A Stratigraphic Analysis of a 10 Meter Deep Firn Core from the Inland Area near Syowa Station, East Antarctica

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南極昭和基地付近の内陸地域で採取された10m深の積雪コア解析

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要旨：南極大陸みずほ高原の「S 100」地点（南緯 69°38.1′，東経 42°51′，標高 1630m）から採取された10mの深さまでの積雪コアについて，低温実験室内にて層構造，粒度，密度，硬度などの測定を行なった．さらに表層 1 m の鉛直断面の薄片写真から密度の微細分布，比表面積の測定を行なった．本報告では，これらコア解析の手順，測定方法，結果について述べる．

10m の深さまでの間で，密度は 0.4～0.6g/cm³，硬度は数～数 10kg/cm² でいずれも下層ほど大きな値を示した．粒度は，しまり雪層で c（1.0～2.0mm），しもざらめ雪層で d（2.0～4.0mm）が多く，それぞれ各層の全長に対して 80%，69%を占めた．硬度 (H) と密度 (ρ) の関係をべき函数として回帰させ，$H=4000\rho^8$ kg/cm² を得た．薄片写真からコアの鉛直方向 1 mm の間隔で求めた密度は，同一雪層の中でも大きく変動したが，その平均値は秤量法による密度とほぼ一致した．比表面積は，しまり雪層で 36.5cm²/cm³，しもざらめ雪層で 28.3cm²/cm³ を示した．積雪の諸性質の周期的変動に着目して推定された年間積雪量（最近 2 カ年の平均：6.6g/cm²）は，同地点で雪尺により測定された結果（5.3g/cm²）と近い値を示した．

本解析作業には，筆者等のほかに奥平文雄，中尾正義，石川信敬，上田豊が参加した．

1. Introduction

This paper is to present methods and results of a stratigraphic analysis of a 10 m deep firn core which was collected from the inland area near Syowa Station, East Antarctica, by the 10th Japanese Antarctic Research Expedition (JARE) in 1969 and was subjected to study at the laboratory of Hokkaido University in 1970.

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The analysis includes observations on stratigraphic features, density, hardness, and grain size. Also included in the analysis are detailed observations on snow texture, density, and specific surface by means of enlarged photographs of cross sections of the firn core from the surface down to the depth of 1 m.

2. Core Drilling

A 10 m long firn core was collected by a SIPRE-type hand auger at S 100 on November 10, 1969, during the glaciological traverse of JARE 10 (ANDO, 1971).

The drilling site S 100 (see Fig. 1) is located at 69°38.1′ S, 42°51′ E, about 150 km southeast of Syowa Station; its barometric altitude of 1,630 m was obtained by JARE 10 and JARE 11 (SHIMIZU, NARUSE, OMOTO and YOSHIMURA, 1972), while a slightly larger value, 1,675 m, was recorded by JARE 8 and JARE 9 (FUJIWARA, KAKINUMA and YOSHIDA, 1971). The thickness of ice measured by a radio echo sounder was 1,368 m (SHIMIZU, NARUSE, OMOTO and YOSHIMURA, 1972).

Brief analyses as to firn stratigraphy of 1 m or 10 m long cores were made on the spot at 78 station (NARUSE, 1972).

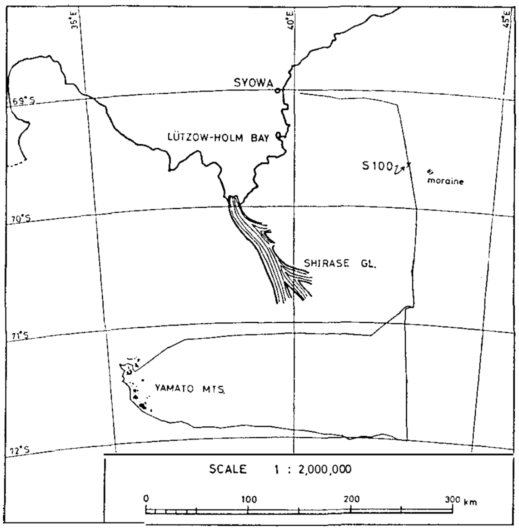

Fig. 1. Map showing the location of S100 and the oversnow traverse route of JARE 10.

3. Procedure of Analysis

The firn core of 7.5 cm in diameter was analysed in the cold room (−10°C in temperature) 6 months after its collection. Analysis was made according to the following procedure [The names of observers engaged in each work are given in brackets]:

1) The core was cut by an electric saw into 3 parts perpendicular to the surface of snow cover. These parts are designated in Fig. 2 as I (with II and III), IV and V. A central part of the core (I, II and III) was placed on a light table so that stratigraphic features may be examined through the transmitted light from below. Photographs were also taken, as shown in Fig. 3-(A) [by Yasoichi ENDO and Tomomi YAMADA].

