STRUCTURAL CHARACTERISTICS OF FIRN AND ICE CORES DRILLED AT MIZUHO STATION, EAST ANTARCTICA*

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Abstract: Sizes, shapes and c-axis orientations of crystal grains as well as specific areas of grain boundaries and internal free surfaces were measured for firn and ice core samples of 147.5 m length obtained in 1971 and 1972 at Mizuho Station (70°41.9′S, 44°19.9′E; 2230 m), East Antarctica. Five critical depths were found at which some structural changes occurred. They were 8 m, 30 m, 55 m, 70 m and 110 m. Their corresponding densities were 550, 730, 840, 855 and 882 $kg \cdot m^{-3}$, respectively.

The densities of 550 and 840 $kg \cdot m^{-3}$ correspond to frequently reported figures at which the densification mechanism changes from mechanical packing of air voids to plastic deformation of ice grains, and from plastic deformation to shrinkage of closed-off air bubbles.

The critical density of 730 $kg \cdot m^{-3}$ (30 m) was first pointed out by MAENO in 1974, who concluded that the bonding between ice grains reached its maximum or optimum state for packing at this density. The present analyses showed that air voids were gathered only at intersections of grain boundaries in the core samples at the critical density.

The remaining two critical densities, 855 $kg \cdot m^{-3}$ (70 m) and 882 $kg \cdot m^{-3}$ (110 m), are related to alterations of mechanical stress fields; samples below 70 m contained layers of small grains intermittently, and at depths deeper than 110 m crystal sizes decreased, suggesting the presence of shear components.

1. Introduction

Three series of cores, one extending to a depth of 70 m and the other two extending to a depth of 150 m, were recovered in the period 1970–1975 by the Japanese Antarctic Research Expedition (JARE) at Mizuho Station (70°41.9′S, 44°19.9′E) in East Antarctica (SUZUKI and TAKIZAWA, 1978).

Structural parameters such as density, crystal size and specific area of internal surface are the most important and fundamental in characterizing the nature of the cores. The present study was aimed to investigate such parameters systematically and to get insight into the thermal and mechanical situation of the Antarctic

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ice sheet at Mizuho Station.

The present paper gives the principal results obtained in the study, and more detailed studies particularly about the crystal growth in the ice sheet, will be reported elsewhere. The analyses were conducted for two Mizuho cores taken in 1971 (designated as JARE-12 cores) and in 1972 (JARE-13 cores). Stratigraphic data, density data and other petrofabric data of these cores have been compiled by NARITA *et al.* (1978), NARITA and MAENO (1978) and NARITA (1978), respectively.

2. Analytical Procedures

Structural characteristics of cores were studied by measuring various geometrical parameters by using thin sections cut vertically or horizontally from the cores.

2.1. Preparation of thin sections

For impermeable cores, namely cores taken from depths deeper than 55 m, thin sections were prepared as follows: A vertical slice of core was frozen to a glass plate, and its thickness was reduced by careful planing. When the thickness was about 2×10^{-3} m, the thin section was photographed under ordinary light; this photograph was used in measuring the concentration of air bubbles involved. Then the same section was planed to a thickness of about 3×10^{-4} to 5×10^{-4} m and one more photograph was taken this time under polarized light; this photograph was used in measuring geometrical parameters which will be described later.

For permeable cores, namely cores above the depth of about 55 m, two different methods were employed to make thin sections. Thin sections for the measurement of geometrical parameters other than *c*-axis orientations were prepared with a special method developed by one of the present authors (NARITA, 1971): a thin section was prepared by cutting an aniline-reinforced core sample vertically. For specific-area measurements a sharp surface was prepared, and then dyed with powder of water blue to produce a clear contrast between ice and voids filled with aniline.

Another method was employed for the measurement of *c*-axis orientations: a core sample was soaked in water at 0°C and then a thin section was cut horizontally. It was assumed that the number and crystallographic orientations of component ice crystals were not varied by this procedure, but the assumption was not checked. Details of the fabric analyses were reported by one of the present authors (NAKAWO, 1974).

2.2. Geometrical parameters measured

Two diameters are used in the present study to describe the size and shape of a crystal grain appearing in the surface of a thin section: one is the diameter, D_{I}, of the largest circle embedded in the crystal grain, and the other is the longest distance, D_{II}, between two arbitrary points on the periphery of the crystal grain. The ratio

D_{II}/D_{I} is called the proportion of the crystal grain in the powder metallurgy, which is used in expressing the shape.

Specific areas of the internal free surface (ice-air interface) and of the crystal grain boundary were estimated by the method developed by SMITH and GUTTMANN (1953). According to probability theory, the specific surface area, S, in a three-dimensional system is approximated as

$$S=2N/L=2n, \tag{1}$$

where L is the total length of parallel lines drawn with an arbitrary distance on an arbitrary test surface, and N is the number of intersections of the lines and the internal surfaces. Hence, n is the number of intersections per unit length of the test line. In the present study, the test lines were drawn in two directions, namely vertically and horizontally, on a test surface prepared vertically from the cores, and the specific area was calculated by taking a mean of the two n's:

$$S=n_{\parallel}+n_{\perp} \tag{2}$$

where $\parallel$ and $\perp$ refer respectively to the vertical and horizontal test lines. Specific areas of internal free surfaces and grain boundaries are depicted as S_f and S_g, respectively.

