Mem. Natl Inst. Polar Res., Spec. Issue, **57**, 38–45, 2003

Scientific paper

Estimation of annual layer thickness from stratigraphical analysis of Dome Fuji deep ice core

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***Abstract*:** Dating of ice cores is of important but is difficult for an ice core where there is low snow accumulation, and also for the deep part because seasonal chemical and isotopic signals are not easily preserved due to vapor migration after snow deposition and molecular diffusion in the deep part of ice sheet. In this paper, an attempt to reveal annual layer thickness is conducted on the basis of precise number density measurement of air bubbles and air hydrates. The annual layer thickness from air bubbles and hydrates agrees well with a calculated value within 10–15% at all depths of the 2500 m deep core. The obtained thickness in the interglacial period according to Eemian period in the Greenland ice core was half of the calculated value.

key words: annual layer thickness, air bubble, air hydrate, deep ice core

1. Introduction

Determination of the accumulation rate of an ice core in successive at depths is very important information for the reconstruction of global paleo-climatic and -environmental conditions, and for the dating of ice cores. In the case of an ice core, seasonal variations of oxygen isotope ratios (δ^{18}O), major ion concentrations and glacier flow have been used to accomplish the age dating with the help of events such as volcanic eruptions as time markers for tuning the age (*e.g.* Hammer *et al.*, 1978; Neften *et al.*, 1985). These methods are not expected to yield easily a precise time scale of a core drilled in a low snow accumulation area such as central Antarctica. Because water vapor and volatile acid move easily under the strong temperature gradient in snow layers, the original profiles are deformed after snow deposition. On the other hand, Meese *et al.* (1997) dated the GIPS 2 ice core continuously from the surface to 2800 m depth by counting the seasonality of laser-light scattering from dust (LLD). According to their results, the errors above 2250 m and below 2500 m are with-

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in 1–2% and 10–20%, respectively. As it is considered that dust in snow hardly moves even under a strong temperature gradient, this method is better for decisions on annual thickness or timescale. Also, as air bubbles and air hydrates, which are depend on voids in snow, are not easily influenced by vapor diffusion after close off, they have a possibility of being kept as a snow layer. Also, the number density of air hydrate fluctuates with climate change in relation to glacier cycles (Uchida *et al.*, 1994; Lipenkov, 2000; Narita *et al.*, 1999). On the basis of the fact, the study started from a conception that the detailed number density may have a seasonal signal.

A deep ice core was recovered at Dome Fuji, Antarctica (77°19′01″S, 39°42′12″E) in 1995 and 1997. The snow accumulation rate at shallow depth is about 3 cm of water equiv./year as average from volcanic events (Watanabe *et al.*, 1997) and annual thickness has been obtained running the 2500 m length of the core by calculation (Watanabe *et al.*, 2002). In this study, we show changes in annual thickness from the surface to 2500 m depth by stratigraphical analyses and number densities of air bubbles and hydrates. The dating errors are assumed to be 10–15% through the ice core. The data coincided well with the calculated value of the D-J model (Dansgaard and Johnsen, 1969). However, the observed values in the interglacial period according to Eemian period in the Greenland core became half of the calculated values.

2. Observations

Snow stratigraphy: the depth of pore close-off in snow is about 100 m at Dome Fuji. We can distinguish a stratigraphical layer down to about 125 m in depth by visual observation or X-ray transmission (Hori *et al.*, 1999) for the Dome Fuji ice core. Figure 1 is an example of a layer structure of snow which is obtained by the X-ray method. The layers can be distinguished as dark and light stripes. The stratigraphy is due to differences of grain size, shape and density. The authors observed layers from the surface to about 125 m depth by visual observation on the light table and measured the thickness of each layer. The core sample used is a slab section of a shallow core, drilled in 1993 with a thickness of about 3 cm (Watanabe *et al.*, 1997).