2) The central part of the core (I, II and III) was cut into 3 portions, I, II and III. Then portion I was subdivided into pieces at intervals of 4 cm lengthwise, so that each piece may be subjected to measurements of density, hardness, and grain size [by Yasoichi ENDO and Tomomi YAMADA].

3) Portion II was reinforced with solidified aniline; thereafter photographs were taken of the surface of the vertical cross section. The photographs were then enlarged, as shown in Fig. 3-(B) and -(C), for the study of detailed texture of grains [by Hideki NARITA and Nobuyoshi ISHIKAWA*].

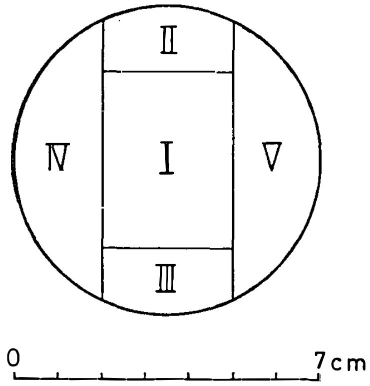

Fig. 2. Horizontal cross section of a core, showing allocation for each analysis.

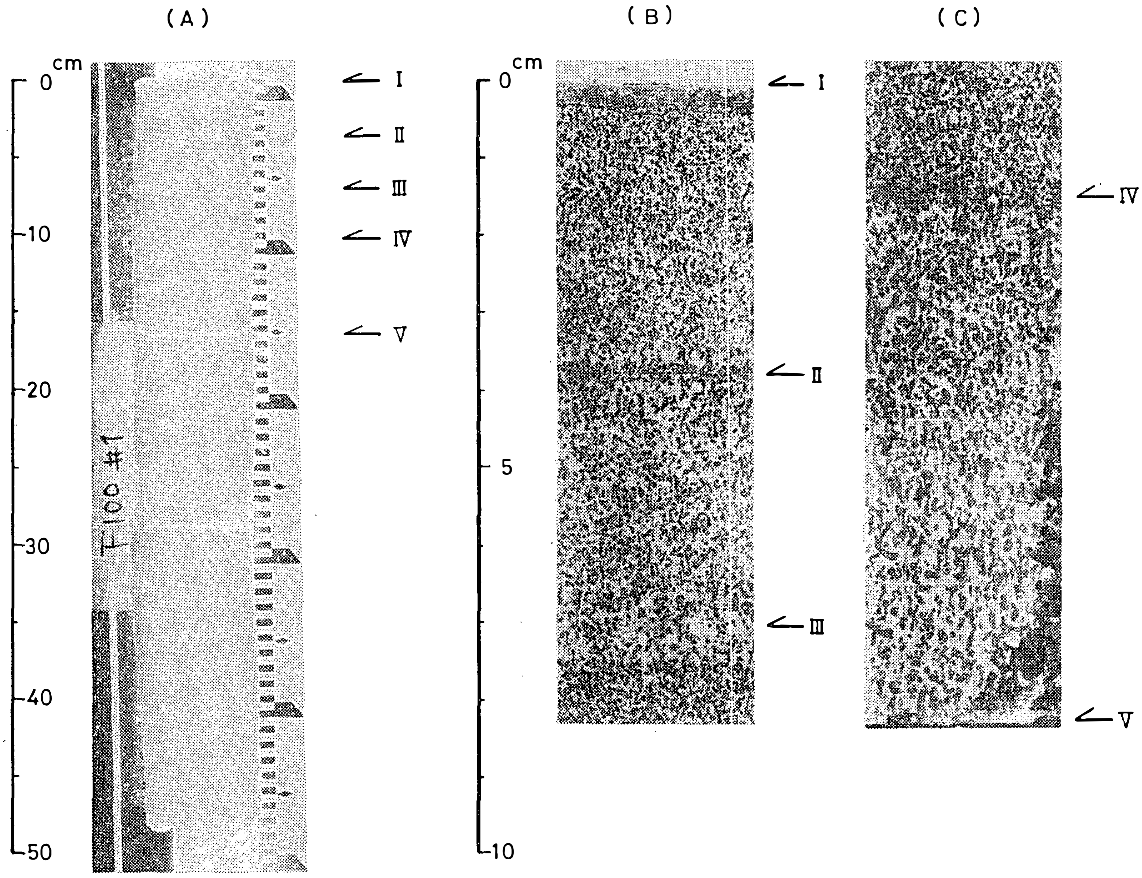

Fig. 3. (A) Vertical cross sections of a firn core observed on a light table. (B), (C) Vertical cross sections of a firn core in enlarged photographs.
Layers indicated by arrow marks I～V in (A) correspond to those in (B) and (C).