In isotropic systems $n_{\parallel}$ is identical to $n_{\perp}$. Accordingly, a difference in the two numbers, if observed to exist, implies that some oriented textures are involved. In this paper the degree of orientation was defined as

$$\omega=\frac{n_{\parallel}-n_{\perp}}{n_{\parallel}+n_{\perp}}. \tag{3}$$

Positive values of ω indicate the dominance of horizontal orientation of the internal surface in question, *i.e.,* the internal surface lying in a horizontal plane is more prevalent, and negative values indicate the dominance of vertical orientation.

C-axis orientations of individual crystal grains were measured under a polarizing microscope, and fabric diagrams were constructed from plots of c-axis made on the lower hemisphere of the Schmidt equal area net.

3. Results and Discussion

Fig. 1 gives a schematic illustration of Mizuho core, together with the bulk density and the concentration of closed-off air bubbles. The densities are mean values in 0.5 m intervals (NARITA and MAENO, 1978). It has been frequently reported that the mode of densification in polar glaciers changes at two critical densities, namely around 550 kg·m^{-3} and 820–840 kg·m^{-3} (PERUTZ and SELIGMAN, 1939; LANGWAY, 1957; BENSON, 1962; ANDERSON and BENSON, 1963). These two transitions are clearly found at depths of 8 m (550 kg·m^{-3}) and 55 m (840 kg·m^{-3}) in Mizuho cores, as marked as **A** and **C** in the density profile in Fig. 1.

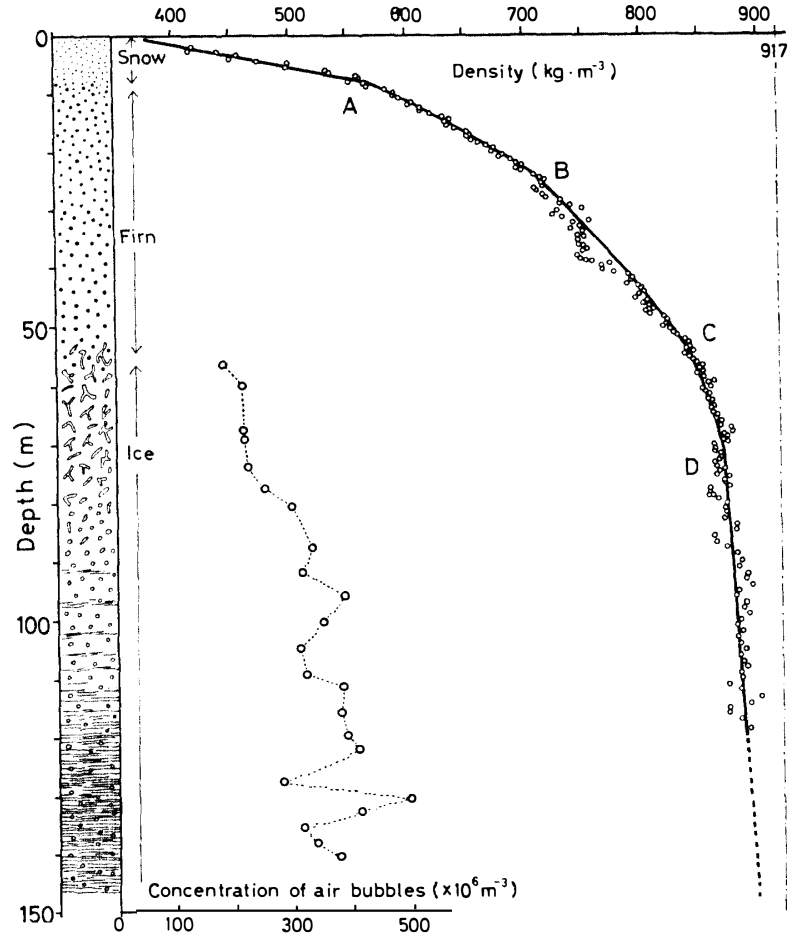

Fig. 1. Bulk density and concentration of air bubbles plotted against depth, together with sketch of core textures. Densities are given in the average in 0.5 m intervals (NARITA and MAENO, 1978).

