Physical Properties and Internal Structure of Greenland Snow*

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Abstract

Physical properties of snow are strongly dependent on its structure. In order to study the correlation between the physical properties and internal structure of snow, various kinds of experiments were carried out at Site 2, near Thule, Greenland. At Site 2, a deep snow trench was excavated on the surface of the Ice Cap and many snow samples were obtained from the vertical walls of this trench. Measurements of elastic modulus, permeability of air, unconfined compression and creep test were made in connection with the internal structure of snow. One of the most characteristic properties of snow is age hardening caused by densification. Densification processes of snow were analyzed and discussed with reference to internal structure.

I. Introduction

In polar region, the deposited snow turns into firn without being subjected to thawing and finally into glacier ice with the lapse of the time. The densification of snow in polar regions can be considered to be a sintering process analogous to powder metallurgy. Snow particles join together and are transformed into a solid mass by reduction of the surface area and a decrease in air voids or pore space. Greenland is of particular interest in the study of such a transformation process from snow to ice. In 1954, at Site 2 Greenland, a huge pit (approximately 30 m deep) was excavated and then a deep drilling was carried out by CRREL in 1957 to obtain core samples of snow through the Ice Cap.

Since 1958, Ukichiro Nakaya conducted many measurements of the visco-elastic properties of snow and ice in the Greenland Ice Cap, and Daisuke Kuroiwa cooperated with him by making experimental apparatuses. Three papers were published by Nakaya as CRREL Report Nos. 46 (1959), 58 (1959) and 82 (1961). In the report No. 46, he showed that the elastic modulus of snow in Greenland changes linearly with its density in the range of 0.5 to 0.9, but it changes exponentially with the density in the range of 0.2 to 0.5, showing some dependences on the internal structure of snow. He reported, in papers Nos. 58 and 82, that the visco-elastic properties of artificially processed snow exhibits so-called age hardening, and the value of the elastic modulus of the processed snow approaches to that of naturally densified snow with time. Snow is a kind

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of dispersed system composed of two components, ice particles and air. The physical properties of snow may be dependent not only on density, but also on internal structure. The complexity and variety of physical properties of snow can not be understood without any information on its internal structure.

To date, many studies concerning the vertical distributions of various physical properties of Greenland snow have been made independently by various authors, but there have been few studies correlated closely with the observation of the internal structures of snow. In 1960, in order to obtain more precise information on the physical properties of Greenland snow, Nakaya attemped to measure the elastic modulus, unconfined compression strength, permeability of air, static compression, and density profile in connection with the internal structures of snow. The internal structures of snow were investigated microphotographically by making thin sections of snow samples. The main information which can be drawn from the thin sections is grain size distribution, two dimensional porosity, pore size, and length of peripheries of pores and so on. In this paper, the profiles of the above mentioned properties of snow are analyzed and discussed with reference to the internal structures. When he returned to Japan from Greenland in the summer of 1960, he fell a victim to a severe disease and passed away in 1962 before he could begin to organize his data. This report was prepared by Kuroiwa to present the late Dr. Nakaya's work for many scientists who have interest in Greenland snow; thus Kuroiwa assumes full responsibilities in the organization of this paper.

II. Experimental Methods

Elastic modulus

Elastic modulus of snow was measured by a flexual vibration method. A snow sample was prepared in the shape of a rectangular bar. This was supported at the nodalpoints by two strings stretched horizontally. A small thin iron plate was frozen to each end of the bar, and two coils (one an exciter, the other a pick up) were placed just below each plate. An ordinary CR oscillator was connected to the exciting coil through an amplifier. When the A.C. frequency matches the proper vibrational frequency of a sample of snow, a resonance took place, and the induced current in the pick up coil became maximum. From the resonance frequency f thus measured, Young's modulus E is computed by the equation,

$$E = \frac{48\pi^2 l^4 \rho f^2}{m^4 h^2},$$

where the l is the length of the bar, h the thickness, ρ the density of snow. The value of m, an abstract number, is 4.730 for fundamental tone. Details of this method are given in literature No. 4 by Kuroiwa (1965).

Unconfined compression strength

Unconfined compression strength (crushing strength) of snow was measured by an ordinary testing machine. A sample of snow, cut in the shape of cylinder, was placed between a solid stage and movable plate and compressed with a constant speed until a visible fracture took place through the sample. When crushing occurred, the compression was stopped and the maximum stress required for crushing was recorded.

Air permeability

Air permeability of snow was measured by CRREL type permeameter developed by Bender (1957). Air permeability is defined by the average flow velocity of air through a snow sample under the unit gradient of air pressure. All observed data of the air permeability were converted to those at normal sea level, because the approximate altitude of Site 2 was 2 100 m.

Static compression

Cylindrical snow samples, approximately 6 cm in diameter and 15 cm in length, were cut and compressed statically under a constant load to observe how the snow structure changes with time and applied stresses. The compression was conducted in the under snow laboratory at Site 2 for various time intervals and loads. The change of internal structure was compared by thin sections before and after the compression.

Observation of internal structure of snow

The thin section of snow was prepared by a new method developed by Kinosita and Wakahama (1959). A small block of snow was immersed in liquid aniline at a temperature of about −6°C. After few seconds, the air space in snow was filled with liquid aniline. When it was cooled down to approximately −20°C, the liquid aniline solidified and the sample turned out to be a solid mass which allows the making of a thin section of snow without disturbing the internal structure of the original snow. In this state, the snow sample could be cut easily to a desired thickness by a microtome on the slide glass. When it was transfered to a warmer room maintained at about −6°C, the solid aniline began to melt and became transparent, showing a two dimensional configuration of snow. In order to observe grain size distribution and the mode of ice bonding, the thin section of snow should be made to about half of an average grain size in thickness. When the thickness of thin section was reduced to less than that of half of an average grain size, some grain and ice bondings were often lost. Therefore, in our experiment, the thickness of the most of thin sections were made within 0.3 to 0.6 mm.

Measurement of grain size distribution

Many microphotographs of thin section were taken by both ordinary and polarized light. The original microphotographs were enlarged in size up to 34.5 cm×27 cm to measure grain size distribution. The total magnification was 17 times of the thin section. The grain size of snow was measured on the enlarged photographs by the following procedures. It was very hard to make a precise measurement of the grain size because of its irregularity. Therefore, a transparent plastic plate on which many circles were depicted according to size from 2 to 40 mm in diameter was used. This plate was placed on the enlarged photographs of the thin sections, and one equivalent circle was selected among these circles in such a way that the area of the circle is equal to the cross sectional area of a snow grain. When an adequate circle was chozen from the circles, the diameter of this circle was defined as the size of snow grain. Thus approximately 300 to 600 grains were measured for one specimen and their diameters were classified for every 2 mm to obtain a frequency distribution curve of grain size.

