Growth Rates of Crystal Grains in Snow at Mizuho Station, Antarctica*

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要旨． 南極みずほ基地で掘削回収した雪試料を用い，その試料の薄片から結晶粒の平均断面積を測定し，深さ 50 m までの結晶粒の成長過程を調べた．

結晶粒の平均断面積は時間に比例して増加した．しかし，結晶粒の成長曲線は深さ約 35 m で不連続となった．成長曲線のこう配から求められる結晶粒の成長速度は深さ 35 m より浅い所の値より 35 m 以深の値の方が2倍も大きかった．この違いは，積雪の荷重による応力増加のためか，35 m 以深の雪の層で雪の年間蓄積量を過少評価したためと考えられる．35 m 以浅で得られた結晶粒成長速度をほかの観測結果と比較することにより，みずほ基地の年間蓄積量は約 70 kg $m^{-2}a^{-1}$ と見積られた．

結晶粒の成長曲線が深さ約 35 m で不連続になること，およびその層で成長速度が急に増加することから，この雪が蓄積した頃，雪の蓄積量の少ない寒冷な時期が襲来したことが示唆された．結晶粒成長曲線から，寒冷期は約 340 年前に約 70 年間続いたと推定される．

Abstract: Measurements of the mean cross-sectional area of crystal grains in snow were made with core samples drilled at Mizuho Station, Antarctica. It was found that the cross-sectional area of crystal grains in snow increased with increasing depth till the depth of about 50 m. The relationship between the cross-sectional area of crystal grains and the time elapsed was essentially linear, but the growth rate of crystal grains was larger in snow at depths below 35 m. The increase in the growth rate can be attributed to the stress-enhancement or the smaller rate of snow accumulation From the growth rate of crystal grains in snow above 35 m, the net accumulation rate at Mizuho Station was estimated to be roughly 70 kg $m^{-2}a^{-1}$

On the basis of the discontinuity of growth curves and the apparent increase in the growth rate of crystal grains, a colder climate or period of smaller snow accumulation was suggested to have lasted for about 70 years roughly 340 years ago.

1. Introduction

In the densification process of snow in cold polar regions, the average size of crystal

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grains, namely that of monocrystalline particles, increases slowly but steadily with time through various sintering mechanisms. The growth rate of the crystal grains has been measured at a variety of locations in Antarctica and Greenland from thin sections of snow samples recovered by drilling (SCHYTT, 1958; HOLLIN *et al.*, 1961; LANGWAY, 1962; STEPHENSON, 1967; NAKAYA and KUROIWA, 1967; GOW, 1969, 1971).

STEPHENSON (1967) and GOW (1969) have found that the time and temperature dependence of the growth rate of crystal grains in snow in polar regions is analogous to that in the isothermal sintering process of metallic and ceramic materials, namely,

$$S=S_0+Kt\,, \tag{1}$$

where S and S_0 are the mean cross-sectional areas of crystal grains at the time t and zero respectively. K is the growth rate and is expressed as

$$K=K_0\exp(-E/RT)\,, \tag{2}$$

where K_0 is a constant, R is the gas constant, T is the absolute temperature and E is the apparent activation energy for the crystal growth . GOW (1969) has obtained $E=48.57\ \mathrm{kJ\cdot mol^{-1}}$ $(=11.56\ \mathrm{kcal\cdot mol^{-1}})$ from measurements for snow at five different points in Antarctica and Greenland.

The purpose of the present paper is to estimate the growth rate of crystal grains in snow at Mizuho Station (70°41′53″S, 44°19′54″E, elevation 2230 m; mean temperature −33°C) in East Antarctica and to compare it with results obtained at other locations. The climate in the vicinity of Mizuho Station is characteristic in that the so-called katabatic winds blow almost throughout the year (INOUE *et al.*, 1978), so that the process of snow accumulation is very complicated and the lack of annual layers was frequently observed in the core stratigraphy (WATANABE, 1978; OKUHIRA and NARITA, 1978). Effects of such climatic circumstances were found in the growth behavior of crystal grains in snow at Mizuho Station.

2. Snow Samples and Measurements of Sizes of Crystal Grains

Measurements of sizes of crystal grains were made using the core samples of snow which were recovered by drilling at Mizuho Station to the depth of 147.5 m (SUZUKI and TAKIZAWA, 1978). Thin sections of 3–5 mm in thickness were prepared by cutting aniline-reinforced snow samples and then photographed under polarized light. Details of the preparation method of thin sections have been reported in a previous paper by NARITA *et al.* (1978), together with the general characteristics and some typical microphotographs of the crystal grains.

The average size of crystal grains was defined in the present paper as the cross-sectional area of a circle with a diameter equal to the mean of two diameters M_I and

M_{II}, where M_I is the arithmetic mean of diameters of the largest circles embedded in individual crystal grains appearing in a thin section, and M_{II} is that of the longest distances between two arbitrary points on the peripheries of the individual crystal grains. Depth profiles of M_I and M_{II} are given in NARITA *et al.* (1978), but in the present paper more data were added.