In addition to these transitions, deviations of measured densities from a smoothed line around 30 m (730 kg·m^{-3}), marked as **B**, and fluctuations around 70 m (855 kg·m^{-3}), marked as **D**, should be noted. The former deviation **B** was interpreted by MAENO (1974a, 1974b) to be related to the completion of bonding between ice grains, and the latter fluctuations **D** seem to be associated with some sort of mechanical disturbances; cores recovered from depths deeper than about 96 m

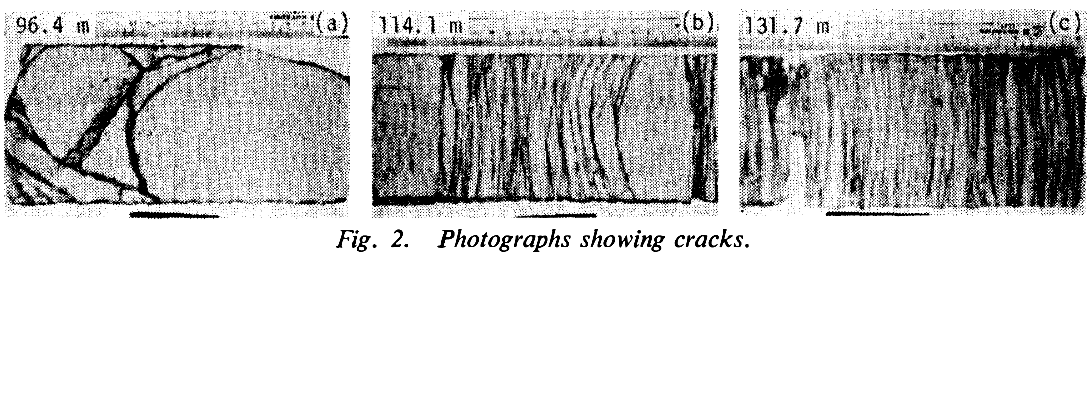

Fig. 2. Photographs showing cracks.

contained many cracks, while shallower cores were perfect in quality. It was also noted that, in the cores from 96 to 110 m, most cracks were introduced diagonally at intervals of about 0.15 m as shown in Fig. 2a. On the other hand, in the cores deeper than 110 m only horizontal cracks were found; around 110 m they were concentrated in bands of about 0.1 m thickness (Fig. 2b) but in deeper cores cracks were found almost continuously at intervals of about 5 mm (Fig. 2c).