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The three kinds of work mentioned above were carried out for the entire length of the core from the surface to the depth of 10 m, except a few thin strata where measurements were not possible because of crashes sustained during the drilling and transporting.

4) Minute studies of stratigraphic features, such as the microscopic distribution of density and specific surface of snow, were made by means of the enlarged photographs of the core from the surface to the depth of 1 m [by Hideki NARITA and Renji NARUSE].

5) On portion III (in Fig. 2), the orientation of the C axis of snow crystals was measured in detail from the surface down to the depth of 1 m; the results of this study are, however, not included in the present report [by Masayoshi NAKAO*, Fumio OKUHIRA** and Yutaka AGETA**].

Portion IV was used for re-measurements at times when measurements were not successful. Portion V is preserved for further investigation.

4. Method of Measurements

4.1. Macroscopic stratigraphy

Placed on the light table, the vertical cross section of the core was examined in respect of the location of wind crust layers or the boundaries of snow strata, the light transmissivity of the firn core, and the types of grain shapes.

4.2. Density

The density (g/cm^3) of firn was measured by weighing the core piece of 3 cm × 4 cm × 4 cm. In the present report, this sort of density is named "bulk density ρ_b" against "ρ_m" which is obtained from a photographic analysis described in section 4.6.

4.3. Hardness

The hardness (kg/cm^2) of firn was measured on the vertical surface of each core piece by the Canadian hardness gage, a hand-pushed spring-loaded circular plate (included in the snow testing equipment by CRREL).

4.4. Grain size

The grain size (mm) of firn was measured on a section paper after the core piece was crumbled into grains.

4.5. Microscopic stratigraphy

Core pieces, each being about 3 cm × 1.5 cm × 30 cm in dimension, were reinforced with solidified aniline; then, the cross section perpendicular to the surface of snow

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cover was shaved. Thereafter, the powder of water blue, which dyes only the portions of ice particles, was rubbed against the surface of the cross section so that the portions of ice grains on the cross section could be identified in blue, and the portions of pores in white. Photographs were taken of cross sections along the entire length from the surface to the depth of 10 m and printed on developing-out paper in 9 times enlargement.

The detailed stratigraphy of snow structure was observed on enlarged photographs.

4. 6. Microscopic distribution of density

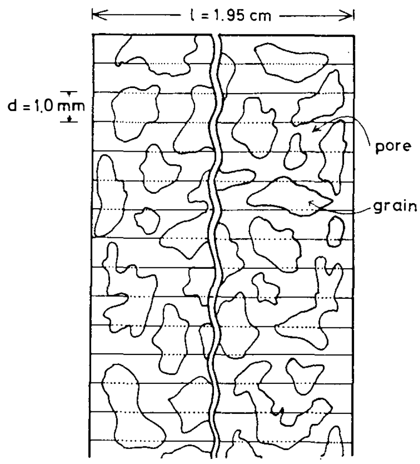

Fig. 4. Schematic figure showing the methods of measurements of microscopic distribution of density and specific surface on enlarged photographs of vertical cross sections.

The microscopic distribution of density was obtained on enlarged photographs by the following method:

1) Drawing parallel lines at intervals of d mm on an enlarged photograph of l cm in width as shown in Fig. 4. In this study, $d=1.0$ mm and $l=1.95$ cm. (The dimensions indicated here are those measured on the original snow piece before photographic enlargement.)

2) Summing the total lengths of the segments of a line which passes across ice grains (dotted lines in Fig. 4).

3) ρ_m (g/cm^3) is given as,

$$\rho_m = \rho_i \frac{\Sigma l_j}{l} \tag{1}$$

where ρ_i denotes pure ice density, namely 0.917 g/cm^3, and Σl_j denotes the sum of the lengths of the ice portions over a line. The values of ρ_m were measured at intervals of 1 mm from the surface to the depth of 1 m.

4. 7. Specific surface

The specific surface of snow, that is, the total surface area of ice particles in a unit volume of snow, was measured on enlarged photographs by drawing parallel lines (same lines as were used for the measurement of density ρ_m) and counting the number of points where the lines intersect the peripheries of ice particles. According to the theory of SMITH and GUTTMANN (1953), $2N/L$ is equal to specific surface s (cm^2/cm^3), where N is the total number of intersections, and L (cm) is the total length of parallel lines.