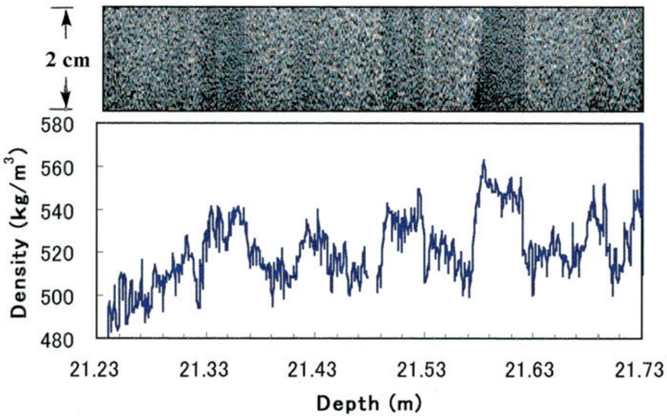

Fig. 1. An example of stratigraphy of the Dome Fuji shallow core, taken by X-ray scanning. Depth of the sample is 21.23–21.73 m.

Air bubbles and hydrates: the Dome Fuji deep core was used for observations of air bubbles and hydrates. The distribution and number density of air bubbles in the ice core are thought to preserve the basic stratification formed near the surface. We counted the number of air bubbles from a thin section of the ice core. The samples of thin section were selected from several depths in the depth range from 300 m to 900 m. Here, air bubbles disappear at about 1100 m and hydrates begin to appear from about 450 m (Narita *et al.*, 1999). The length of sample which was used for the analysis of air bubbles is about 1.0 m. The size of one thin section is 10 cm in length in the direction of depth, about 3 cm wide and 0.1 cm thick. Air bubbles were counted on enlarged microscopic photographs of each thin section. The spatial accuracy of size measurement is 10 μm. The number of air bubbles is counted at every 3 mm depth interval. On the other hand, in order to examine the fluctuation of the number density of air hydrates, the observation was conducted with a microscope using a laser beam as a light source. The presence of hydrates is confirmed by refraction-index measurements. Samples 10 cm long, 4 cm wide and 5 mm thick were prepared for measurement of hydrates and area of 1.1×1.1 mm^2 were photographed by using a charge coupled device camera analyzed computer. The number of hydrates was counted on the microscopic photograph initially, and the number density was calculated (Narita *et al.*, 1999).

3. Results

Figure 2 shows a fluctuation of unit snow layer thickness, values of calculated annual layer thickness, accumulation rate obtained from volcanic events and oxygen isotope ratio (δ^{18}O) that were obtained for a 125 m shallow core. Line ① is the average value of the observed layer at intervals of 2.5 m. The value is to be converted into water equivalent. Line ② is a fluctuation of annual thickness which was obtained as follows: Accumulation rate is

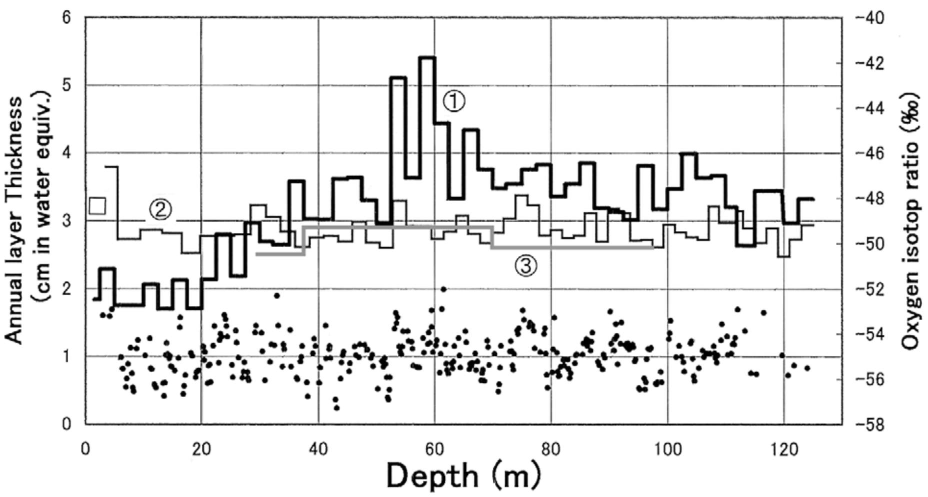

Fig. 2. Fluctuation of thickness of layer at near surface (line ①). Line ② is annual thickness obtained from D-J model. Another line ③ is the average accumulation rate from volcanic signals. □-mark is the accumulation rate obtained from the tritium signal. Small dots indicate values of the oxygen isotope ratio (δ^{18}O).