3.1. Characteristics of crystal grains

Fig. 3 gives typical microphotographs of thin sections of the Mizuho core

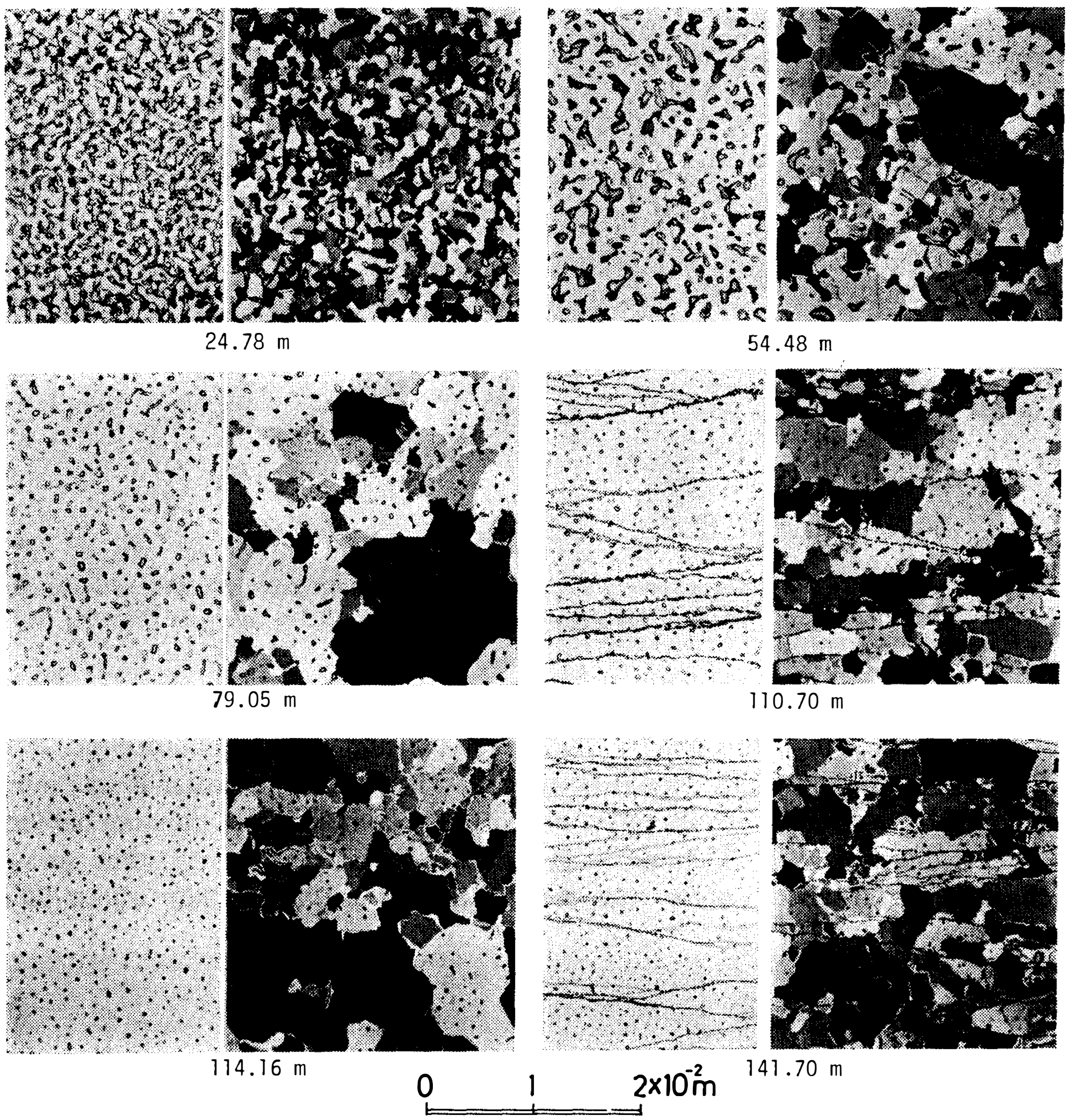

Fig. 3. Microphotographs of thin sections. In each pair the left was photographed in ordinary light, and in crossed polarized light.

for six different depths; more photographs are compiled by NARITA (1978). It is apparent that, as the depth increases, complicated shapes of air voids change to simpler and smaller ones due to splitting and spheroidization, and sizes of crystal grains become large in general. Histograms of crystal sizes, D_{I} and D_{II}, obtained from thin sections are given in Fig. 4; more histograms were also prepared by

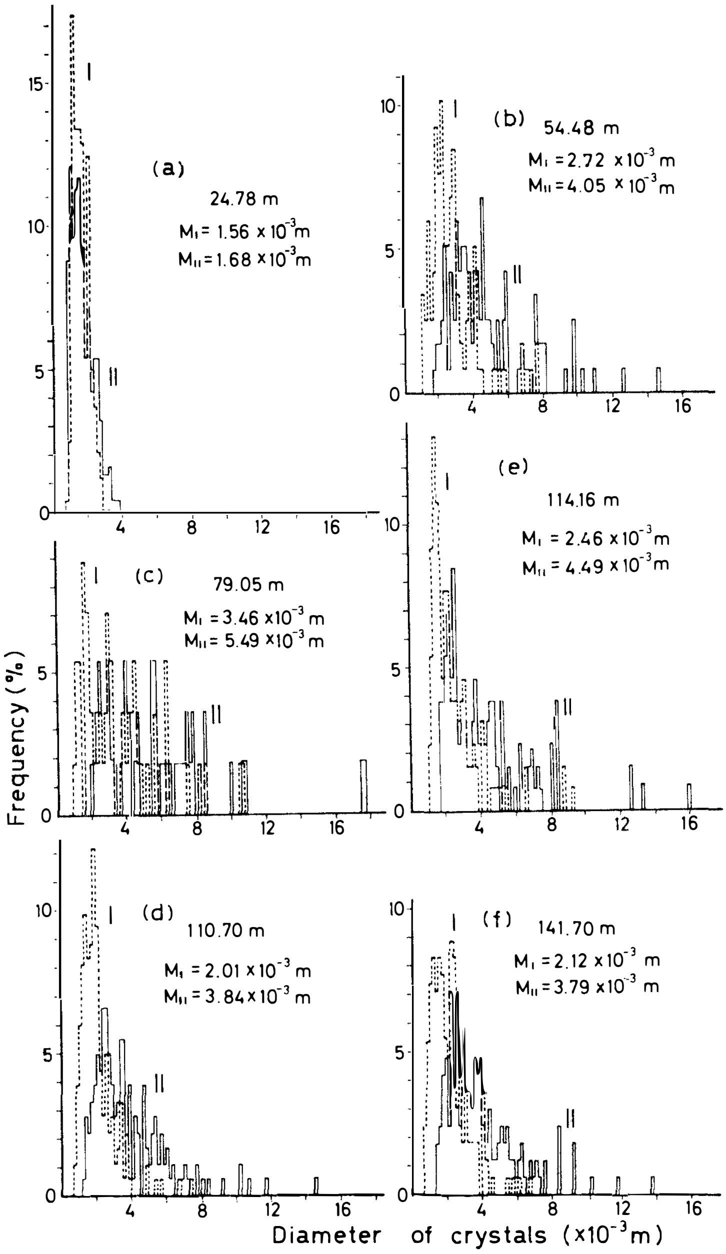

Fig. 4. Histograms of crystal diameters, D_{I} (broken line) and D_{II} (solid line). The mean values, M_{I} and M_{II}, are also given.

NARITA (1978). The shapes of histograms are not always identical to each other and complex in most cases, suggesting that the crystal growth in the Antarctic ice sheet is influenced by various complicated parameters.