Total length of peripheries of pores and two dimensional porosity

Apart from grain size, other information concerning internal structure which can be drawn from the thin section of snow, are total length of peripheries of pores and two dimentional porosity. Both factors may be useful to interpret structure dependences of physical properties of snow. The total length of the periphery of cross sectional area of pore in snow was measured on an enlarged photograph by tracing the periphery of pore with a kilbimeter. A kilbimeter is an surveying instrument used to measure distance between two points on a map. The two dimensional porosity of snow was measured by the following procedures. All cross sections of pores were traced precisely with a pencil on a white paper and they were cut with scissors. The total weight of these cuttings of pores were measured by a balance. The ratio of this weight against the weight of the original paper which is equal to the total area of the thin section, gives the percentage of the total cross sectional area of pores in snow, that is a two dimensional porosity. In our experiment, almost all thin sections were made fairly thick, because our main purpose was to observe grain size distribution of snow. Therefore, the value of two dimensional porosity measured from a thin section may be found to be less than that obtained from the bulk density of snow. If the thickness of thin section is too thick in comparison with the average grain size, the apparent value of two dimensional porosity may become zero. As the difference between both porosities may depend on the thickness of thin section and tortuosity of grains, we can derive a conception on tortuosity of snow grains from this difference. (Details on this problem will be given in reference 8.)

III. Experimental Results

Density profile

Many blocks of snow were cut out from the vertical wall of the snow pit every 30 cm from the surface to the bottom of the pit. Five samples were prepared from the same block of snow to measure density, Young's modulus, unconfined compression strength, air permeability, and internal structure. Since the depth of the pit was approximately 15 m, a boring was conducted to obtain deeper snow samples at a depth lower than the bottom of the pit.

Figure 1 shows a density profile of snow measured from the surface to 26 m in depth. All data, 148 in total, are distributed along a solid line A–A. The solid line A–A is the mean density obtained in 1954. It appears that there may be a wavy fluctuation in density as depicted by the broken line. A similar wavy fluctuation can be seen in the profiles of Young's modulus and air permeability as illustrated in Figs. 8 and 11. In Fig. 1, the broken line B–B shows the integrated overlying weight of snow expressed by the unit of kg/cm^2, and the estimated age of snow is given on the ordinate. The age of snow shown in this figure was reproduced from Fig. 46 of the reference 8. One can easily understand that the surface snow would reach to a depth of about 20 m, and to the densily 0.6 approximately 25 years later, from the time of accumulation. On the contrary, the already densified snow found at 20 m in depth would have been surface snow approximately 25 years ago. Thus densification of snow proceeds very slowly in

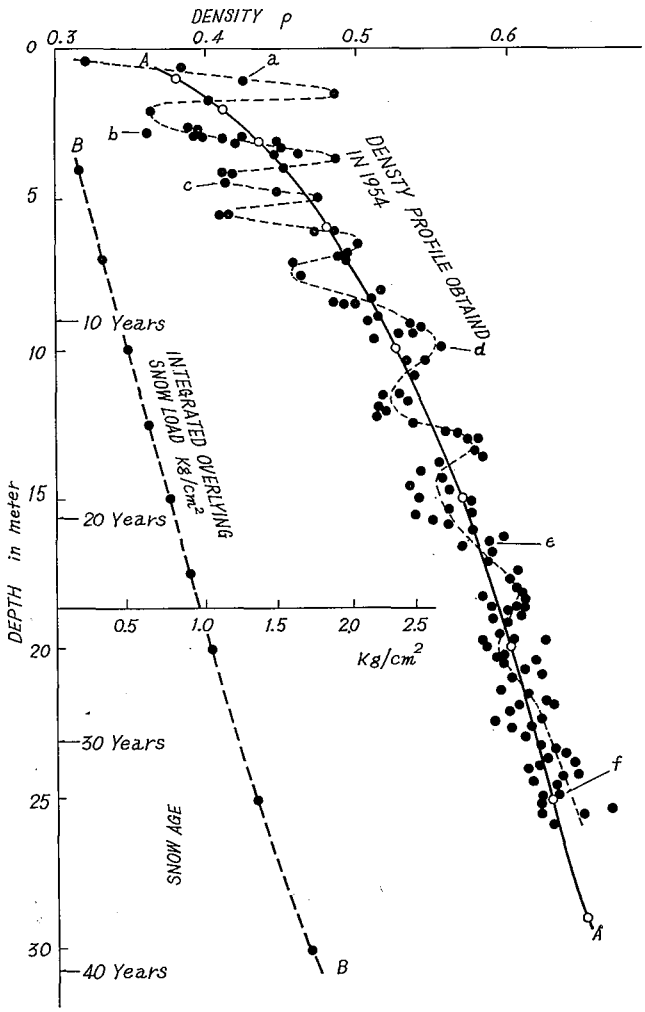

Fig. 1. Density profile at Site 2, Greenland

Greenland. From the age of snow, the annual precipitation of snow at Site 2 can be estimated as roughly 80 to 90 cm in depth. Therefore, the period of the wavy fluctuation of the density near the surface seems likely to be a seasonal variation, and the period becomes longer, and the deviation from the line A–A decreases gradually with depth.

Internal structures of typical snow samples

In order to investigate how the internal structure of snow changes continuously with the depth, approximately 80 thin sections were made from the surface to 26 m in depth and their microphotographs were taken. Typical microphotographs of the thin sections of snow obtained at various depths are show in Fig. 2 (a), (b), (c), (d), (e) and (f). The densities of these snow are indicated on the profile in Fig. 1 as (a), (b), (c), (d), (e) and (f). Figure 2 (a) shows a thin section of snow located at a depth of 1.1 m from the surface. The age of this snow may not be so old, but in all probability it may be

