Ice Fabric Studies on a 75 m-Long Core Drilled at Mizuho Camp, East Antarctica

Masayoshi NAKAWO*

東南極みずほ観測拠点で採取された 75 m ボーリングコアーの構造解析

中 尾 正 義*

要旨：第12次日本南極地域観測隊（1971–1972年）によりみずほ観測拠点で75mのボーリングコアーが採取された．採取直後，密度が測定されるとともに水平薄片がつくられ，偏光写真撮影ののち，その結晶主軸方位が測定された．

密度は深さとともに増加していくのに対して，平均結晶粒度は約35m深までほぼ一様であり，そこから急激に大きくなっていた．結晶粒度がほぼ一様な範囲においては，結晶主軸はほとんど鉛直方向を向いており，35mより深くなるとその分布図は，鉛直軸まわりのガードル状を呈していた．

Abstract: A 75 m-long snow/ice core was drilled at Mizuho Camp, East Antarctica, by the glaciological members of the 12th Japanese Antarctic Research Expedition (1971–1972), and its density and the orientations of the *c*-axes of crystal grains composing it were measured immediately after recovery.

It was found that the density increased with the depth, but that the average grain size was almost constant down to about 35 m, at which depth it began to show a sharp increase. At depths shallower than 35 m the directions of the *c*-axis were almost vertical, while the fabric patterns for the samples deeper than 35 m showed a so-called girdle pattern.

1. Introduction

This paper is aimed at providing useful data on petro-fabric studies of fresh snow/ice core samples. The samples studied were obtained from a core above a depth of 75 meters drilled by glaciological members of the 12th Japanese Antarctic Research Expedition, 1971–72, in connection with a project of ice drilling, which constitutes one of the Glaciological Research Programs in Mizuho Plateau–West Enderby Land. It was started in 1971 at Mizuho Camp (70°42.1′S, 44°17.5′E) under the supervision of Dr. Tamotsu ISHIDA and Dr. Yosio SUZUKI. Whereas it is

* 北海道大学低温科学研究所. The Institute of Low Temperature Science, Hokkaido University, Sapporo.

desirable to examine ice core samples as soon as possible in view of the possibility of structural changes due to metamorphism, the density measurement of each sample was made immediately after recovery, whereby its structural analyses were made within about a month at Mizuho Camp.

2. Measurements and Results

A core (10.5 cm in diameter, 75 m in length) was obtained by a mechanical drill for the upper half and a thermal drill for the lower half designed by Dr. Yosio SUZUKI (YAMADA, KIMURA, and NAKAWO, 1973). A cube ($3 \times 3 \times 3$ cm) was cut out as a sample every 3 cm from the surface and weighted to give an average density. Figure 1 shows the density distribution of this core ; the density increased exponentially with the depth. A sample of the core located near the surface was so fragile that the measurement of its density was very difficult. The highest value of density of this core was $0.9\ g/cm^3$ at 75 m. Horizontal thin sections were prepared from these cubes to observe the distributions of crystal size and *c*-axis orientations of individual crystals under a polarization microscope. Since the preparation of a thin section of a fragile core sample near the surface was difficult, the following convenient procedure was used for it: the sample was warmed to approximately $-2°C$, and soaked in water maintained at 0°C, to let each of the component crystals grow uniformly without changing its crystallographic orientation. When a thin section prepared from this "snow ice" was analyzed, it provided a reliable *c*-axis distribution of crystals of such an original fragile snow sample (WATANABE and ÔURA, 1968).