3. Growth Rate of Crystal Grains in Snow at Mizuho Station

Fig. 1 shows the mean cross-sectional area of crystal grains in snow at Mizuho Station plotted against the depth from the snow surface. Though the shape of the curve is rather complicated, the increase in the mean cross-sectional area with increasing depth is clearly noted till the depth of about 50 m. At depths deeper than 50 m, the relation between the mean cross-sectional area and the depth becomes obscure. This result seems to imply that the mechanism of the grain growth in the top 50 m snow layer is different from that in the deeper layer; the bulk density of snow at 50 m is approximately

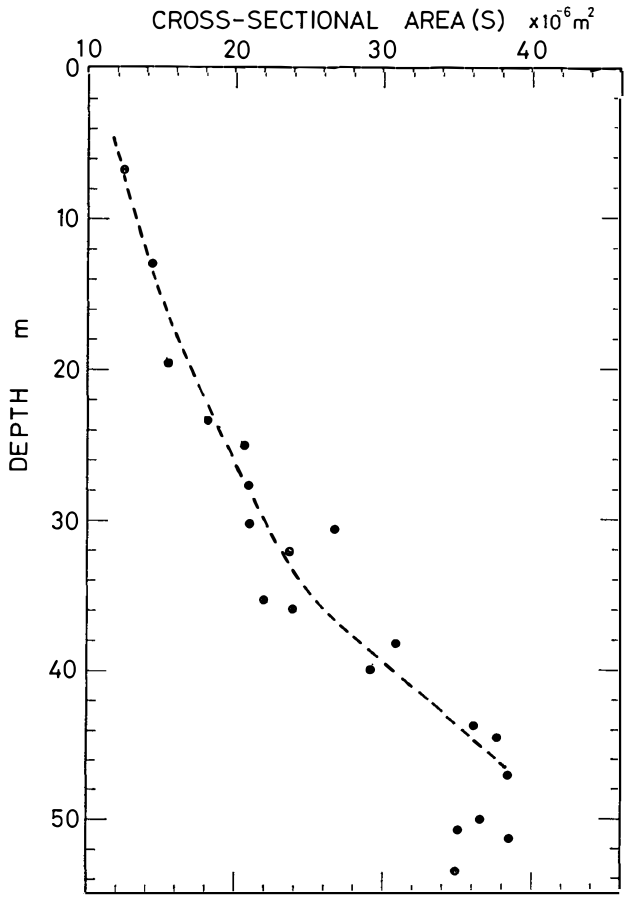

Fig. 1 Mean cross-sectional area (S) of crystal grains in snow versus the depth Mizuho Station

830 kg·m^{-3} and its air permeability is negligibly small (MAENO *et al.*, 1978), so that the plastic flow of the ice sheet is considered to affect more strongly the growth and/or recrystallization of crystal grains in the layer. We will not be concerned with behaviors of crystal grains at depths deeper than 50 m in the present paper.

If the net accumulation rate and the density-depth relation are known, the age of snow, that is the time elapsed from deposition, can be estimated. Fig. 2 shows the mean cross-sectional area of crystal grains plotted against the cumulative mass of overburden snow, which was calculated from the density-depth relation (NARITA and MAENO, 1978). The cumulative mass of snow on the ordinate was not transformed to the time elapsed, since the reliable value for the net accumulation rate at Mizuho Station is not known. However, it seems reasonable to assume that the value lies between 50 and 100 kg·m^{-2} a^{-1} when we take into account MAENO and NARITA's (1979) discussion of the snow accumulation by the use of a variety of observation data including structural characteristics, snow-stake and stable isotope measurements. The time elapsed can be obtained by simple division of figures on the ordinate by an appropriate figure of the accumulation rate.

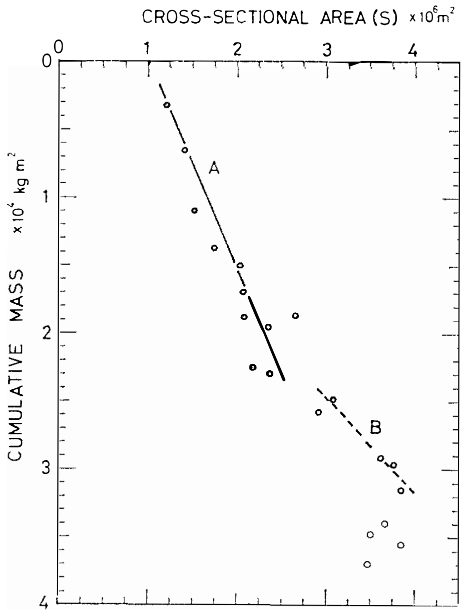

Fig. 2. Mean cross-sectional area (S) of crystal grains versus the cumulative mass of overburden snow per unit area. Mizuho Station. The cumulative mass was calculated and tabulated by NARITA and MAENO (1978). Open circles indicate the data for snow at depths deeper than 50 m. The figures on the ordinate can be transformed to the time elapsed simply by division by the net accumulation rate.