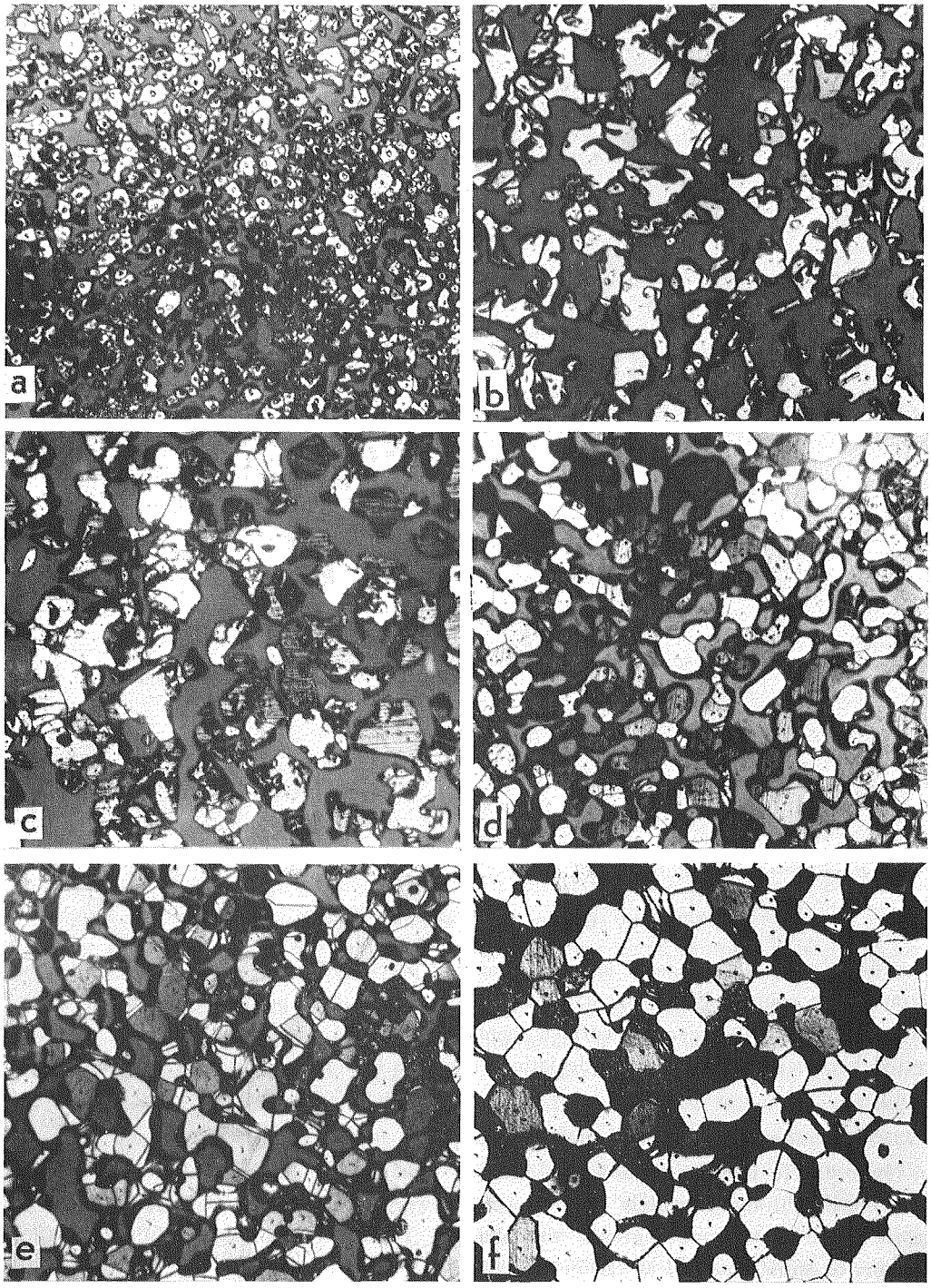

Fig. 2. Typical microphotographs of thin sections of Greenland snow. (× 4.7)

1 year or so. At first sight, one can easily understand that the average grain size of this snow is very small and homogeneous. The size of each grain (1 389 in total) was measured on the enlarged photograph of the thin section by the method described in the previous section, and its frequency distribution curve was made. In Fig. 3 (a), curve I represents the frequency distribution curve of the grain size of this snow. The ordinate is the frequency and the abscissa is the diameter of the grain of snow expressed in millimeter. As seen in this figure, the curve is very narrow and sharp, implying that the grain size of this snow is homogeneous. The maximum of this curve I is located at 0.3 mm in diameter. Curve II is the frequency distribution of the cross sectional area of grains. It is quite natural that the maximum of this curve shifted towards a larger grain size than that of curve I. The average diameter that gives the mode of frequency of cross sectional area is 0.4 mm. The cross sections of pores of the thin section were traced on a white paper, and they were cut out with scissors. The total weight of these cuttings of the pores were measured by a balance, and the ratio of this weight against the weight of the total area of the original paper was made. The value of this ratio, 0.245, is considered to be the two-dimensional porosity of this snow. Whereas since the actual density of this snow was 0.429, the three dementional or bulk porosity of this snow should be 0.535. Therefore, the two dimentional porosity observed from the thin section of this snow was found to be less than that of the bulk porosity. We shall discuss this problem later.

The length of peripheries of individual pore was measured on the enlarged photograph of the thin section by a kilbimeter. The total length of peripheries of pores which appeared in Fig. 2 (a) was 90.3 cm, and the total area of the original thin section was 3.26 cm^2. If we denote the length of peripheries of pores per unit area of this thin section as L, L becomes 27.7 cm/cm^2.

The total number of grains measured, N, two dimensional porosity, ε, the length of peripheries of pores per unit area of thin section, L, density, ρ, and depth, D, are given in Fig. 3 (a).

Figure 2 (b) shows the thin section of snow located at a depth of 2.76 m from the surface. This snow seems to be depth hoars. The density of this snow is shown by b in Fig. 1. Though this snow is deeper than the snow of Fig. 2 (a), its density was small and a more spacious structure could be seen. Curves I and II in Fig. 3 (b) show the frequency distribution curves for grain size and for cross sectional area, respectively. The maxima of these two curves are found at larger grain size than those of Fig. 3 (a). This means that the mode of grain size was increased from 0.3 to 0.4 mm as a result of metamorphism, and the shape of the curve become more broader than (a). The maximum of curve II also shifted from 0.4 to 0.8 mm. In the case of this snow, the total number of grains measured to depict frequency curves was 696, and the observed two dimensional porosity was 0.410.

The length of peripheries of pores became smaller than that of snow shown in Fig. 2 (a). The numerical values of these factors are given in Fig. 3 (b).

Figure 2 (c), is the thin section of snow located at a depth of 4.51 m below the surface, and its density was 0.41 as shown by c on the profile of Fig. 1. The grain size and internal configuration of this snow are quite different from those of snow samples