Figure 2 shows the profile of the average crystal size; the average crystal size was found to be almost uniform from the surface to about 35 m in depth, but it

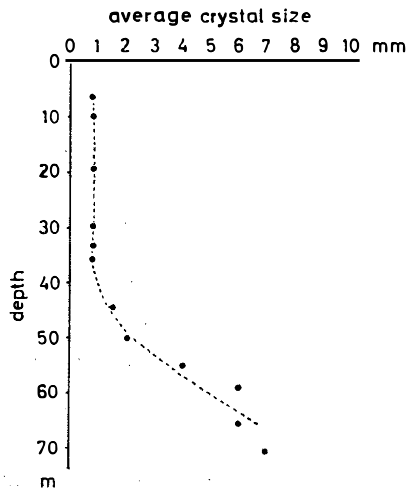

Fig. 1. Density profile.

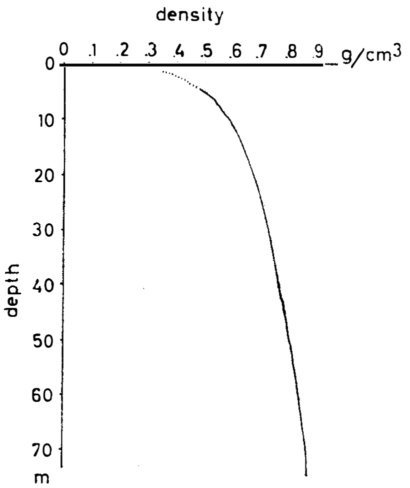

Fig. 2. Average crystal size distribution.