calculated from the oxygen isotope ratio on the basis of the present relation between accumulation rate and oxygen ratio in the area above 3000 m a.s.l. (Satow *et al.*, 1999). Then, the annual layer thickness at a certain depth is calculated using simple empirical model proposed by Dansgaard *et al.* (1993). A □-mark shows an accumulation rate of 3.2 cm in water equivalent/year obtained by tritium profile (Ageta *et al.*, 1989) and line ③ shown by an arrow shows a long term average of accumulation rate which was obtained by volcanic time markers in 1464AD, 1259AD, 865AD, 639AD and 346BC (Watanabe *et al.*, 1997). We found from Fig. 2 that the value observed from the snow layer gradually approached the value obtained from the model with increasing depth. The gap between the two in the surface 30 m is attributed to the existence of thin layers which may have been formed under short term weather conditions. The large value of line ① around the depth range between 50 and 70 m is due to heavy snowfall, because, when atmospheric blocking induces a significant rise of temperature in the polar region, warm air advection lasts several weeks. A concurrent increase of snow depth was observed at Dome Fuji (Enomoto *et al.*, 2000). It is thought that the thick layer is due to the blocking phenomena. Small dots are values of $\delta^{18}O$. They seem generally to be larger in the depth range between 50 and 70 m than at other depths, the same depth range contains excessively large values of $\delta^{18}O$. This is the one of the supporting factors that may be able to explain the blocking phenomenon.

Voids in snow change to air bubbles with the progression of densification. The number of air bubbles is related to the density and grain size and shape of snow. Therefore, the distribution of air bubbles in ice after close off of the void matrix of snow seems to have reappeared as a stratigraphical feature even at deeper depth. Figure 3 shows an example of the fluctuation of number density of air bubbles in a 500 mm length of ice core at 394.75 m depth. The thick line is the running mean of three data. We consider a change of the wave shape to reappearance of the layers and show a layer positions by marking them with an arrow as indicated in Fig. 3. The layer thickness obtained from air bubble fluctuation was calculated as an average through a 1.0 m-long sample. It is assumed from model calculation that the annual layer of 40 to 60 layers will contain in 1.0 m in length. That is, an value obtained by the calculation is an average over 40 to 60 years.

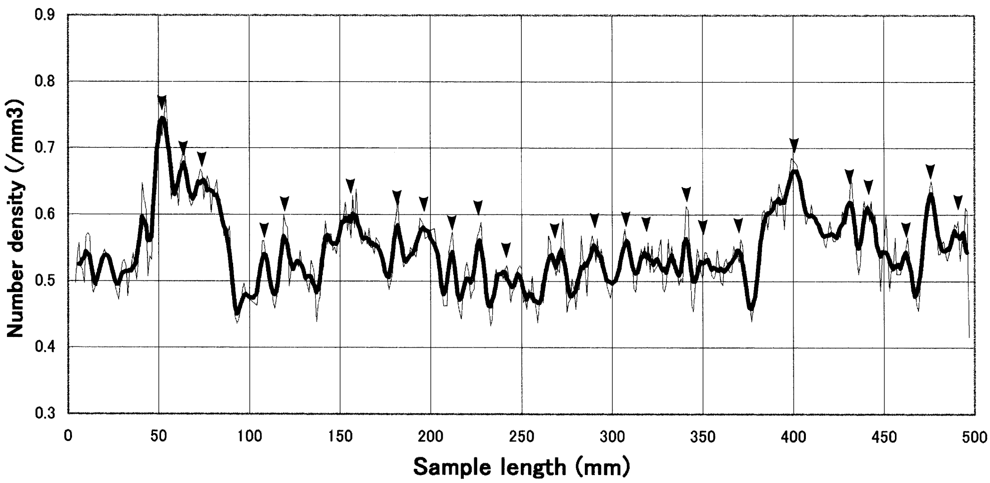

Fig. 3. The fluctuation of number density of air bubbles in direction of depth.