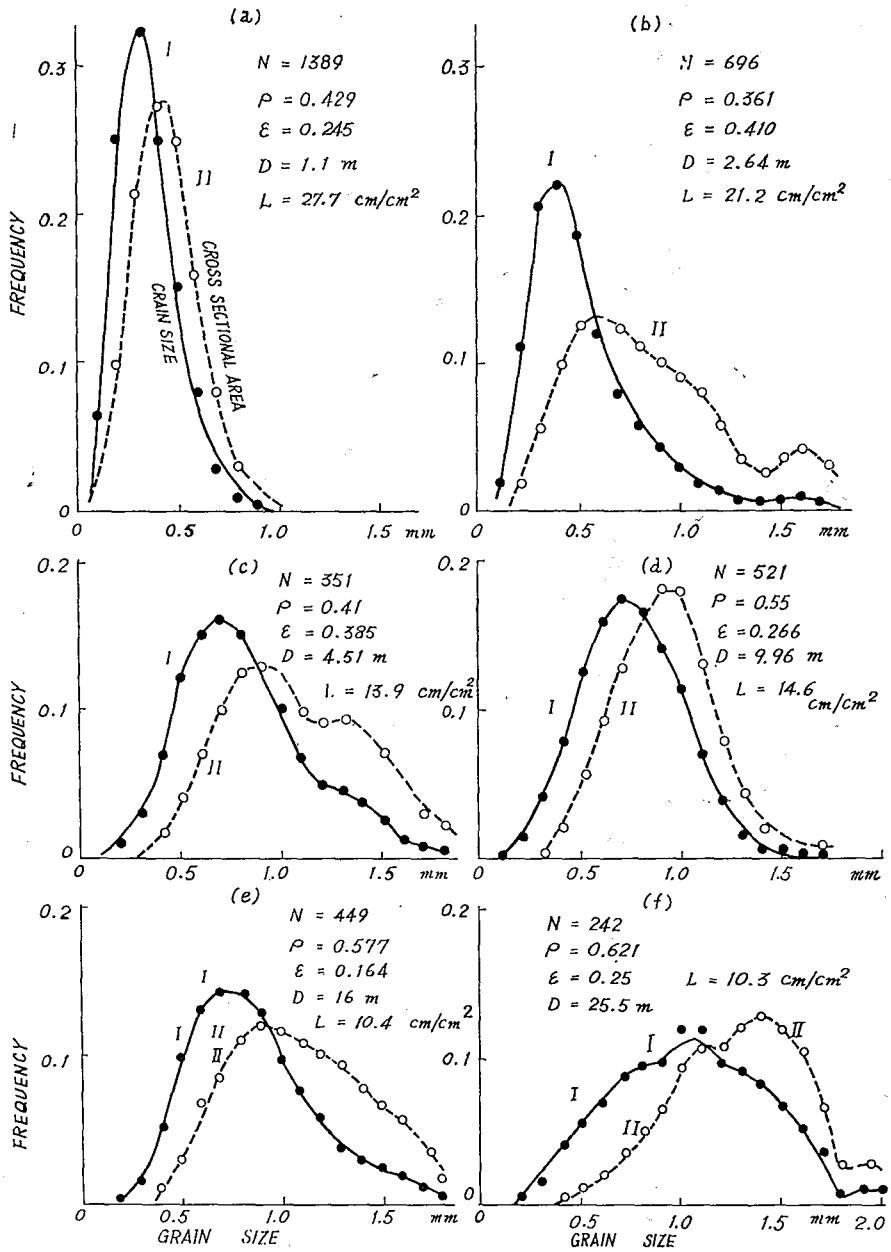

Fig. 3. Frequency distribution curves for grain size (I) and cross sectional area (II) of snow located at various depths

shown in Figs. 2 (a) and (b). As seen in the two frequency curves depicted in Fig. 3 (c), the average grain size, the maxima of curve I and II, become larger than those of Figs. 3 (a) and (b). Various numerical values obtained from the thin section of this snow are given in Fig. 3 (c).

Figures 2 (d), (e) and (f) are the thin sections of snow located at the depths of

9.96, 16 and 25.5 m from the surface. The estimated ages of these snow were approximately 11, 20 and 33 years old, respectively. The densities of these snow are shown as (d), (e) and (f) on the profile of Fig. 1. As seen in these pictures of thin sections, the densification process is quite clear, the average grain size becomes large gradually and the shape of grain becomes rounded with the increasing depth. Pore spaces also decrease with depth and they tend to spherical air bubbles enclosed within grains. All grains join together tightly and form strong net works. The frequency distribution curves for grain size and cross sectional area of grains are illustrated in Figs. 3 (d), (e) and (f). If we compare again curves in (f) with those of (a), one can understand easily how the average grain size of snow developed with increasing depth.

Profile of average grain size

In Fig. 4, curve I and II show changes of the grain size of snow with depth. The solid and open circles represent the grain size measured from the maximum of each frequency curve for grain size or cross sectional area of grains. They are distributed along both curves I and II, implying that grain growth or coarsening of snow takes place gradually with the increasing depth. According to curve I, the grain size of snow

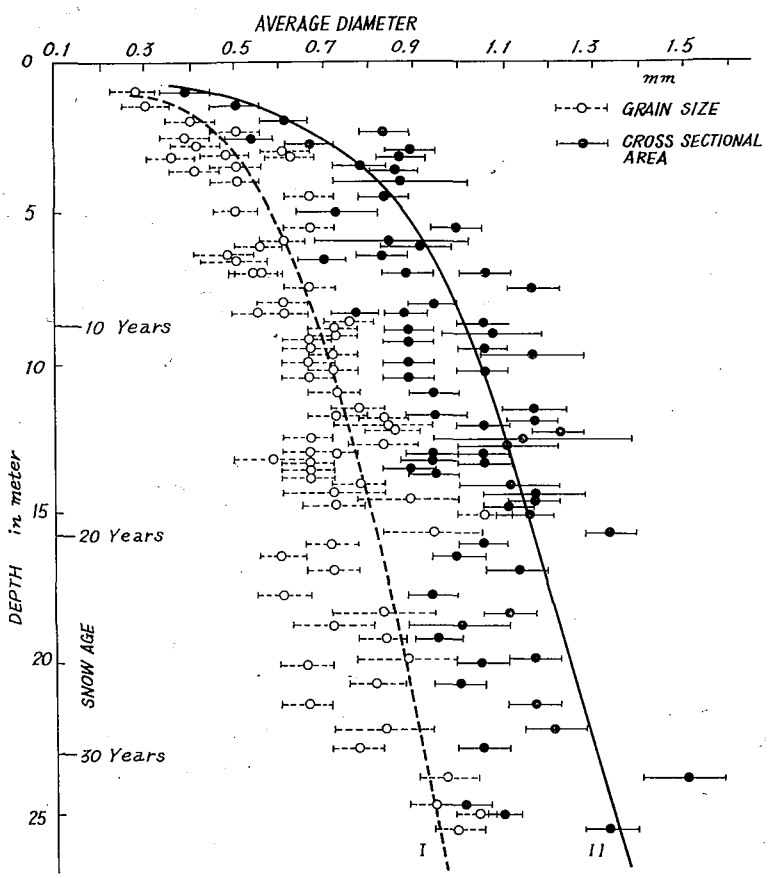

Fig. 4. Profile of the maximum value of grain-size distribution curves

near the surface was about 0.3 mm, but it grew to approximately 1.0 mm at a depth of 25 m below the surface. Figure 5 illustrates the logarithmic plot of these two curves against depth and snow age. As seen in this figure, these two curves I and II bend sharply at approximately 3 m in depth, showing that the rate of grain growth or coarsening in snow layers near the surface is different from that in deep layers. This suggests that the mechanism which causes grain coarsening near the surface may differ from that in deep layers. In this figure, curve A shows the overlying snow load (kg/cm^2) against depth. The overlying snow load increases with depth, but it is not so large within snow layers from the surface to 3 m in depth. Therefore, the overlying snow load may not be amenable for grain coarsening within the shallow layers, but diurnal or seasonal temperature variation may be responsible for grain growth in snow layers near the surface. The grain coarsening may be caused by vapor transfer from grain to grain. However, in deep layers of snow, the coarsening may be developed mainly by the overlying snow load. As seen in curve A, the overlying snow load increases gradually from 0.1 to 1.6 kg/cm^2 between 3 to 30 m in depth, but these values would not be enough to cause rapid coarsening of snow grains. It may be added that the mean temperature of snow is very low in Greenland. Therefore, the rate of coarsening in deep layers