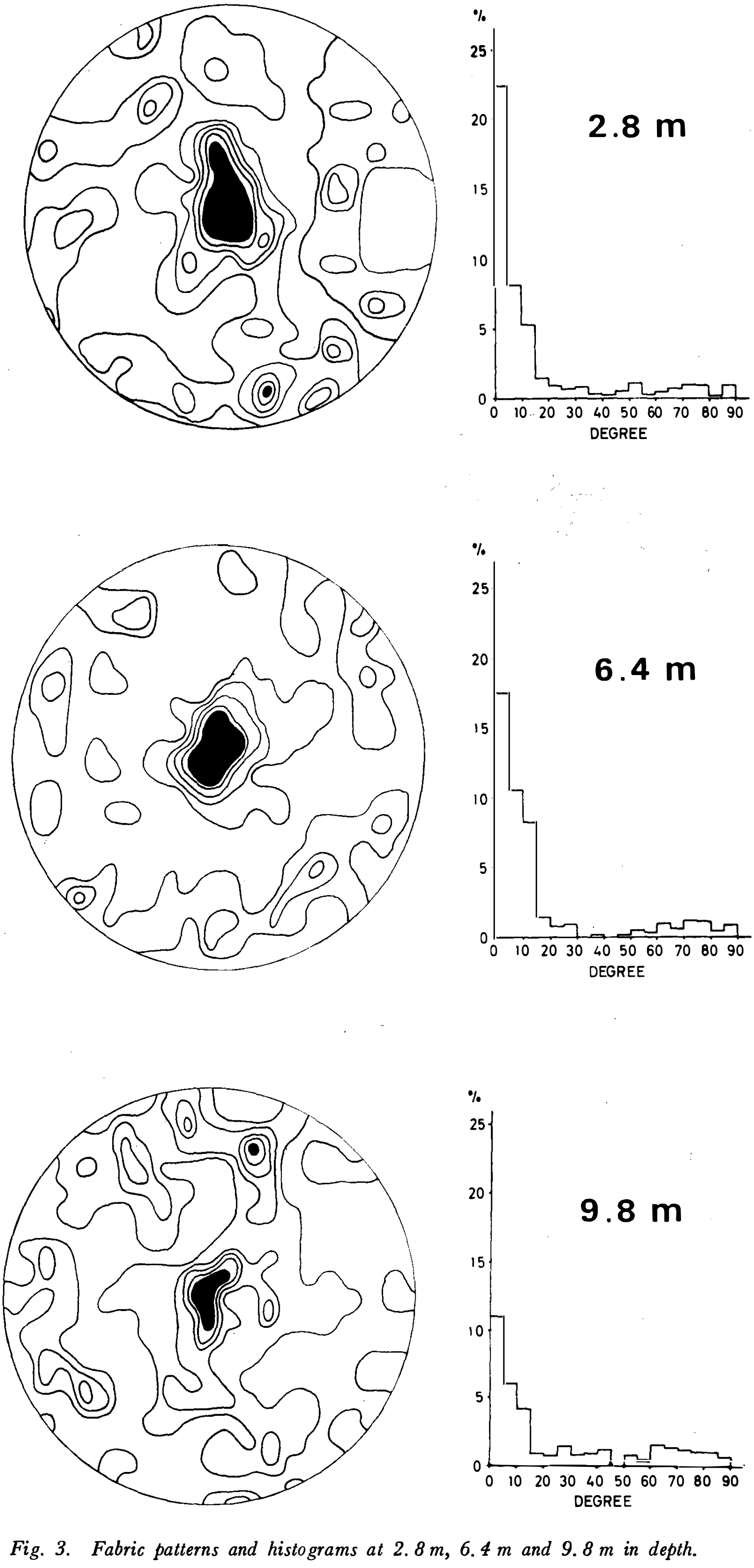

Fig. 3. Fabric patterns and histograms at 2.8 m, 6.4 m and 9.8 m in depth.