The following conclusion can be drawn from Fig. 2: the relationship between the mean cross-sectional area of crystal grains and the time elapsed is essentially linear and can be represented by two straight lines with different slopes. The result is in good agreement with that obtained at other locations and expressed by eq. (1). The two straight lines, A and B in the figure, were obtained by the least squares method, line A refers to snow at depths shallower than about 35 m corresponding to the cumulative mass of roughly 2.3×10^4 kg·m^{-2}, and line B refers to snow at depths between 35 m and 50 m.

The mean growth rate of crystal grains calculated from the slope of the straight line A is $K=3.19\times10^{-3}$ (6.33×10^{-3}) m^2 a^{-1} if the net accumulation rate is put to be 50 kg·m^{-2} a^{-1}. The number in the parentheses is the growth rate when the accumulation rate is put to be 100 kg·m^{-2} a^{-1}. The growth rate in snow at depths deeper than 35 m is larger, namely $K=7.18\times10^{-3}$ (14.36×10^{-3}) m^2 a^{-1}. The increase in the growth rate in the lower layer may be attributed to the possible stress-assistance due to the overburden snow load or to the smaller accumulation rate caused by some climatic changes, but more detailed study is required before a definite conclusion is obtained.

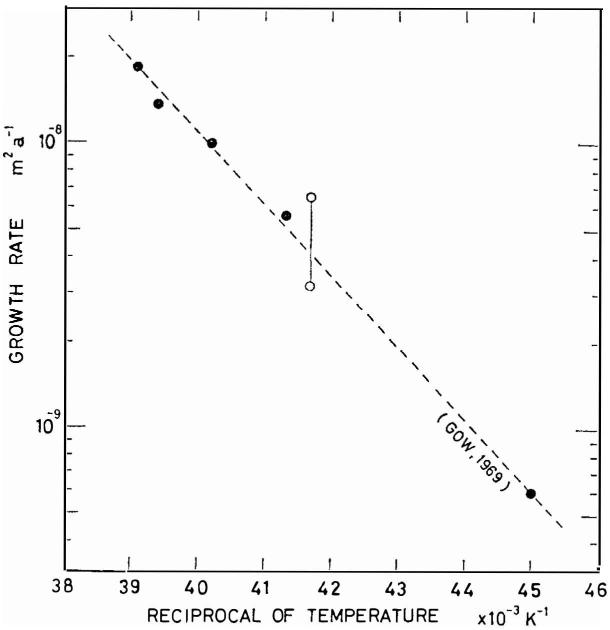

Fig 3 Mean growth rate (K) of crystal grains versus the reciprocal of the absolute temperature. Open circles refer to Mizuho Station (line A in Fig. 2), and solid ones refer to other stations in Antarctica and Greenland (GOW, 1969). The slope of the straight line corresponds to the apparent activation energy of $E=48.57$ kJ mol^{-1} (GOW, 1969).

Fig. 3 shows the mean growth rate of crystal grains plotted against the reciprocal of temperature. Solid circles refer to South Pole (mean annual air temperature −51°C), Southice (−31°C), Site 2 (−24°C), Wilkes (−19°C) and Maudheim (−17°C): the data were cited from Gow (1969). Open circles are the values calculated from the slope of line A in Fig. 2 by assuming the net accumulation rate at Mizuho Station to be 50 and 100 kg·m^{-2} a^{-1}. If we assume that Gow's result (the straight line with a slope corresponding to the activation energy of $E=48.57$ kJ·mol^{-1} in Fig. 3) is applicable to the grain growth in snow at Mizuho Station, we can estimate the appropriate value for the net accumulation rate at Mizuho Station, which is roughly 70 kg·m^{-2} a^{-1}. The figure obtained by the crude estimation is comparable to that estimated from the visual determination of annual layers (WATANABE *et al.*, 1978) and the depth of snow-ice transition (MAENO and NARITA, 1979).

4. Concluding Remarks

From the structural analyses of snow samples at Mizuho Station, the mean cross-sectional area of crystal grains was found to increase linearly with time, and the comparison of the growth rate with that at other locations showed that the net accumulation rate at Mizuho Station should be roughly 70 $kg \cdot m^{-2} a^{-1}$.

It should be mentioned that the discontinuity of the growth lines at the depth of about 35 m in Fig. 2 might be due to the lack of considerable numbers of annual layers; the lack of annual layers suggests that a colder climate or smaller accumulation of snow occurred in the period when the snow in the depths around 35 m was deposited An estimate of the time interval from the discontinuity of the straight lines A and B in Fig 2 leads to a tentative conclusion that such cold climate lasted for about 70 years approximately 340 years ago. Several other evidences to support the past occurrence of such climatic change are found in the core samples in the depth range between 30 m and 40 m; they are the apparent increase in the growth rate of crystal grains shown by line B in Fig. 2, a marked negative peak of $\delta^{18}O$ values (WATANABE *et al.*, 1978), large variations and deviation of snow density, and extremely large values of compactive viscosity of snow (MAENO and NARITA, 1979)

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