To obtain the specific surface of a core piece, the number of intersections N was counted along the 27 lines, namely, $L=27\,l=52.7$ cm (as $l=1.95$ cm) covering an

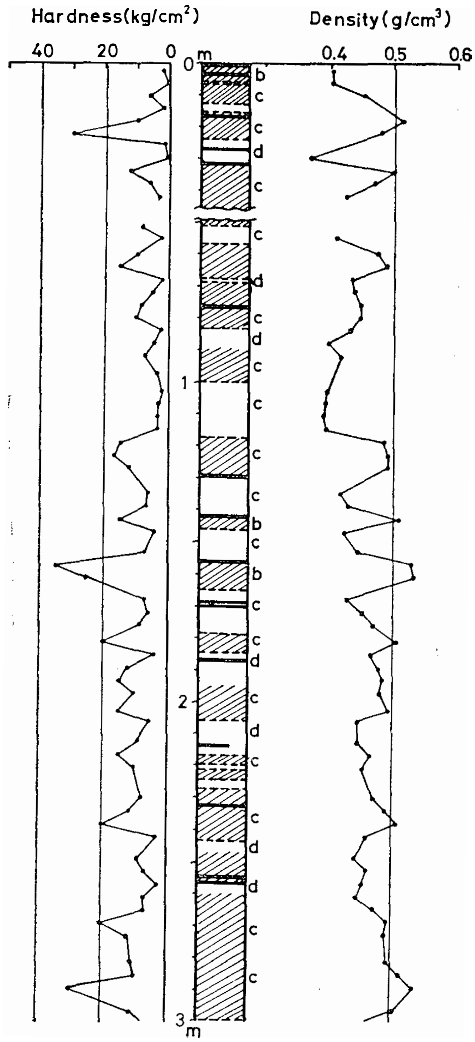

Fig. 5 (a)

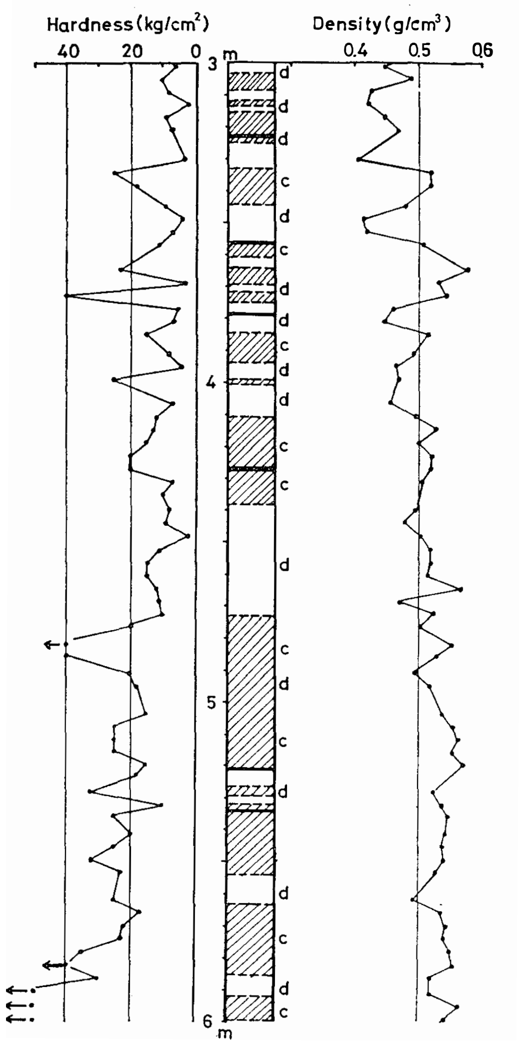

Fig. 5 (b)

Figs. 5 (a～c). Macroscopic stratigraphy, and the profiles of density and hardness along 10 m deep firn core.

The shaded portions in the central column express the darker layers of firn on a light table, and the blank portions express the lighter layers. Grain sizes b, c, or d are given at the right-hand side of the column.

area, $A=27\times d\times l=5.27\ \mathrm{cm}^2$ (as $d=0.1$ cm), on the surface of a vertical cross section of a firn core.