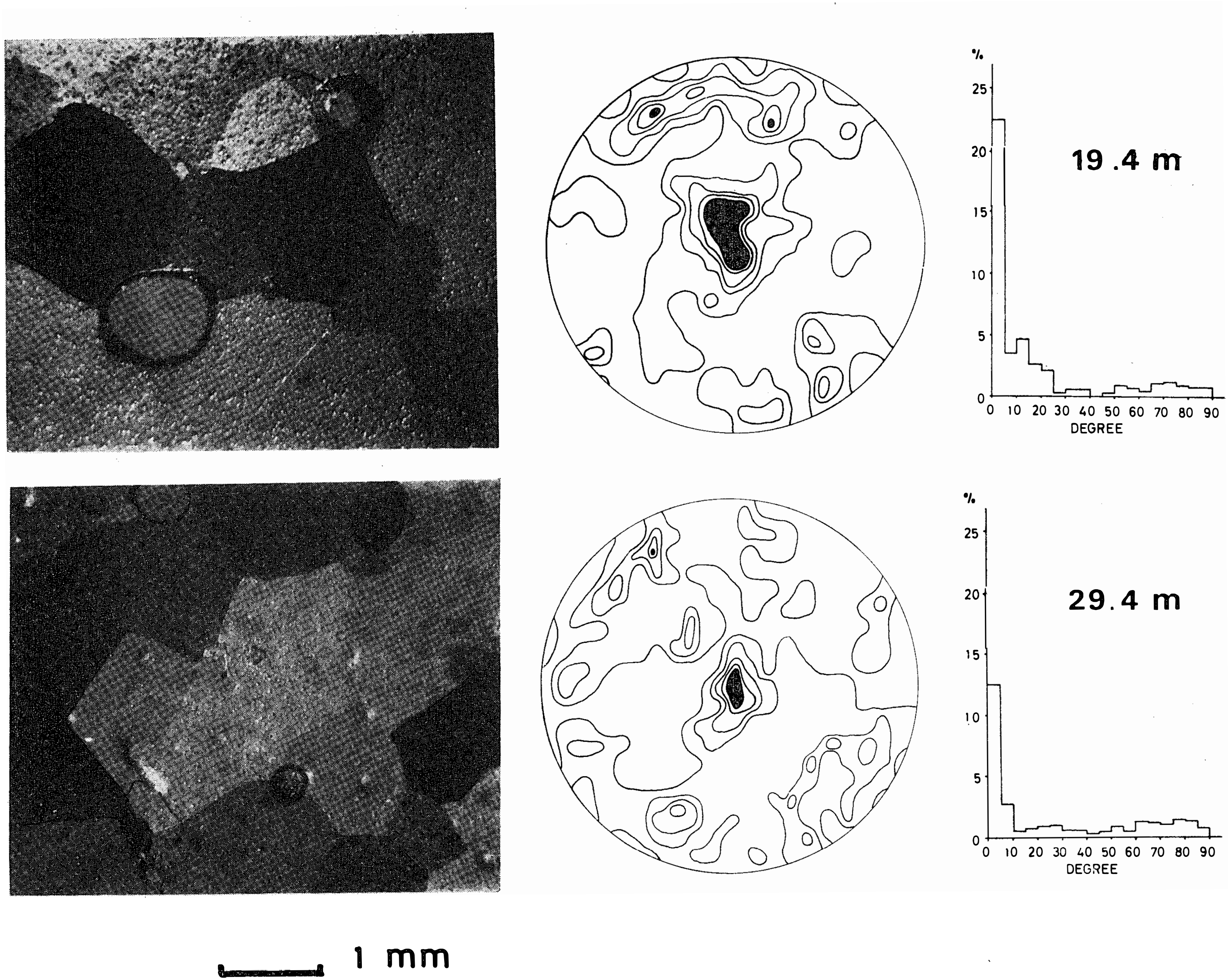

Fig. 4. Photographs of horizontal thin sections, fabric patterns and histograms at 19.4 m and 29.4 m in depth.