Arithmetic means of $D_{\rm I}$ and $D_{\rm II}$, denoting $M_{\rm I}$ and $M_{\rm II}$, respectively, are plotted against depth in Fig. 5, which also includes the mean proportion of crystal grains, that is $M_{\rm II}/M_{\rm I}$. With increasing depth until about 30 m, $M_{\rm I}$ and $M_{\rm II}$ increase slowly, and the mean proportion decreases and approaches unity, *i.e.*, shapes of crystal grains become spherical. The large values of the mean proportion near the surface are considered to be caused by the predominant development of depth hoar crystals. At 30 m, which corresponds to the density of 730 kg·m^{-3}, the crystal sizes become much larger and at the same time the mean proportion increases suddenly.

The increase of crystal sizes at the next characteristic depth at 55 m is remarkable. At this depth, $M_{\rm I}$ and $M_{\rm II}$ become twice as large and remain unchanged until the

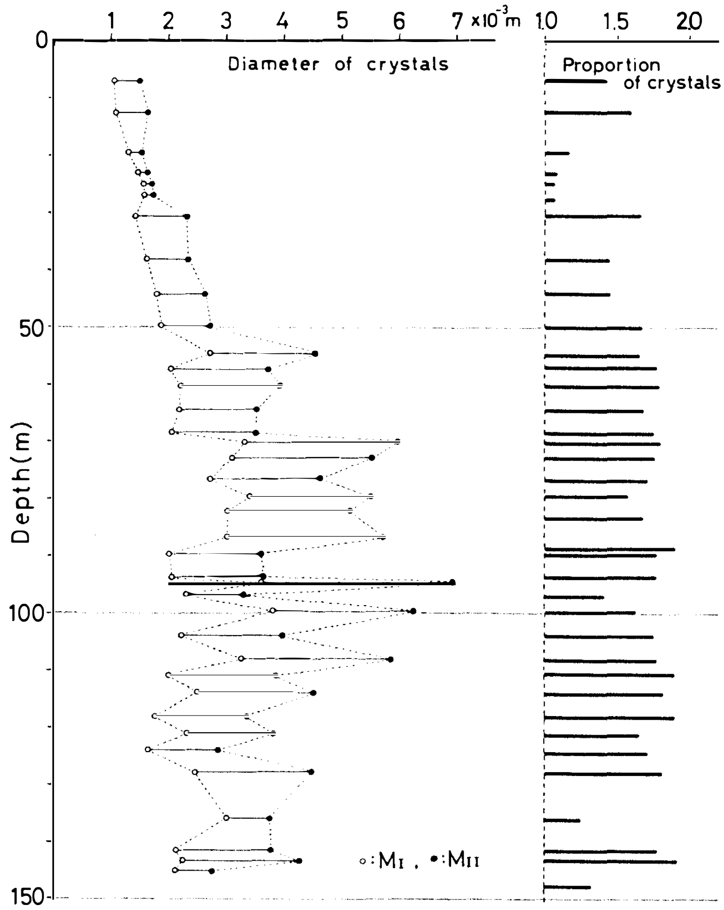

Fig. 5. Mean diameters of crystals ($M_{\rm I}$ and $M_{\rm II}$) and mean proportion of crystals ($M_{\rm II}/M_{\rm I}$) plotted against the depth.

depth of about 70 m. The mean proportion in this density region is fairly large.

At the depth around 70 m M_{I} and M_{II} show a sharp increase, exhibiting maximum values observed in the present measurements. Large crystals were found between 70 m and 110 m. It should be noted, however, that layers composed of smaller crystal grains were also found in this depth range. The approximate thickness of such layers was 1 m and these layers were located at intervals of about 2 to 3 m. The shapes of air bubbles changed to spheres by the depth of 80 m, and cracks appeared around 96 m. Cracks were frequently found in the small-crystal layers.

At depths deeper than about 110 m, crystal sizes became smaller; more properly speaking, the small-crystal layers, appearing in the depth range from 70 m to 110 m, became to dominate. Examples of such small-crystal layers are shown in the photographs of 110.70 m and 114.16 m in Fig. 3.

3.2. Specific areas of grain boundary and internal free surface

Fig. 6 gives three schematic pictures of vertical thin sections of core samples, in which only the internal free surfaces (ice-air interfaces) and grain boundaries (ice-ice interfaces) are drawn. It should be clearly understood that as the depth increases the area of grain boundary increases and that of internal free surface decreases, and it should be remembered that air voids tend to be present only at intersections of several grain boundaries.

Specific areas of grain boundary S_{g} and internal free surface S_{f} are plotted against depth in Fig. 7; near the surface, S_{g} is only one fourth of S_{f}, but at depths below about 8 m S_{g} increases and becomes about 900 $\mathrm{m^2/m^3}$ at about 30 m. On the other hand, S_{f} fluctuates and maintains an almost constant value around 1500 $\mathrm{m^2/m^3}$ until 30 m, suggesting the splitting of air voids into many smaller ones during densification processes.