5. Results and Discussions

5.1. Macroscopic stratigraphy on a 10 m deep core

The macroscopic stratigraphy of a firn core from the surface down to 10 m deep is shown in Fig. 5. The layers of wind crust and the boundaries of snow strata are

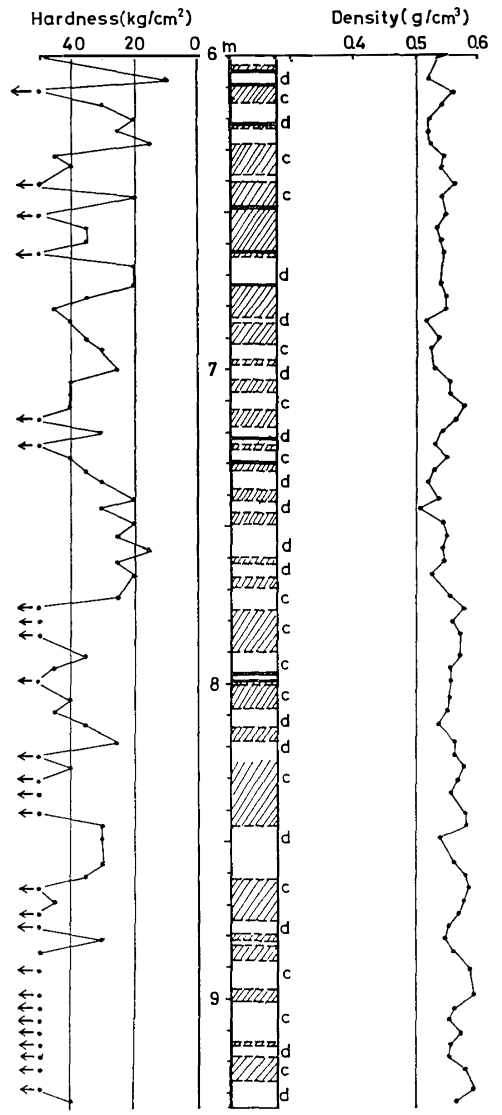

Fig. 5 (c)

indicated in a central column of Fig. 5 by solid and broken lines, respectively. The portions of the firn which looked darker when placed on the light table are displayed in the column by the shade; the portions which looked lighter by the blank. Grain sizes expressed in marks b, c, and d at the right-hand side of the column are defined as follows: $0.5 \leq b < 1.0$ mm, $1.0 \leq c < 2.0$ mm, and $2.0 \leq d < 4.0$ mm; grain sizes $a < 0.5$ mm and $e \geq 4.0$ mm were not observed in this core.

The lighter portions of firn in the transmitted light, as shown by arrow mark III in Fig. 3, correspond roughly to the layers of depth hoar of large grains mostly of the size of d. On the contrary, the darker portions, as shown by arrow mark IV in Fig. 3, correspond to the layers of fine- or medium-grained compact snow mostly of the size of c. The distribution of frequency in each grain size of snow particles is shown in Fig. 6 for the lighter, darker, and total layers. The frequency for the lighter layer is expressed for each grain size in percentage by the proportion

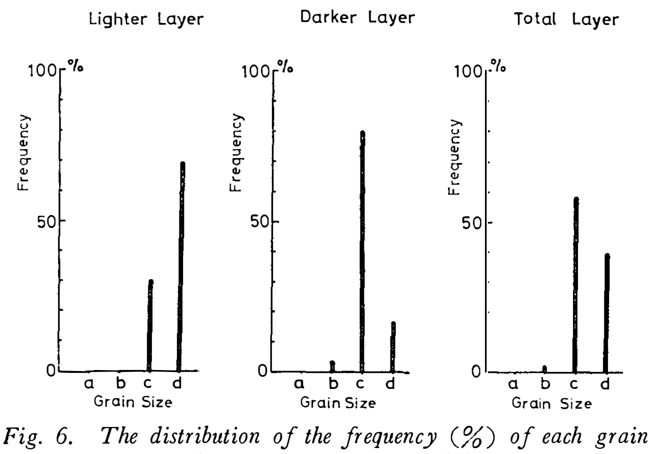

Fig. 6. The distribution of the frequency (%) of each grain size in the lighter, darker, and total layers.

of the total length of such layers as those having this grain size against the total length of all the lighter layers. The frequencies for the darker and total layers are likewise shown. For the darker layers, the grain size of c has 80.2% of the total length, while for the lighter layers, the grain size of d has 69.2%.

A number of wind crust layers, as shown by arrow mark II in Fig. 3, are clearly identified on the light table; however, the ice lenses or ice glands due to the melting phenomena are never observed.