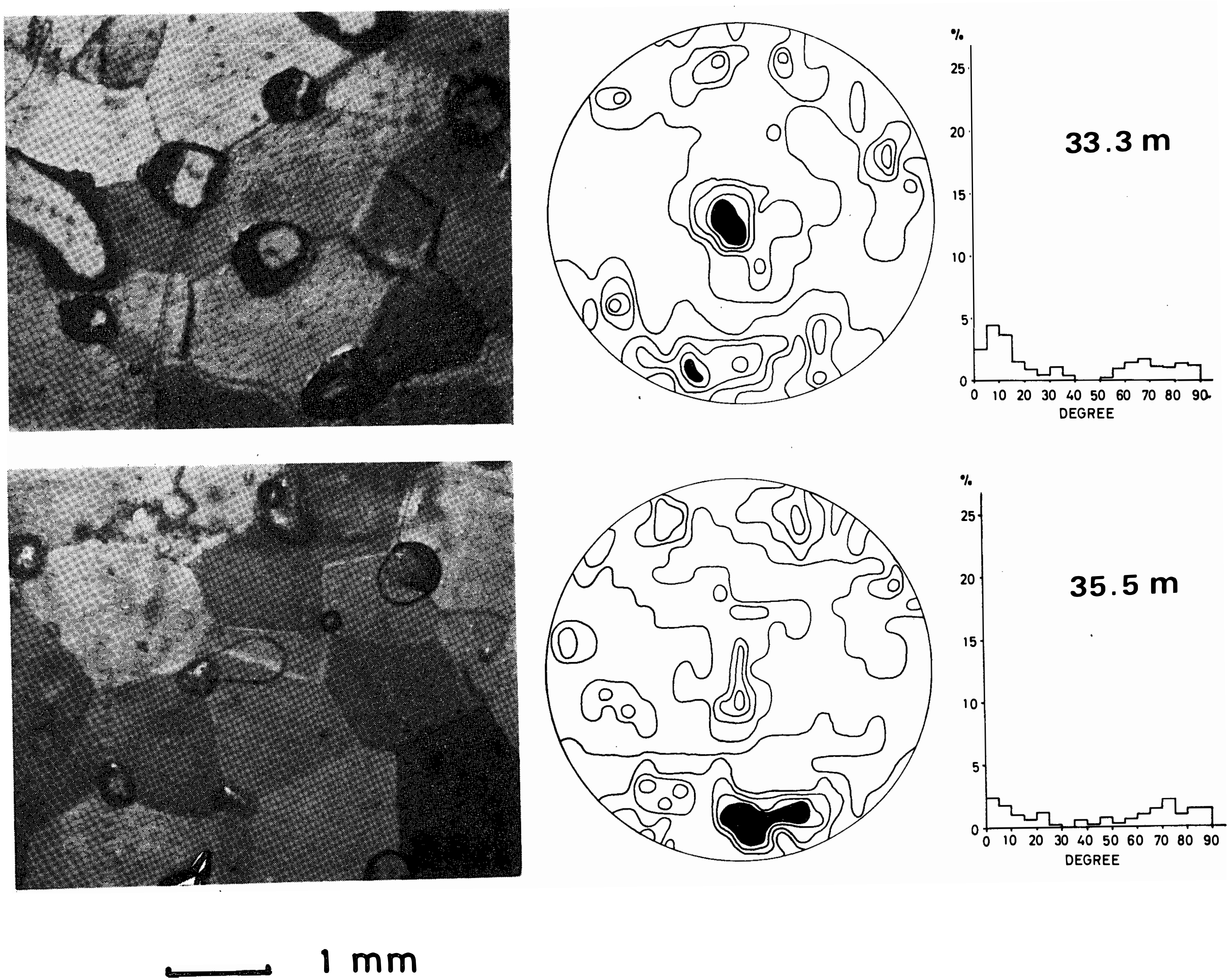

Fig. 5. Photographs of horizontal thin sections, fabric patterns and histograms at 33.3 m and 35.5 m in depth.