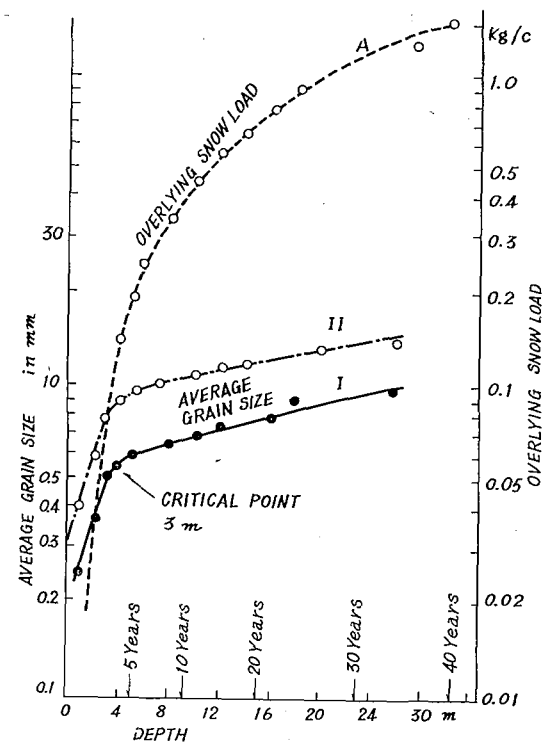

Fig. 5. Logarithmic plots of the average grain size and overlying snow load

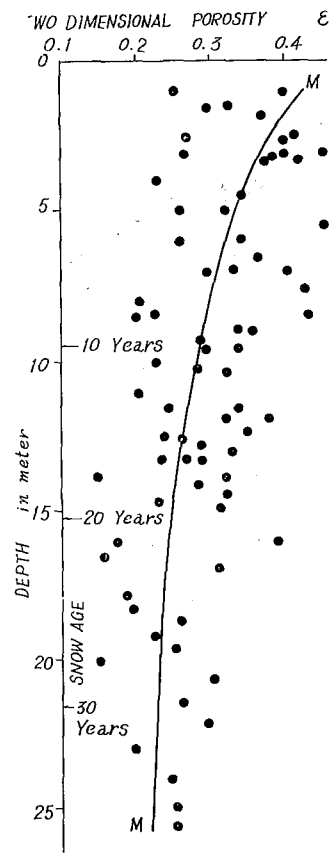

Fig. 6. Two dimensional porosity and depth

may become slow.

Profiles of two dimensional porosity and total length of peripheries of pores

Figure 6 depicts the vertical distribution of the two dimensional porosity, ε obtained by weighing the pieces of paper cut in the shape of pores of thin section. All data are widely scattered around curve M–M, but they tend to decrease with depth. A similar tendency is also seen in the profile of total length of peripheries of pores L as shown in Fig. 7. The value of L is large in the snow layers near the surface (young snow), because the average grain size is small and shapes of grains are irregular. However, L tends to decrease with increasing depth and age of snow. The decrease of both ε and L with depth means that snow densifies gradually by a reduction in size and in surface areas of pores.

A question arises as to why the observed data of ε and L were so widely scattered as seen in Figs. 6 and 7. The main reason of the scattering may be caused by the difference of thickness of thin sections used. In our experiment, most of thin sections were made to observe grain size distribution and internal configuration of snow. Therefore, the thin sections were prepared in such a way that their thickness would not have been less than half of the average grain size. In fact, the thickness of our thin section

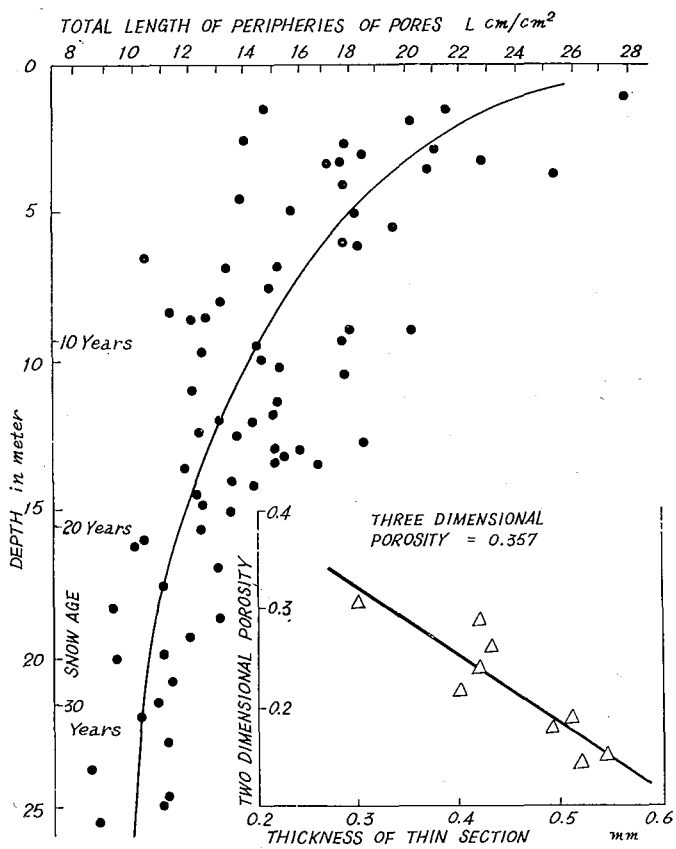

Fig. 7. Profile of total length of peripheries of pores

ranged within 0.27 to 0.65 mm. If pore spaces in snow are small and distributed homogeneously, the value of two dimensional porosity observed from thin section may be found to be equal to that of three dimensional porosity obtained from a bulk density. However, if the thickness of thin section is too thick, the two dimensional porosity must be apparently observed to be smaller than three dimensional porosity. In the lower part of Fig. 7, it is shown that how apparent two dimensional porosity changes as a function of thickness of thin section. In this figure, data obtained from various samples having approximately the same bulk density were plotted. The main reason of the wide scattering of the values of ε and L may be attributed to the variety in thickness of thin section used. It is obvious that the difference between both two- and three-dimensional porosities depends upon thickness of thin section and tortuosity of snow grains. We can derive a conception concerning the tortuosity of snow grains from the difference of these two porosities, but detailed discussion will be found in reference 8.

Vertical distribution of Young's modulus

Figure 8 depicts a profile of Young's modulus measured by the flexual vibration method. All data are distributed around a curve A–A, showing a tendency of gradual increase of Young's modulus with depth. A wavy fluctuation of Young's modulus can be seen as shown by a broken line. This wavy fluctuation is very similar to that of