At the depth around 30 m, S_{f} begins to decrease rapidly, but S_{f} remains constant (about 990 $\mathrm{m^2/m^3}$) until about 70 m. In the range from 70 m to about 110 m, S_{g} fluctuates because of the presence of small-crystal layers in this depth range,

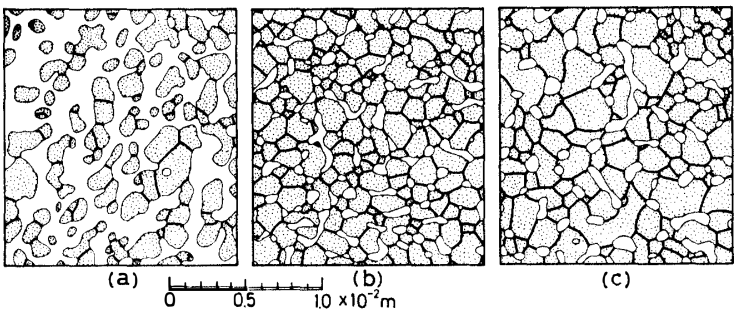

Fig. 6. Sketch of grain boundaries (thick line) and free surfaces (thin line) of thin sections of cores. (a) 12.5 m, 611 kg·m⁻³, (b) 34.5 m, 761 kg·m⁻³, (c) 52.4 m, 810 kg·m⁻³.

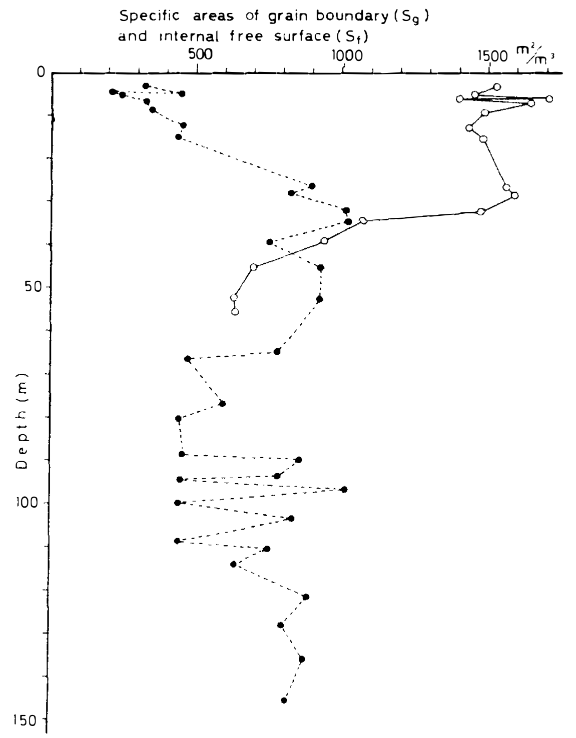

Fig. 7. Specific areas of grain boundary (S_g) and internal free surface (S_f) plotted against the depth.

as explained in Section 3.1.; large values of S_g correspond to small sizes of crystal grains, and small values of S_g to large sizes of crystal grains. Large values of S_g at depths deeper than 110 m are due to the small sizes of crystal grains there.

Fig. 8 gives the degrees of orientation for grain boundaries ω_g and internal free surfaces ω_f. As noted in Section 2.1., positive and negative values of the degree of orientation imply the dominance of surfaces in question lying in the horizontal and vertical planes, respectively. As for the internal free surfaces, above the depth of about 20 m ω_f is negative and large in magnitude. This is consistent with the above result that the proportion of crystal grains is large in the surface region (Fig. 5). According to YAMADA's (1978) measurements, large anisotropy was found in the sonic velocity of the Mizuho core samples. These results can be explained by the predominant development of depth hoar crystals. Near-zero values of ω_f at deeper depths mean the spheroidization of air bubbles.

On the other hand, variations with depth of ω_g are more complicated; with increasing depth negative ω_g approaches zero and hence it can be said that at about 30 m the orientation of grain boundaries is almost isotropic. Below the depth of 30 m ω_g is mainly positive though some negative values are found at 70 m, 95 m,

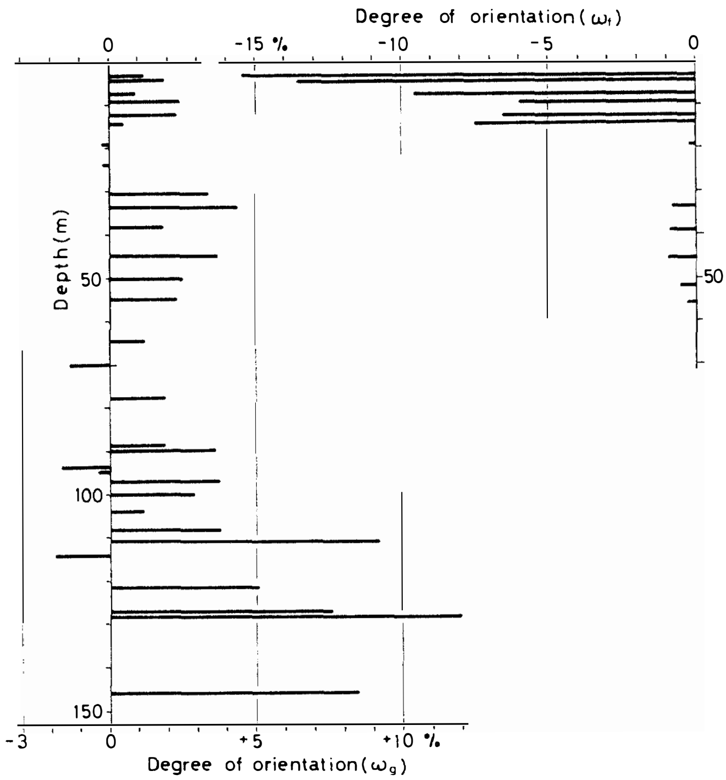

Fig. 8. Degrees of orientation for internal free surfaces (ω_f) and grain bounaries (ω_g).