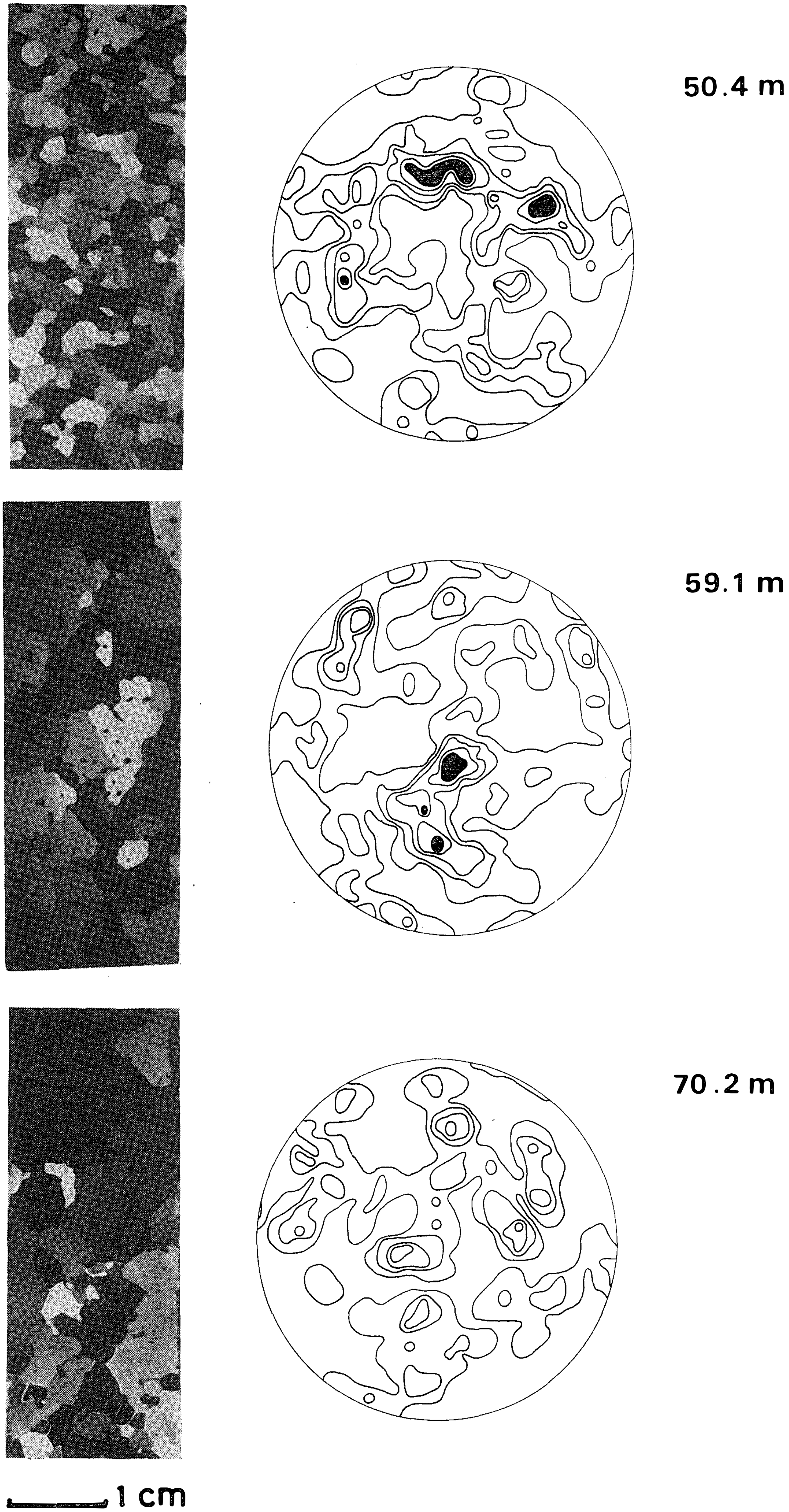

Fig. 6. Photographs of horizontal thin sections, and fabric patterns at 50.4 m, 59.1 m and 70.2 m in depth

increased rapidly with the depth. Air bubbles contained in core samples were carefully examined, but no bubble foliations or lineations were observed throughout the core.

The results of petro-fabric analyses of thin sections at various depths are shown in Figs. 3, 4, 5 and 6. The center of each diagram coincides with the vertical direction, perpendicular to the surface of the snow. The number of crystals of which orientations were measured was almost 100. Fabric contours are drawn at 4, 3, 2 and 1 crystals per 1 % area. A black area shows the area where the number of crystals exceeds 5 crystals per 1 % area. The histogram illustrated at the right-hand side of each fabric diagram shows the number of crystals per unit area against the angle between their *c*-axes and the vertical direction. The interval between angles measured was 5 degrees. Photographs of thin sections taken under the polarized light are shown in Figs. 4, 5 and 6. The lateral lengths of the sections are 5 mm in Figs. 4 and 5, and 18 mm in Fig. 6.

As shown in these figures, strongly oriented *c*-axis distributions can be seen in the vertical direction at depths from 2.8 m to 29.4 m. At 33.3 m, two maxima appeared, but at 35.5 m it seemed that one of the two maxima was slightly shifted toward the horizontal direction. The fabric patterns observed at depths deeper than 40 m were found to be different from those above 40 m. Figure 6 showed a so-called small girdle pattern, where several maxima were distributed along a girdle. It appears that the center of the small circular girdle coincides with the vertical direction in case of a sample at 50.4 m. The patterns of samples obtained at 59.1 m and 70.2 m seem to have two or three weak maxima on a small circular girdle.

It should be noted that the *c*-axes of crystals were strongly oriented toward the vertical direction with an interval from 0 to 5 degrees in samples obtained at 2.8 to 29.4 m, but these strong *c*-axis orientations were weakened with the depth and several maxima were found in a range from about 50 to 90 degrees as shown in Figs. 5 and 6. The shapes of crystals in shallow-core samples in Figs. 4 and 5 were polygonal and the crystal boundaries were found to be straight. In Fig. 2, the average crystal diameter down to 35 m was about 0.8 mm. It should be noted, however, that the crystal boundaries shown in photographs of Fig. 6 were complicated and interlocked, and the average crystal size was much larger than that in the shallow samples.

