kyr Vostok ice core shows prominent cycles at 100 kyr and 41 kyr (Petit *et al.*, 1999; Muller and MacDonald, 2000).

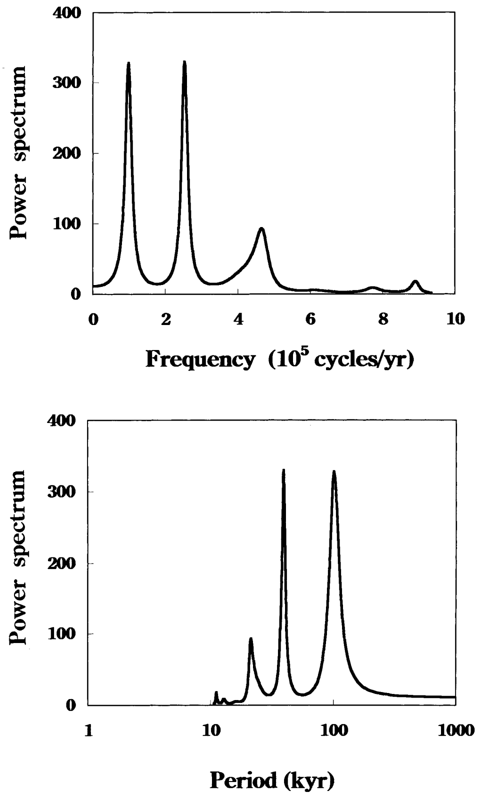

Fig. 9. Power spectrum of $\delta^{18}O$ change for the 320 kyr Dome Fuji ice core. The top figure shows the spectral power versus the frequency, and the bottom figure shows the spectral power versus the period. The vertical-axis unit is arbitrary.

Results of the spectrum analysis covering the past three glacial periods are shown in Fig. 10. Prominent cycles were obtained at 135 kyr, 42 kyr and 24 kyr in the Wisconsin glacial period, at 106 kyr, 34 kyr and 21 kyr in the Illinoian glacial period, and at 116 kyr, 51 kyr, and 27 kyr in the Kansan glacial period. It is thought that these remarkable cycles of each glacial period correspond to Milankovitch cycles.

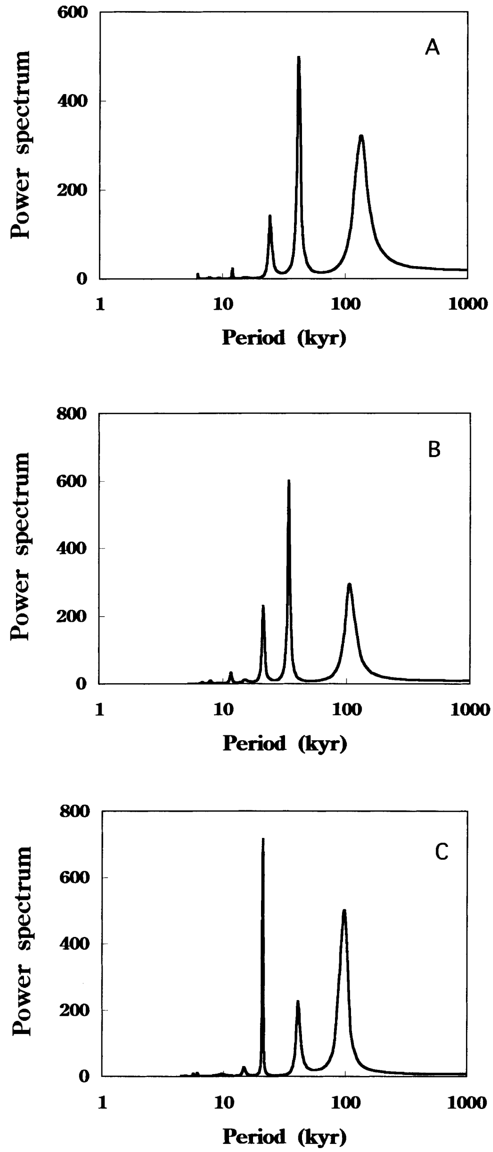

Fig. 10. Power spectrum for each glacial period in the Dome Fuji ice core. The power spectrum for the Wisconsin glacial period is shown in the upper figure (A) ; for the Illinoian period in the middle figure (B); for the Kansan glacial period in the lower figure (C). The vertical-axis unit is arbitrary.