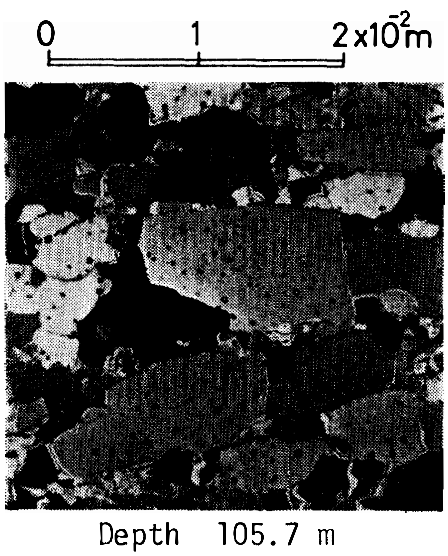

Fig. 9. Microphotograph showing the coincidence of cracks with grain boundaries.

and 115 m. It was already mentioned that many horizontal cracks were found to occur at grain boundaries. It is anticipated that the horizontal grain boundaries might be a result of formation of horizontal cracks. An example is shown in Fig. 9. However, it was confirmed that cracks were only found where the degrees of orientation exceeded about 5%.

3.3. *C-axis orientations*

Fabric patterns of *c*-axis orientations for the Mizuho cores above 70 m were reported by one of the present authors (NAKAWO, 1974). According to the results, at depths from the surface to about 30 m, *c*-axis distributions were strongly concentrated in the vertical direction. An example is given for a depth of 19.4 m in Fig. 10. At deeper depths two maxima appeared, and then one of the two maxima in horizontal directions became more dominant (35.5 m in Fig. 10). At depths roughly from 40 m to 70 m, so-called small girdle patterns appeared, in which several maxima were distributed along a girdle shape (50.4 m in Fig. 10). Laboratory experiments on preferred *c*-axis orientation of compressed snow (WATANABE and OURA, 1968; TANAKA, 1972) suggest that uniaxial vertical compression might be the predominant stress in the top 70 m of the ice sheet at Mizuho Station.

At the depth of about 70 m, girdle patterns were weakened and maxima disappeared (70.2 m in Fig. 10), but at deeper depths several maxima appeared again as shown in the diagrams of 88.9 m and 145.4 m in Fig. 10. These fabric patterns

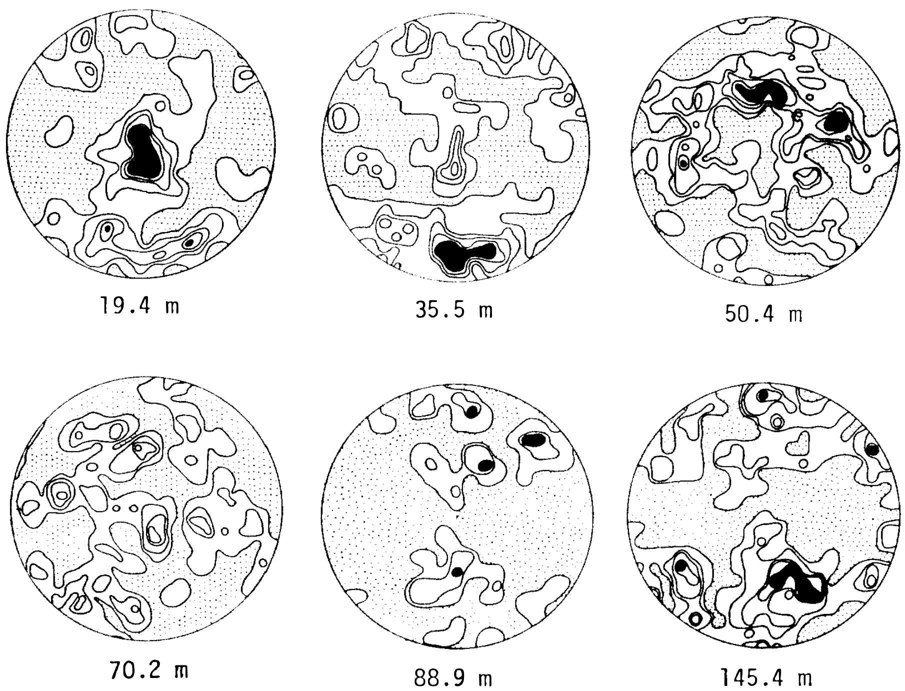

Fig. 10. C-axis fabric patterns for six different depths.

may be considered to be those of girdles with their symmetric axes lying in the horizontal plane. If this is correct, these fabric patterns suggest the predominance of horizontal uniaxial compression. Small-crystal layers found at depths below 70 m (Figs. 5 and 7) suggest, in conjunction with the present results and the experiments by WATANABE and OURA (1968) and NAKAWO (1977), that some shear components are also involved.