3. Discussion

The depositional one-maximum pattern has been hypothetically attributed to a mimetic recrystallization of snow after the deposition of stellate snow flakes (KI-

ZAKI, 1969). However, in cold region, below −20°C, snow crystals are expected to take a somewhat columnar shape, according to the NAKAYA diagram (NAKAYA, 1954). It was reported that the abundant shapes of snow crystals in the South Pole region, were bullets, a combination of bullets, columns and side planes (KIKUCHI and YANAI, 1971). At Mizuho Camp it was also observed that the snow crystals on the surface were almost the hollow prism type and bullet type from October, 1970, to January, 1971, and from April, 1971 to September, 1971 (NARITA and NAKAWO, unpublished). Judging only from the shapes of the snow flakes, the *c*-axes of the crystals of surface snow would not tend to orient vertically rather than horizontally.

Snow crystals start undergoing metamorphism shortly after precipitation on the surface, becoming spherical ice crystals. In Antarctica, subsurface snow is subjected to negative and positive temperature gradients in summer and winter seasons, producing alternations of coarser and finer granular layers, respectively. However, the amplitude of the annual mean temperature of snow becomes aproximately zero below 10 m in depth, suggesting that the metamorphism of snow crystals proceeds nearly under an isothermal condition at depths deeper than 10 m. STEPHENSON (1966) reported that snow at Southice in Antarctica showed the preferred vertical elongation of ice crystals because of a continuous vapor flow due to a negative temperature gradient; the petro-fabric analysis of these snows showed a one-maximum pattern in depth-hoar layers, implying that the *c*-axes of the crystals are vertically concentrated, though almost all specimens of his gave very weak or virtually random orientations for *c*-axes with the exception of wind-crusts and depth-hoar layers.

At Mizuho Camp, where depth-hoar is well developed throughout the subsurface layer as well as in the Mizuho Plateau area (NARUSE, 1972; WATANABE, 1972), fabric patterns at depths of 0–20 m showed a preferred vertical orientation of the *c*-axes as shown in Figs. 3 and 4. Therefore, the formation of this preferred *c*-axis orientation seems to be associated with the formation of depth-hoars though the precise mechanism of it is not known. One piece of evidence to support these observational results seems to be AKITAYA's experiment. AKITAYA (private communication) found that the *c*-axis of depth-hoar formed in snow was oriented in the direction of the temperature gradient.

One of the notable findings in these Mizuho core samples was the profile of the average crystal size shown in Fig. 2. ANDERSON and BENSON (1963) reported that, when a densification of snow proceeds beyond 0.55 g/cm^3, grain growth occurs as the result of release of stresses. However, in case of Mizuho cores, as was described before, the average crystal size down to 35 m in depth was about 0.8 mm with an accuracy of 0.2 mm and no discernible change in texture was observed in spite of the fact that the density of the snow increased from 0.3 g/cm³ to about 0.74 g/cm³. As seen in Fig. 2, the average crystal size increased at depths deeper than 35 m and attained a diameter of approximately 7 mm at 75 m depth. This means that crystals grew about 350 times in volume with an increase of 40 m in depth. From the dielectric measurements of the Mizuho core samples, MAENO (1974) concluded that the bonding between the component ice particles had reached its maximum mode by the depth of about 30 m (0.73 g/cm³), so that the further growth of crystals might take place more easily because of their closer contact. It should be noted that the significant change of petro-fabric patterns occurred above and below the depth of 33.3 m as seen in Figs. 4, 5 and 6.