6. Annual layer thickness

To investigate the difference between Dome Fuji and Vostok core data in detail, the annual layer thickness (cm of ice equivalent) with depth, a good measure for ice flow condition assessment, was examined. The results obtained are shown in Fig. 11 for Dome Fuji and Vostok data, respectively. Annual layer thickness generally decreases with depth for the Dome Fuji core, with small increases during interglacial and interstadial periods. However, it is almost constant during glacial periods (Wisconsin and Illinoian) for the Vostok core. This means that the ice flow condition at Dome Fuji is quite simple as compared to Vostok, where "tuning" and/or "modification" with other data is needed to obtain the ice chronology. One can expect that for Dome Fuji, only a minor "modification" will be required for a more reliable ice core chronology in the future.

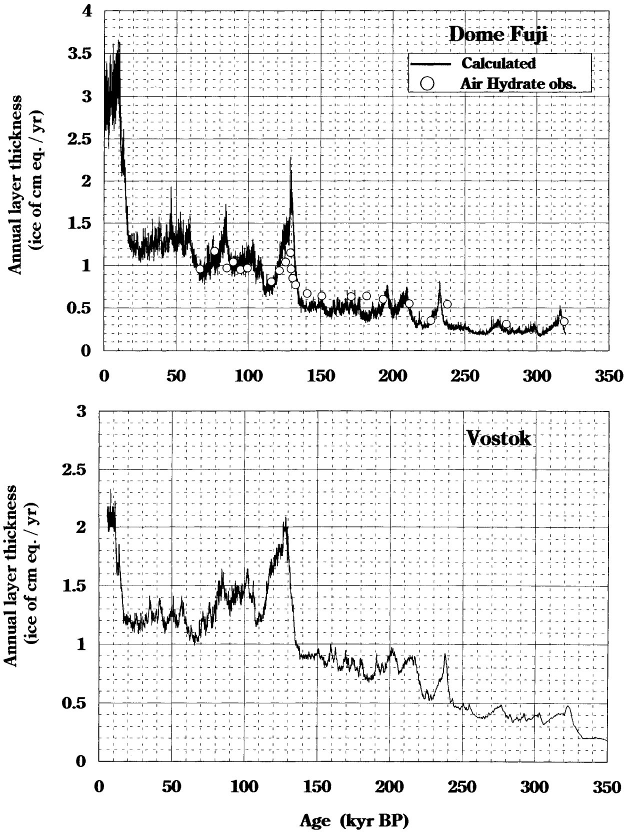

Fig. 11. Annual layer thickness profile, calculated (solid line) and estimated values from air hydrate measurements (circle) for Dome Fuji (top figure) and annual layer thickness profile calculated for Vostok (bottom figure).

7. An estimate of $\delta^{18}O$ variation below 2500 m

The deeper part of the continuous Vostok core has been extracted, and preliminary results reported (Petit *et al.*, 1999). Major features seem to coincide quite well between $\delta^{18}O$ and δD variation sequences representing the hemispherical climate variation record.

One of the principal advantages of the Dome Fuji core is the simplicity of the flow condition around Dome Fuji down to 2500 m depth, although the flow in deeper parts should be further examined. An estimate was made of the number of glacial-interglacial cycles, which might exist below 2500 m depth at the Dome Fuji coring site. The following calculation method was first suggested by Sigfus Johnsen, Denmark (unpublished). Assuming that MIS 2 through 7e will be repeated below 2500 m depth, the $\delta^{18}O$ variation was calculated as shown in Fig. 12, which shows six more cycles down to a depth of about 2820 m at approximately one million years before the present.