5. 2. Relation between density and hardness

The profiles of (bulk) density and hardness are also shown in Fig. 5. The value of density tends to increase slightly with depth: namely, from 0.4～0.5 g/cm³ at the layers in the vicinity of snow surface to 0.5～0.6 g/cm³ at the layers 5 m deep and below. The value of hardness tends to increase remarkably with depth; that is to say, nearly all values of hardness at deeper layers are more than 50 kg/cm².

It is recognized in Fig. 5 that hardness in the darker layers shows a higher value, and in the lighter layers it shows to the contrary. The mean value of hardness is given as follows:

Darker layer…………27 kg/cm²,

Lighter layer ………20 kg/cm².

(Note: The calculation of the mean value was made on the assumption that the values of hardness expressed as "more than 50 kg/cm²" in Fig. 5 were 60 kg/cm².)

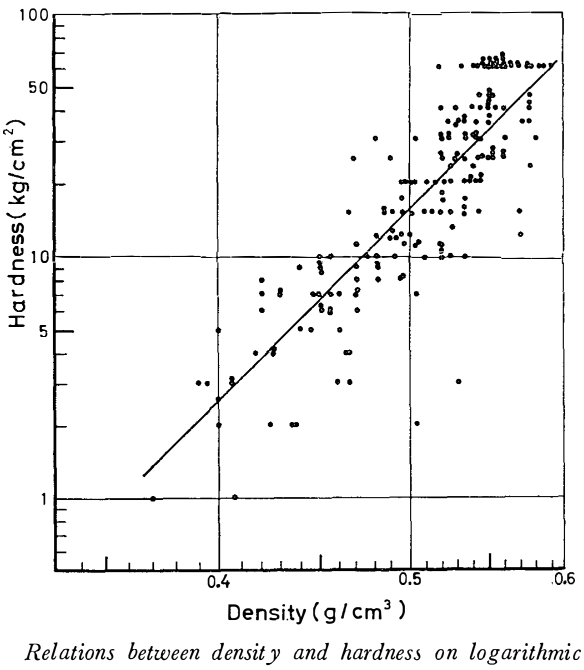

Fig. 7. Relations between density and hardness on logarithmic scales. A straight line shows the empirical relation between them, expressed by $H=4{,}000\rho^8$ kg/cm².

Fairly strong correlations between density and hardness are also noticed in Fig. 5. The correlation coefficient between them was calculated, given as 0.76.

Figure 7 shows the relations between density and hardness both on logarithmic scales. The values of hardness measured to be more than 50 kg/cm² were plotted in the figure assuming that they were 60 kg/cm². The relationship between them at the temperature of $-10°C$ was derived by the method of least squares as follows:

$$H=4{,}000\rho^{8}\ \text{kg/cm}^2 \tag{2}$$

where H is measured by the Canadian hardness gage, and ρ is bulk density (g/cm³).

KINOSITA (1960) has proposed the following relationship on the dry fine grained compact snow of 0.07 to 0.47 g/cm³ in density and at 0°C to $-9°C$ in temperature:

$$H=100\rho^{4}\ \text{kg/cm}^2 \tag{3}$$

where H is measured by the Kinosita's hardness gage.

WAKAHAMA and others (1969) have obtained the following relationship on the wet firn snow of 0.3 to 0.75 g/cm³ in density and at 0°C in temperature:

$$H=700\rho^{7}\ \text{kg/cm}^2 \tag{4}$$

where H is measured by the Kinosita's hardness gage.

The relationship, eq. (2), which is obtained in this study, is not comparable with eq. (3) or eq. (4), since there are differences between eq. (2) and eq. (3) or eq. (4) in both temperature condition and method of hardness measurement.

5.3. Detailed stratigraphy and density profile on the upper 1 m of a core

The results of a detailed stratigraphic analysis on the upper 1 m of a core are shown in Fig. 8. The layers of wind crust and the boundaries of snow strata are indicated in a central column of Fig. 8 by solid and broken lines, respectively.

The vertical profile of density, ρ_m, measured at intervals of 1 mm on enlarged photographs is also shown in Fig. 8; the values of ρ_m are subjected to the method of the moving average over 9 pieces of ρ_m (*i, e*, the mean covering 9 mm). The mean of ρ_m roughly coincides with bulk density ρ_b, but in some layers it does not.

The standard deviation of differences between ρ_b and ρ_m, which has not been subjected to the moving average, was calculated over the 720 pieces of data, given as 0.077 g/cm³; the arithmetical mean value of differences was 0.009 g/cm³.