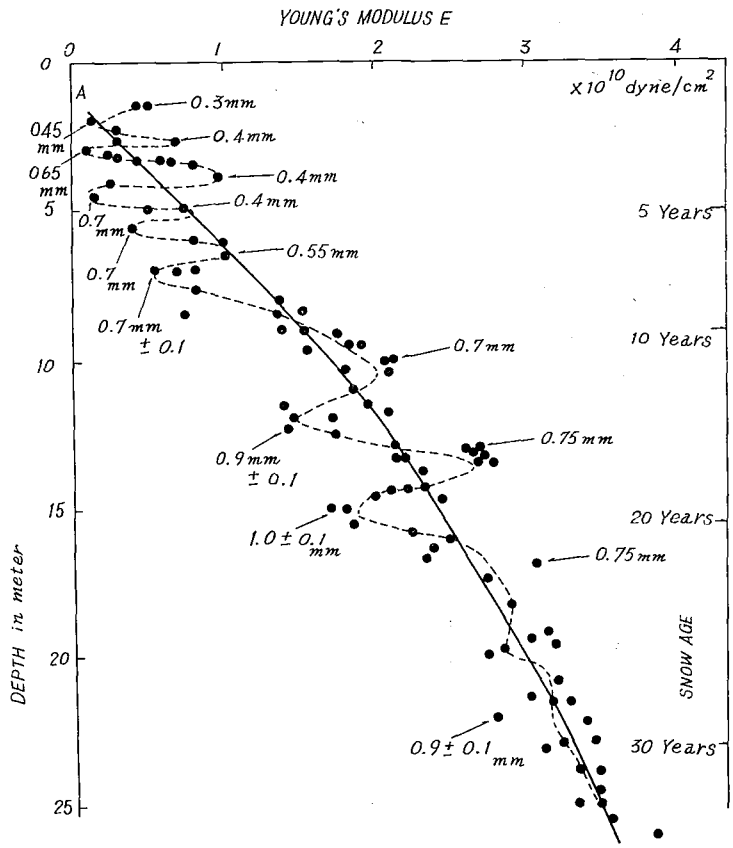

Fig. 8. Profile of Young's modulus

the density profile as illustrated in Fig. 1. It appears that there may be a parallelism between both profiles. In Fig. 8, the numerical values of the average grain size measured from the thin sections were given at every maximum and minimum of the wavy curve. As seen in this figure, the value of grain size given to each maximum is always smaller than those given to two adjacent minima. From the parallelism between the profiles of density and Young's modulus, it may be reasonable to expect that the snow located at minima of the density profile has a larger grain size than those of snows located at

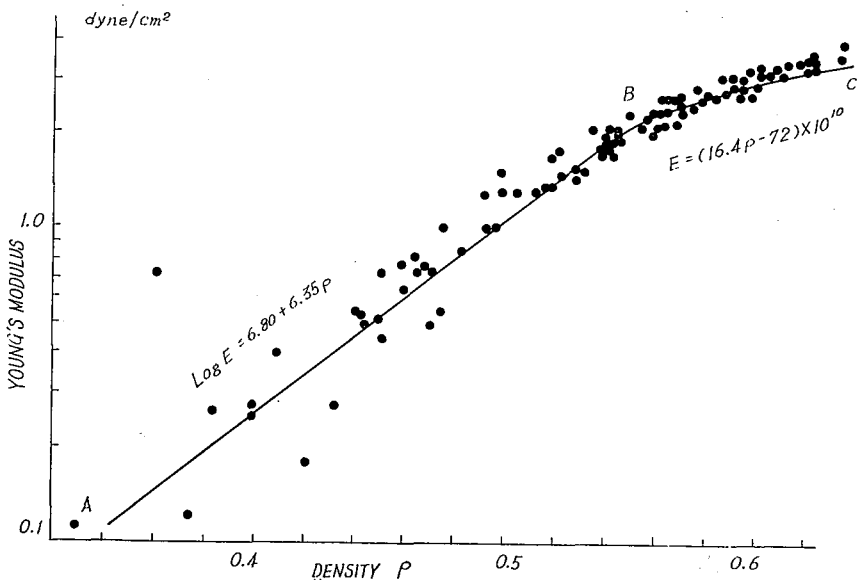

Fig. 9. Correlation between Young's modulus and density

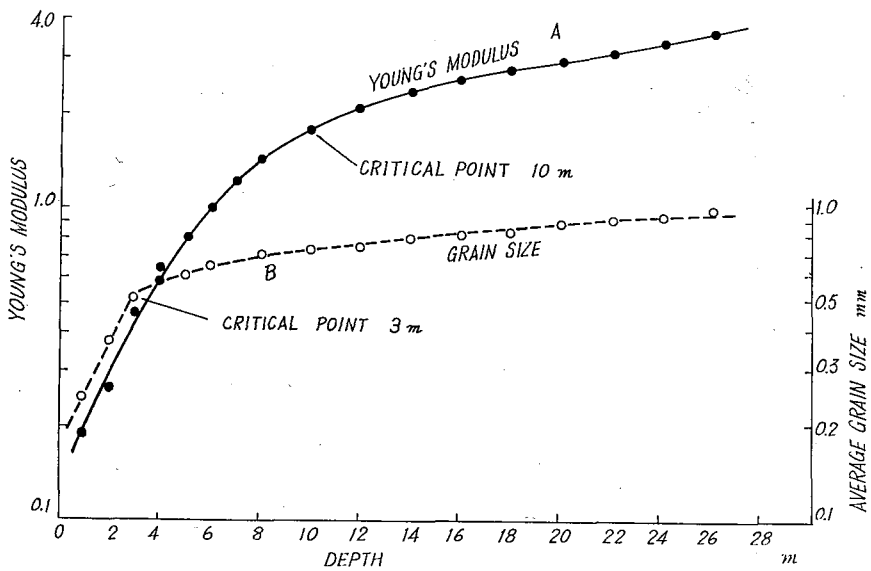

Fig. 10. Correlation between Young's modulus, grain size and depth

adjacent two maxima. In other words, the average grain size of relatively low-density snow is larger than that of relatively high-density snow. As may be seen in Fig. 8, the distance from maximum to maximum or minimum to minimum on the wavy curve of Young's modulus is approximately 80 to 90 cm, and it may be roughly equal to the annual precipitation in Site 2. Therefore, this wavy fluctuation of Young's modulus may be caused by the seasonal variation of temperature and snowfall. Figure 9 illustrates a correlation between Young's modulus and density. All data are distributed around a curve A–B–C obtained by Nakaya in 1959. It appears that there may be a critical point B at a density around 0.55 where the curve bends sharply. According to Nakaya, the correlation between Young's modulus and density of snow is given by

$$\log E = 6.8 + 6.35\rho \quad \text{(curve A–B)} \quad 0.25 < \rho < 0.5,$$

$$E = (16.4\rho - 7.25) \times 10^{10}\ \text{dyne/cm}^2 \quad \text{(curve B–C)} \quad 0.5 < \rho < 0.9.$$

In Fig. 10, the observed Young's modulus and grain size are plotted semi-logarithmically against depth. As seen in this figure, the curve of Young's modulus bends gradually around at 10 m in depth, while the profile of grain size bends sharply around at 3 m in