The question arises as to whether if molecular diffusion smooths out the $\delta^{18}O$ variations. The ice thickness for the oldest cycle is about 20 m, which is comparable to the depth interval for Wisconsin ice observed in Renland ice cap, Greenland (Johnsen *et al.*, 1992). However, the diffusion distance for $H_2{}^{18}O$ molecule should be ten times longer for a hundred times longer period, which may smooth out the $\delta^{18}O$ variation. Quite encouraging is that the $\delta^{18}O$ profiles obtained from Devon Island ice cap (Paterson *et al.*, 1977) reveal climatic change information during the Wisconsin age period from a depth interval of a few meters only. The depth could be shallower and the depth-interval could be even shorter for the last cycle, if MIS 8 and 9 have shorter time periods as shown in the Vostok ice core. In such a case, much older ice might be observed at 2820 m depth, far beyond the age of the bottom ice at Vostok, although the retrieval of detailed information could be difficult for some types of core analysis, such as gas analysis.

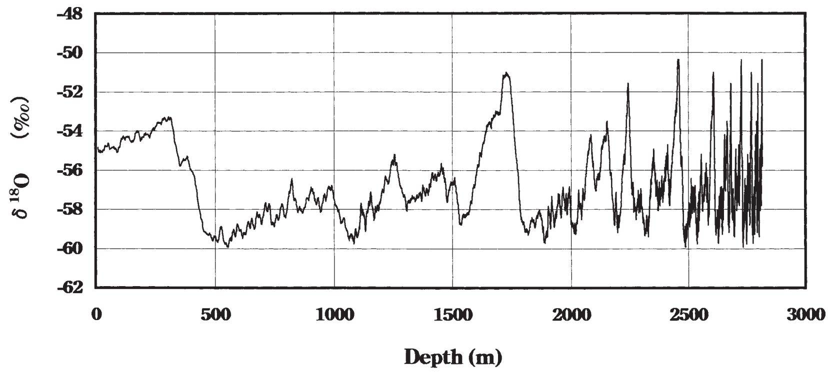

Fig. 12. Estimation of a glacial-interglacial $\delta^{18}O$ cycle below a depth of 2500 m at Dome Fuji.

8. Conclusions

A time scale for the Dome Fuji ice core is calculated from past accumulation rates and an ice flow model. The major features of the Dome Fuji ice core obtained with this simple flow model calculation are summarized as follows:

1) All major features of Marine Isotope Stages (MIS) No. 1 through No. 9 are recognized within about 10% uncertainty in time scale.
2) The δ^{18}O profile with the calculated time scale shows that time duration of MIS 1, 6, 7 matches almost exactly to that of the Vostok profile, but MIS 6 through 7 is shorter compared with the Vostok core.
3) The maximum temperature difference between glacial and interglacial periods is about 10°C, and a temperature range of 4 to 6°C was observed in the glacial periods.
4) The highest temperature of the Holocene is 2–3°C lower than that of the past three interglacial periods.
5) In general, the temperature variation pattern seems identical to that of the Vostok core data, but the amplitude seems a few degrees larger than that in the Vostok data.
6) The spectrum analysis of the δ^{18}O change for the past 320 kyr shows three dominant peaks: 102 kyr, 40 kyr and 21 kyr.
7) The ice flow condition at Dome Fuji is relatively simple as compared to the Vostok location, and possibly six more glacial cycles might be observed for global change information.

These findings strongly support the paleo-climate information obtained in the Vostok core data in general, and support the hypothesis of a simple flow condition at Dome Fuji. Chronological accuracy for this time scale calculation could be estimated to be about 10% for long-term variations. Further studies are required for the core chronology of the Dome Fuji Station deep core. Cross-correlation analysis of δ^{18}O values with other data by physical and chemical study on the Dome Fuji ice core will reveal more detailed information on paleoclimatic changes in the southern hemisphere.

Acknowledgments

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