WATANABE and ÔURA (1968) and TANAKA (1972) reported that the small girdle pattern was found in the petro-fabric diagrams of uniaxially compressed snow or ice. The symmetric axis of the girdle coincided with the direction of compression. The pattern of a 50.4 m deep sample shown in Fig. 6 was very similar to that obtained by them. This agreement may suggest that the stress condition occurring about 50 m beneath the surface of Mizuho Camp was almost identical to that of the uniaxial compression. Patterns having two or three maxima on a small circular girdle (Fig. 6) were also found in TANAKA's experimental results in which the uniaxial compression was applied in a definite speed and then the load was kept constant. In his samples, the active grain growth was observed to have taken place, which is also seen in Figs. 2 and 5. At Little America V similar patterns were reported by GOW (1970); The fabric patterns at 61 m and 70 m have small circular girdles having no and two maxima respectively, and the symmetric axis of the small circular girdle coincides with the vertical direction. WAKAHAMA (1974) also reported similar fabric patterns in the samples taken from the summit of Wilks Dome, East Antarctica, where the stress state was considered to be uniaxial compression, lacking a lateral flow of ice. Therefore, it might be considered that the ice/snow layer at a depth of 50–70 m at Mizuho Camp is not much affected by a lateral flow but vertical compression.

Acknowledgments

The author would like to express his gratitude to Professor Daisuke KUROIWA for reading the manuscript and giving valuable suggestions and to Dr. Norikazu MAENO for his critical reading of the manuscript.

References

ANDERSON, D. L. and C. S. BENSON (1963): The densification and diagenesis of snow. Ice and

Snow, ed. by W. D. Kingery, 390–411.

Gow, A. J. (1970): Deep core studies of the crystal structure and fabrics of antarctic glacier ice. CRREL Research Report **282**.

KIKUCHI, K. and K. YANAI (1971): Observation on the shapes of snow crystals in the South Pole region in the summer. Antarctic Rec., **41**, 34–41.

KIZAKI, K. (1969): Fabric analysis of surface ice near Casey Range, East Antarctica. J. Glaciol., 8 (54), 375–383.

MAENO, N.(1974): Investigations of electrical properties of deep ice cores obtained by drilling in Antarctica. Kyokuchi hyôshô-hyô no butsuriteki kagakuteki kenkyû (Physical and Chemical Studies on Ices from Glaciers and Ice Sheets), 45–56.

NAKAYA, U. (1954): Snow Crystals: Natural and Artificial. Harvard University Press, Cambridge, Mass., 119–120.

NARUSE, R. (1972): Stratigraphic observation of the surface snow cover in Mizuho Plateau, East Antarctica, 1969–1970. JARE Data Rep., **17** (glaciology), 77–87.

STEPHENSON, P. J. (1966): Some considerations of snow metamorphism in the Antarctic ice sheet in the light of ice crystal studies. Physics of Snow and Ice, Proc. Int. Conf. Low Temp. Sci., ed. by H. Ôura, **1**, 725–740.

TANAKA, H. (1972): On preferred orientation on glacier and experimentally deformed ice. J. Geol. Soc. Japan, **78** (12), 659–675.

WAKAHAMA, G. (1974): Petro-fabric studies on deep-core ices from Amery Ice Shelf, Wilks Dome and Cape Folger, Antarctica. Kyokuchi hyôshô-hyô no butsuriteki kagakuteki kenkyû (Physical and Chemical Studies on Ices from Glaciers and Ice Sheets), 99–108 (Text in Japanese).

WATANABE, O. and H. ÔURA, (1968): Experimental studies on preferred orientation of polycrystalline ice by unconfined compression. Low Temp. Science, A **26**, 1–28 (Text in Japanese with English summary).

WATANABE, O. (1972): Stratigraphic observation of the surface snow cover in West Enderby Land, East Antarctica, 1970–1971. JARE Data Rep., **17** (glaciology), 88–110.

YAMADA, T., T. KIMURA and M. NAKAWO (1973): Glaciological research work of the 12th Japanese Antarctic Research Expedition, 1971–1972. Antarctic Rec., **47**, 77–85 (Text in Japanese).

(Received March 28, 1974)