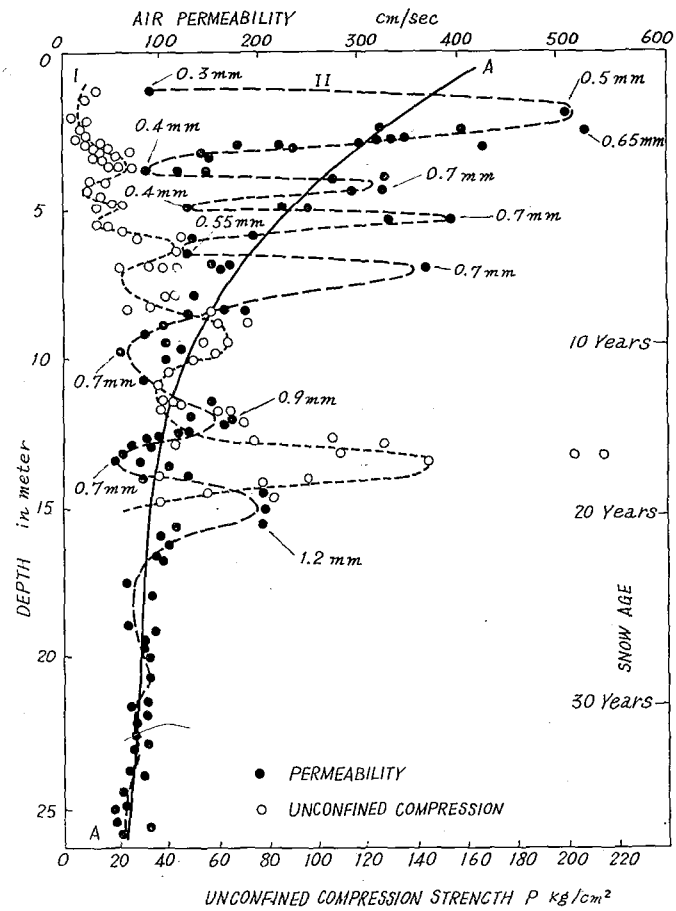

Fig. 11. Inverse correlation between profiles of air permeability and unconfined compression strength

depth. Anderson and Benson (1963) found that there may be a critical point at around 10 m depth in the density profile of polar snow or glacier. The coincidence between both critical depths of Young's modulus and density profiles seems to be quite reasonable, because a close correlation can be seen between both profiles. However, the critical depth for grain-size profile was found at around 3 m in depth. This suggests that the grain coarsening of snow near the surface may be accelerated by the annual temperature variation. Therefore, the critical depth for grain size profile does not coincide with that of Young's modulus or density profile.

Unconfined compression strength and permeability of air

Figure 11 shows profiles for strength of unconfined compression (open circles) and air permeability (solid circles). Though an unconfined compression test was not conducted for snow deeper than 15 m, some inverse correlation can be seen between both profiles as shown by the solid and the broken lines I and II. The snow which has a relatively high value of permeability seems to have a relatively low value of unconfined compression strength. Similar inverse correlation may be found between the profile of air permeability and obtained Young's modulus or density profile. The observed values of air permeability disperses widely around the curve A–A, showing a wavy fluctuation. If we give the numerical value of grain size to every maximum and minimum of the wavy curve of the permeability II, one can see that the relatively high values of grain size are found on the maxima of the curve and relatively low values are found on the minima. This situation may be understandable, because the relatively low-density and large grained snow may have a higher value of air permeability and more spacious structure than snow having a high density and small grain size. The permeation of air through porous media, in general, is very complicate problem, it may depend not only porosity but also on internal structure such as grain size, grain configuration, and tortuosity of grains (detailed discussion will be given in reference 8).

Figure 12 illustrates a correlation between observed unconfined compression strength P (solid circles) and density of snow ρ. This relationship may be expressed by

$$P=1.82\times10^{-3}\exp(14.85\times\rho)\ \mathrm{kg/cm^2},$$

within the range of ρ 0.3 to 0.6. The values of P for highly densified snow obtained by

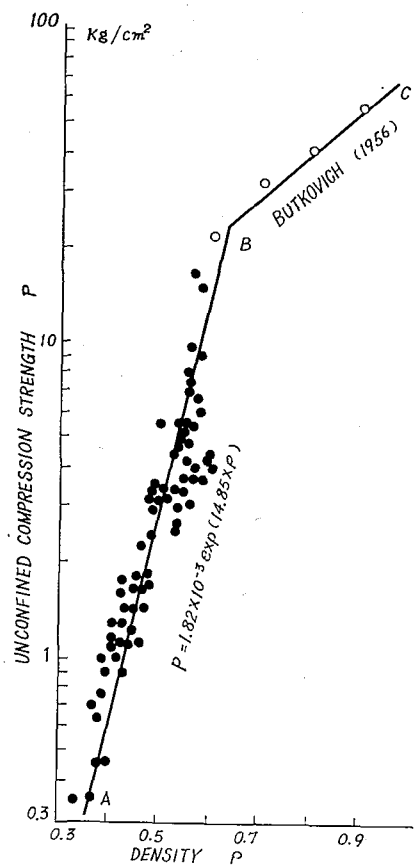

Fig. 12. Unconfined compression strength and density. Open circles show data obtained by Butkovich

Butkovitch (1956) are plotted by open circles. The open circles are distributed along another straight line B–C, showing a different slope with A–B. It appears that the critical point is found at the intersection of both straight lines. The value of density against this critical point is 0.6. As this value may be found at approximately 20 m depth on the profile shown in Fig. 1, the critical depth for unconfined compression strength can be considered to be 20 m. As shown in the previous section, the critical depth for Young's modulus profile was found around 10 m in depth. This difference, however, may not be substantial and may be attributed to the difference of experimental procedure used. Because, Young's modulus was measured by a non-destructive method, while the unconfined compression test was destructive.

Change of internal structure caused by static compression

In deep snow layers in Greenland, densification proceeds mainly by overlying snow load, because seasonal temperature variation does not exert any influence on deep snow. In order to examine how the internal structure of snow changes with time and applied stress, the following experimentation was conducted in the under snow laboratory at Site 2, Greenland. Three cylinders of snow, approximately 15 cm long and 6 cm in diameter, were cut out from the same block of snow, and a static compressive load (200 p.s. i=14.04 kg/cm^2) was applied to each snow cylinder at a temperature -12°C. After 1 hour and 35 minutes, 29 hours and 45 minutes, and 22 days, the applied load was removed from each cylinder, and a thin section was made to observe the change of internal structure before and after the compression. In Fig. 13 (A) illustrates the initial frequency distribution curve of grain size (I) and cross sectional area (II). The average grain size was 0.7 mm for curve I, and 0.9 mm for curve II. After 1 hour and 35 minutes load application, the frequency curves changed as shown in (B). A little broadening of the curves occurred, but very little difference in shape was observed. The initial length of this snow cylinder L was 15.1 cm, but it shrank to 12.55 cm after the compression. The total shrinkage was found to be $\Delta L/L_0=0.176$. The density was increased from 0.549 to 0.617. Figures 13 (C) and (D) show changes of the frequency curves after 29 hours and 45 minutes, and 22 days load application, respectively. As seen in this figure, the frequency curve became more and more broad and the values of maxima gradually decreased with time. The broadening of the frequency curve suggested that the grain coarsening developed with the lapse of time. It was observed from the thin sections of these cylinders that in the initial stage of the compression, after 1 hour and 35 minutes load application, the individual grains of snow were simply compacted in such a way that they were transfered into pore spaces. This is substantiated by the facts that the total number of grains N found in the same area (3.26 cm^2) of the thin sections was increased from 266 to 327 before and after the compression, and that the apparent density increased from 0.549 to 0.617 and the porosity decreased from 0.402 to 0.326. The value of 0.326 is very close to the minimum value of the porosity obtainable in ordinary packing experiments for various solid particles. However, after 29 hours and 45 minutes load application, predominant recrystallization was observed in the thin sections. After 22 days load application, a still higher densification and recrystallization developed, showing that almost all pores became spherical