4. Summary and Comparison with Other Results

Our structural analyses of Mizuho cores extending to the depth of 147.5 m have revealed that the structural characteristics of the cores differ between six layers, namely 0–8 m, 8–30 m, 30–55 m, 55–70 m, 70–110 m and 110–147.5 m. The five dividing depths correspond to densities of 550, 730, 840, 855 and 882 $kg \cdot m^{-3}$, respectively. Among these five the densities of 550 and 840 $kg \cdot m^{-3}$ are considered to be those at which the mode of densification changes, as already mentioned, from mechanical packing to plastic deformation of ice grains and from plastic deformation to shrinkage of closed-off air bubbles, respectively.

The dividing depth 30 m (730 $kg \cdot m^{-3}$) was first found by MAENO (1974a, 1974b); from his electrical measurements of Mizuho cores, MAENO has proposed that the bonding between ice grains develops with increasing depth and reaches its maximum at a density around 730 $kg \cdot m^{-3}$, at which dielectric constants give the theoretical maximum values. This concept is in harmony with the rapid rate of crystal growth at this density (Fig. 5). In Fig. 6, it was emphasized that air voids gathered at intersections of several grain boundaries. The configuration of air voids was more clearly shown by the following three-dimensional observation: when a block of cores was soaked in liquid aniline at $-5°C$ and then cooled to $-20°C$, the penetrating aniline was solidified and revealed clearly the network of air voids within the sample. In a core sample having a density near 730 $kg \cdot m^{-3}$, they were found to be located only at intersections of grain boundaries, making a network of intercommunicating air channels. The authors suspect that these air channels lie three-dimensionally along edges of polyhedrons of ice grains and that the polyhedrons may be a kind of tetrakaidecahedron in taking account of the requirement of space-filling (UNDERWOOD, 1970; MAENO *et al.*, 1978). This configuration of air voids seems to be one of the most favorable for maximizing the contact between ice grains, *i.e.*, maximizing the bonding extent between them.

Other physical properties measured from the Mizuho cores are given against depth in Fig. 11. Static dielectric constant (κ') and high-frequency conductivity (σ_∞) show marked changes at the critical depths of 8, 30 and 55 m, details of which were reported by MAENO (1974a, 1974b, 1978). Air permeability (k) also gives remarkable changes at the critical depths. The rapid decrease in air permeability at the depth of about 30 m (730 $kg \cdot m^{-3}$) is in accordance with that in S_f (Fig. 7).

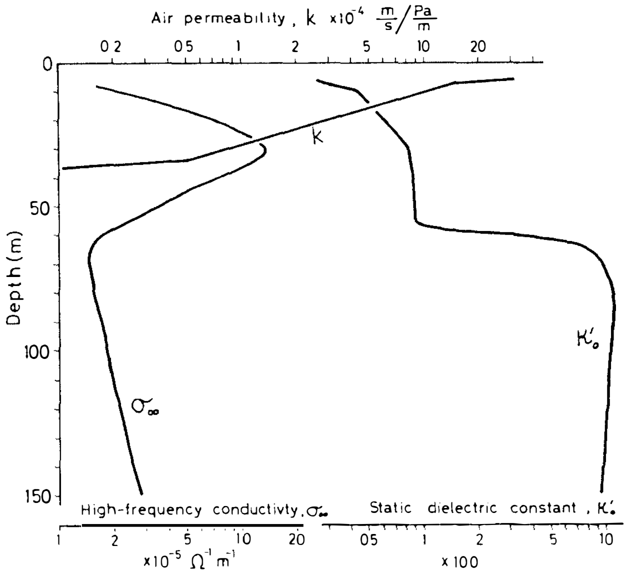

Fig. 11. Various physical properties plotted against depth. Data of dielectric constant (κ') *and high-frequency conductivity* (σ_∞) *are quoted from a paper by* MAENO *(1978), and those of air permeability* (k) *from a paper by* MAENO *et al. (1978).*

The decrease is caused because air channels are cut by further densification (MAENO *et al.*, 1978).

Acknowledgments

The authors would like to thank to Dr. Y. SUZUKI of Hokkaido University and Prof. K. KUSUNOKI of the National Institute of Polar Research for comments on this paper, and to Mrs. S. NAGAYAMA, Mrs. Y. UEMATSU, Mr. K. ARAOKA and Mr. Y. KANEDA for their assistance in measurements and preparation of manuscripts.

The expence of this study was partly defrayed from a Special Fund for Scientific Research of the Ministry of Education, Science and Culture, Japan.

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(Received June 15, 1978; Revised manuscript received September 25, 1978)