On the other hand, transition of air bubble-air hydrates in the Dome Fuji core is from 450 m to 1100 m in depth (Narita *et al.*, 1999). Below 1000 m, the number of air hydrates was counted by use of the laser tomography technique as described before, and the number density was calculated. Figure 4 shows the fluctuation of number density of air hydrates with depth. Here, arrows are placed at the peaks of fluctuation in the same way as the procedure in the analysis of air bubbles. This is based on the following consideration: Air bubbles metamorphose to air hydrates under high pressure. Then, it is assumed that the number of air hydrates formed will be in proportion to the number of air bubbles. The length of one sample for air hydrates measurement was 10 cm. The annual layer thickness calculated by the model is 0.5–1.0 cm at depth below 1000 m. Therefore, values obtained from the sample are

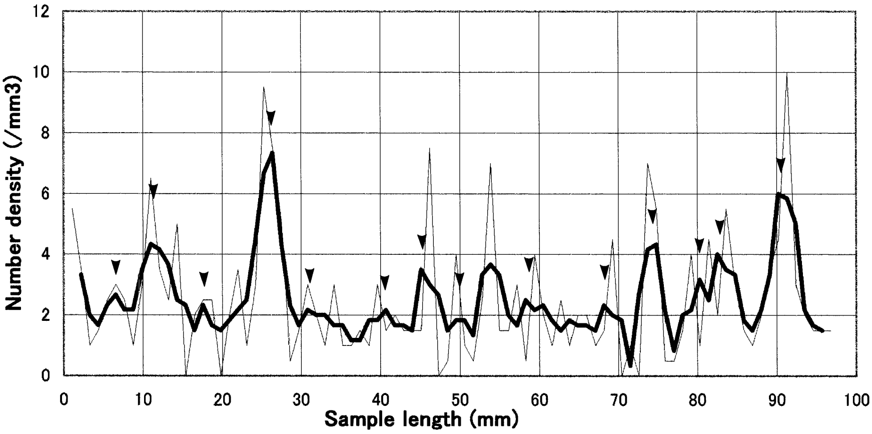

Fig. 4. The fluctuation of number density of air hydrates in direction of depth.

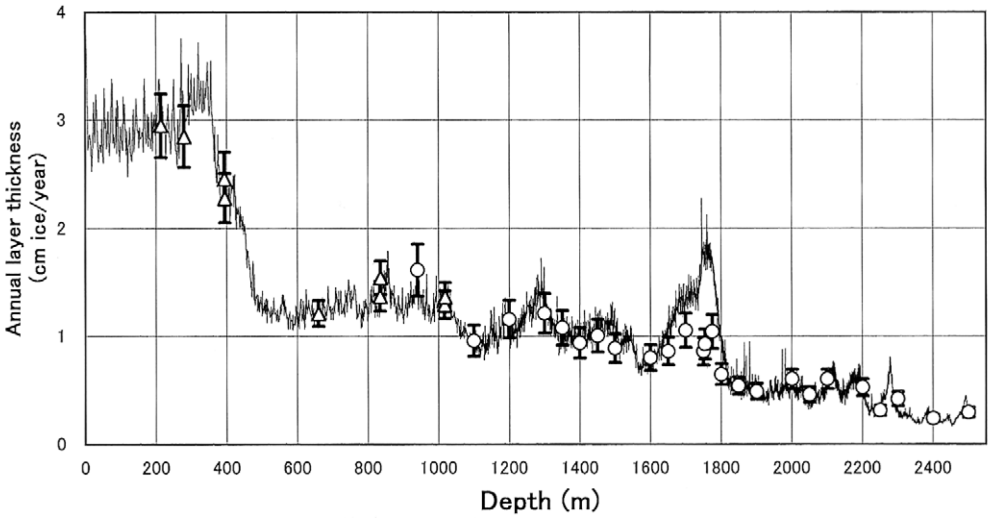

Fig. 5. Relationship between observed layer thickness and annual thickness calculated on the basis of the D-J model. △ and ○ are obtained from fluctuations of number densities of air bubbles and hydrates, respectively. Bars are error bars. EEM is the depth corresponding to the Eemian period.