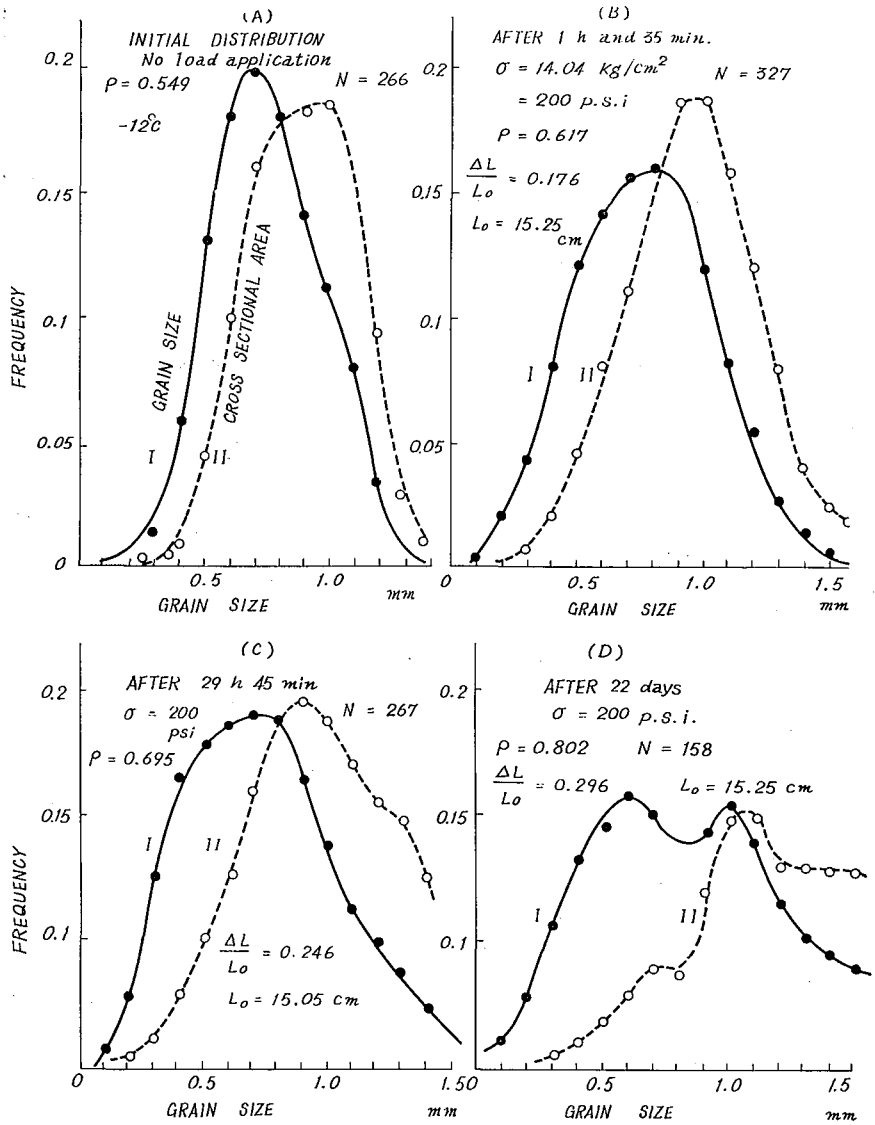

Fig. 13. Change of frequency distribution curves for grain size (I) and cross sectional area (II) caused by static compression

and were entrapped within grains. In this final stage of the compression, the apparent density became 0.8 and the porosity was extremely decreased.

Figure 14 illustrates the relation between shrinkage of the snow cylinder and time. The observation of shrinkage was begun immediately after the load application and stopped at after 29 hours and 45 minutes. As seen in this figure, the shrinkage curve is composed roughly of two straight lines AB and BC. The change of slope of this curve (the rate of shrinkage) suggests that the densification mechanism in the initial stage of the compression is different from that of the later stage.

If we use Nutting's expression for ordinary visco-elastic materials, shrinkage may

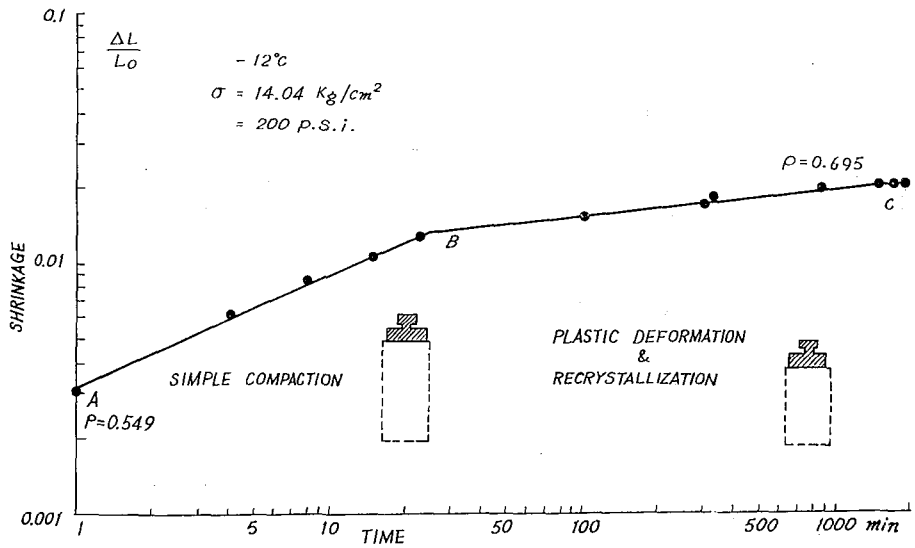

Fig. 14. Time dependence of shrinkage of snow cylinder

be expressed as the functions of applied stress σ and time t as follows:

Shrinkage $\Delta L/L_0 = \phi^{-1}\sigma^{\alpha}t^{\beta}$

where α and β are numerical constant. In this expression,

if $\left.\begin{array}{l}\alpha=1\\ \beta=1\end{array}\right\}$ ϕ means the coefficient of viscosity,

and

if $\left.\begin{array}{l}\alpha=1\\ \beta=0\end{array}\right\}$ ϕ means the elastic modulus.

In general, α and β are considered to be structure dependent constants of the material. From the slope of curve, β is found to be

$\beta = 0.472$ for the initial stage of the compression,

$\beta = 0.142$ for the later stage of the compression.

The decrease of the value of β with time means that the snow behaves in much the same manner as a viscous material in the initial stage of the compression, but it behaves like a more elastic in the later stage. According to observation of the thin sections, the densification proceeded mainly by the mechanical packing of grains in the initial stage of load application, but it developed by the plastic deformation and recrystallization of grains at the later stage of the compression. The creep mechanism of Greenland snow will be discussed in detail in connection with microscopic observation of thin section being compressed statically (see reference 8).

IV. Conclusions

The vertical distributions of physical properties of Greenland snow were revealed by a simultaneous investigation of thin sections of snow. Approximately 80 thin sections

of snow were made from the surface to 26 m in depth, and the average grain size, two dimensional porosity and total length of peripheries of pores were measured statistically. The aspects of the vertical distributions of density, Young's modulus, unconfined compression strength, and air permeability could be understood in connection with various information derived from the observations of the thin sections of snow.

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