5.4. Distribution of specific surface

The vertical distribution of specific surface (cm²/cm³) is shown in Fig. 8. Each value of specific surface was obtained from measurements in an area covering 5.27 cm² on a vertical cross section of the firn core. To obtain values of specific surface approximating to the real ones, NARITA (1971) has studied many types of snow, coming to suggest such optimum values of d and L that are shown in Table 1: as to d, the suggested value shows the maximum optimum value to be taken; as to

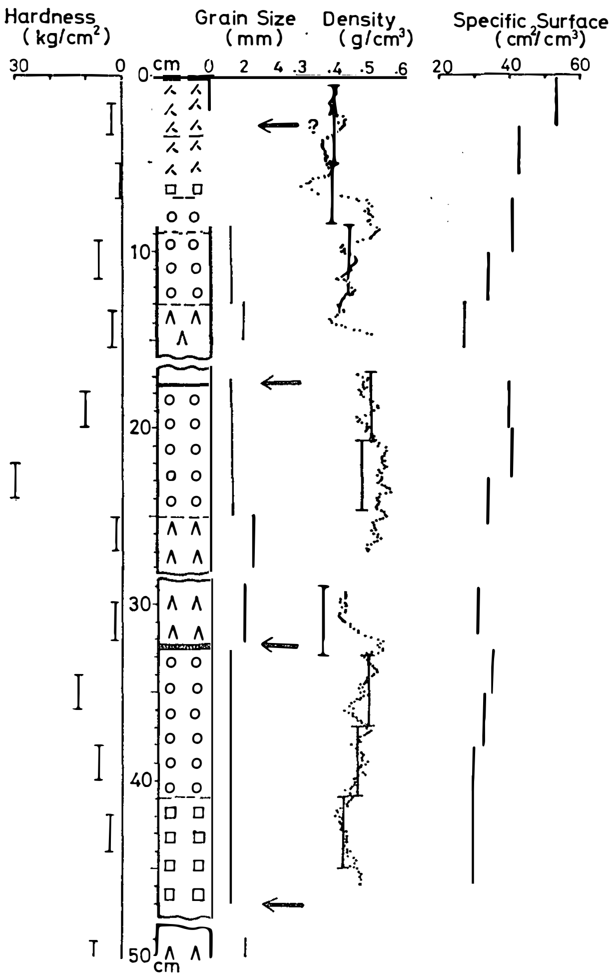

Fig. 8 (a)

Figs. 8 (a, b). Detailed stratigraphy, and profiles of density, specific surface, grain size, and hardness. At the central column, the types of snow particles are shown by the graphic symbols explained as follows:

(人人) *Very fine-grained compact snow which has just been metamorphosed from new snow without melting.*

(○○) *Fine-grained compact snow metamorphosed from the foregoing type of snow without melting.*

(□□) *Medium-grained depth hoar not developed well; sometimes corresponds to the solid type of depth hoar (AKITAYA, 1965, 1967).*

(/\/\) *Coarse-grained, well developed depth hoar; sometimes corresponds to the skeleton type of depth hoar (AKITAYA, 1965, 1967).*

The locations of wind crust layers and the boundaries of snow strata are shown by solid and broken lines, respectively. Annual boundaries of snow layers are indicated by the arrow marks at the right-hand side of the central column. The arrows with (?) are possible boundaries, and those without (?) are likely ones. At the density column, density obtained from enlarged photographs is shown by dots, and bulk density by solid lines.