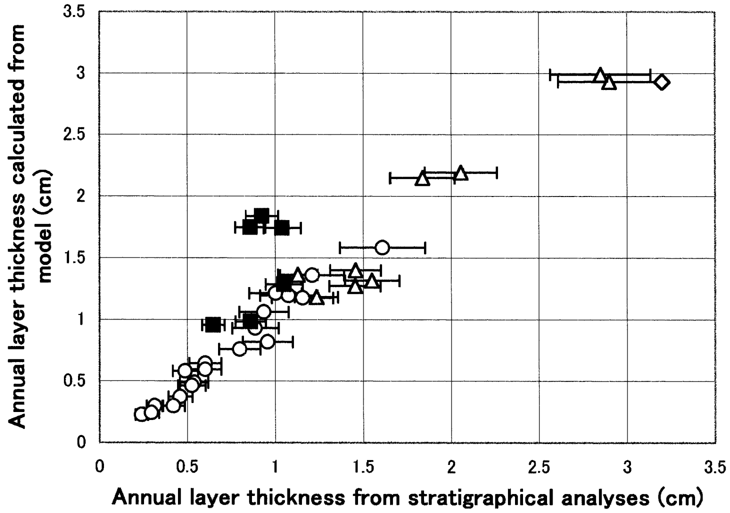

Fig. 6. Correlation of annual thickness from stratigarphical analyses and the D-J model. Error bars are added to each mark. ■ *is the value in the Eemian period.*

the averages during 10 to 20 years. Those values were plotted in Fig. 5 together with the annual thickness calculated from the model (Watanabe *et al.*, 2002, 2003). The fluctuation of layer thickness obtained from air bubble and air hydrate measurements agrees well with the value. However, the observed value in the warmer Last Interglacial at around 1700 m in depth is about half of the calculated value. Figure 6 shows the correlation between these two values, indicating good coincidence within about 15%. But, values in the middle of the Interglacial are apparently different from the others.

4. Discussion

Snow layer thickness fluctuates from 2 to 5 cm in water equivalent, probably due to snow deposition and the successive depth hoar formation process. However, an average value for 2.5 m depth intervals approaches the annual layer thickness calculated below about 80 m in depth. At Dome Fuji, thin multi-layered ice crusts are formed in a year (Y. Fujii; personal communication). This may be the reason why the layer thickness is less than the calculated value. At about 30 m depth, snow density exceeds 550 kg/m^3 and densification of snow occurs by deformation of snow grains below this depth (Narita *et al.*, 1997), where the thin layer structure may disappear and an annual layer boundary may be preserved. This may be the reason why the layer thickness approaches the calculated value. Also, Shiraiwa *et al.* (1996) have described the seasonal stratification of snow at altitude above 3500 m, which includes the Dome Fuji area, thin-hard summer and thick-soft winter layers. The observed fact explains the reason.

The number density of air bubbles reflects the space among grains of snow; it relates closely to snow structure. Therefore, it is considered that the periodic change of fluctuation indicates again the layer thickness of snow. Also, air bubbles are converted to air hydrates in the range of about 600 m to 1100 m depth.

5. Conclusion

In this study, we show that annual layer thickness can be obtained on the basis of number density of air bubbles and air hydrates. Furthermore, it is expected that this method contributes to high resolution ice core dating even in the deep part of the ice core where chemical or isotopic seasonal signals disappear due to molecular diffusion.

Acknowledgments

The members of the drilling team of JARE-36 and-37 recovered a deep ice core. The authors would like to thank them. This work was supported by a Grant-in-Aid for Scientific Research (No. 10204101) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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(Received December 14, 2002; Revised manuscript accepted February 1, 2003)