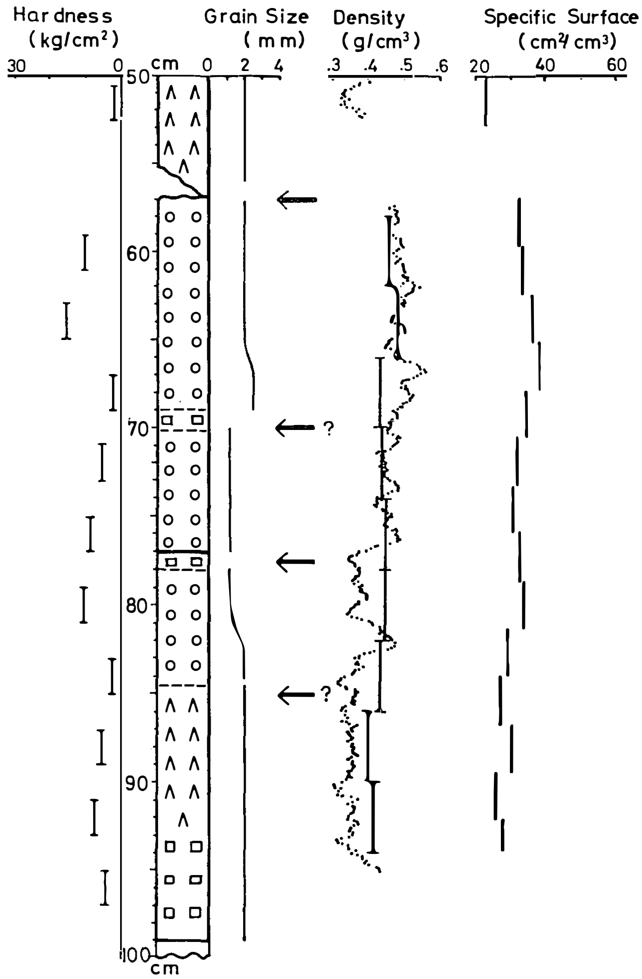

Fig. 8 (b)

L, the suggested value shows the minimum optimum value to be taken, where d (mm) is the interval of parallel lines and L (cm) is the total length of parallel lines. The values of d and L used by the authors to obtain the distribution of specific surface are 1.0 mm and 52.7 cm, respectively.

It is noticed in Fig. 8 that the value of specific surface tends to decrease slightly

Table 1. The optimum dimensions of d and L used to obtain specific surface by the method of calculating 2N/L.

	d (mm) (maximum)	L (cm) (minimum)
compact snow	1.2	23
depth hoar	1.0	62

(after NARITA, 1971)

with depth, namely, from 50 to 20 cm^2/cm^3.

The mean value of specific surface was given separately in the layers of compact snow and those of depth hoar, as follows:

Compact snow············36.5 cm^2/cm^3,

where $d=1.0$ mm, $L=965$ cm, A (the total surface area of a cross section) $=96.5$ cm^2, and N (the number of intersections) $=17,600$.

Depth hoar············28.3 cm^2/cm^3,

where $d=1.0$ mm, $L=386$ cm, $A=38.6$ cm^2 and $N=5,460$.

NARITA (1971) showed that the specific surface ranges from 5 to 75 cm^2/cm^3 for the different types of snow from 0.70 to 0.06 g/cm^3 in density. The values obtained by the authors lie midway between the maximum and the minimum values given by NARITA.

5.5. Estimate of the annual accumulation of snow

Generally speaking, summer layers are coarse-grained and are of low density and of low hardness; winter layers are fine-grained, rather homogeneous, of high density and of high hardness. GOW (1965) mentions that the autumn period seems to offer the greatest opportunity for the formation of depth hoar. By paying attention to such a cyclic seasonal variation in the properties of snow cover, the boundaries of annual layers are distinguished, as indicated by the arrow marks in Fig. 8. The arrow mark with (?) expresses a possible boundary, and that without (?) does a likely one.

From the thickness and density between annual layers (both possible and likely boundaries), the annual net accumulation of snow for the past 7 years was estimated as shown in Table 2. The snow accumulations measured by the stake method in 1968–70 are noted in Table 3 (FUJIWARA and ENDO, 1971; AGETA and WATANABE, 1972). The mean annual accumulation of snow for these two years obtained by

Table 2. The annual accumulation of snow estimated from firn stratigraphy.

Annual layers from present backward	Thickness of snow accumulation	Mean density	Snow accumulation in water equivalent
I	14.5 cm	0.43 g/cm^3	6.2 g/cm^2
II	15.0	0.46	6.9
III	14.5	0.44	6.4
IV	10.0	0.37	3.7
V	13.0	0.47	6.1
VI	7.0	0.45	3.2
VII	8.0	0.44	3.5
Mean of 7 years	11.7 cm	0.44 g/cm^3	5.1 g/cm^2

Table 3. Snow accumulation at S 100 measured by the stake method (by JARE 9 and JARE 10).

Jan. '68 ~ Nov. '68	Nov. '68 ~ Jan. '69	Jan. '68 ~ Jan. '69
19.0 cm	−6.5 cm	12.5 cm

(After FUJIWARA and ENDO, 1971)

Feb. '69 ~ Nov. '69	Nov. '69 ~ Jan. '70	Feb. '69 ~ Jan. '70
18.0 cm	−4.0 cm	14.0 cm

(After AGETA and WATANABE, 1972)

stratigraphy amounted to 14.8 cm in thickness of snow (6.6 g/cm^2 in water equivalent), which agrees fairly well with the mean accumulation by the stake method, 13.3 cm (5.3 g/cm^2 in water equivalent).

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