The First Stage in the Change of Snow into Glacier Ice

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積雪から氷河への変化の初段階

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要　旨

南極大陸につもった雪は，長年月とけることなく，氷となって氷河にかわる．北海道の雪も冬はほとんどとけない．そして，冬のあいだに大きな変化をうけ，春とけさるころには，しまった固い雪になっている．それで，北海道の雪が冬のあいだにうける変化は，南極の雪が氷に変ってゆく過程のはじめの部分と多くの点で似ているにちがいない．この意味で，低温科学研究所で行なわれた北海道の雪についての研究結果は，南極の雪氷を研究するにあたって参考になると思う．これらの研究結果のうちから，次のものをえらび，簡単な説明を加える．

(1) 積雪の微細組織の変化．(2) 焼結現象．(3) 積雪全層の一般的変化．(4) 日射による積雪の内部融解．

The snow deposited on the Antarctic continent is transformed into glacier ice without melting due to the cold lasting through many years. No change of such a long period can be seen anywhere in Japan. The snow in this country does not keep more than one year. But, so far as only the first stage of the change in the Antarctic snow is concerned, the like is found in the snow of Hokkaido. The snow in Hokkaido undergoes great changes without melting in winter. Those changes must have many things in common with the early stage changes of the Antarctic snow. Therefore a description of the change occurring in the snow of Hokkaido will prove to be a help in understanding how the snow in the Antarctic begins its change into glacier ice. The research men of the Institute of Low Temperature Science have been making studies on Hokkaido snow. Some of their findings will be described in the following.

The change in the microscopic texture of snow

Fig. 1(a) shows the microscopic texture of soft snow one day after it was deposited. The crystals composing this snow are irregular in shape with many frozen droplets. In the photograph the crystals are seen to have joined one another at their tips while they had lain on the ground for one day. This microphotograph as well as the ones which will be shown below were made on thin sections. The sections were prepared in the following way. A small sample of snow was dipped in liquid aniline at −5°C. The liquid filled up the spaces in the snow. The sample was cooled down to −20°C with the liquid aniline solidifying. In this rigid state the sample of snow could be

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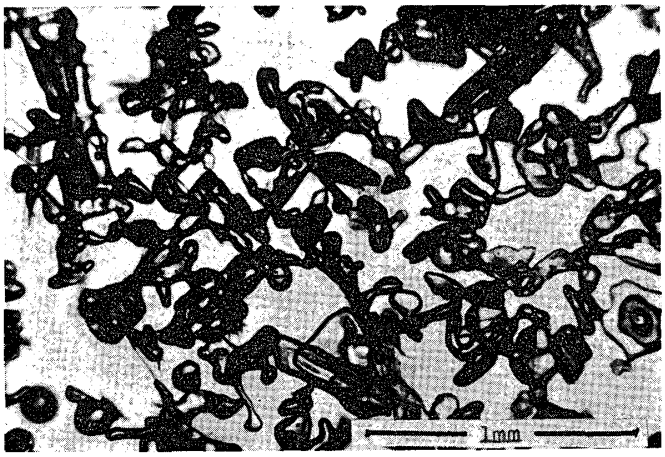
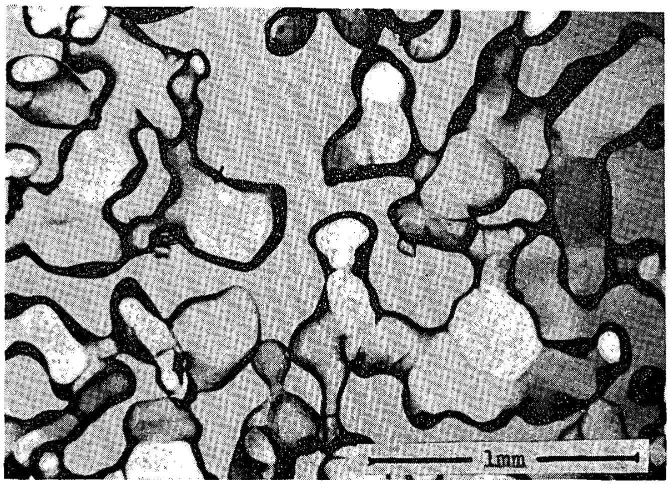


(a)



(b)

Fig. 1.

cut with a carpenter's plane into a section as thin as one-hundredth of one millimeter. After the time of Fig. 1(a) the ice elements composing the snow kept thickening, joining one another more strongly and after 30 days had the appearance shown in Fig. 1(b). In this state the texture of the snow may be said to be a three dimensional network of ice. The photograph of Fig. 1(b) was taken through a polarising microscope. The ice network appears to be divided into many regions of different colours. (In the black and white photograph here the differences in colour are indicated by different grades of shadow.) Each of the regions represents a single crystal of ice. The orientation of its crystallographic axes was determined with the aid of a universal stage and with the aid of etch pits made on the surface of the crystal. It may be expected that the directions of the axes of the ice crystals thus found will be useful in making clear in what way the snow changes its texture as time goes on.

The ice network was found not to be uniformly connected when looked at under smaller magnification. It is divided by weak lines into domains within which the ice elements are strongly connected. Across the weak lines the ice bonds are very few in number. The weak lines are illustrated in Fig. 2 by thick black lines.

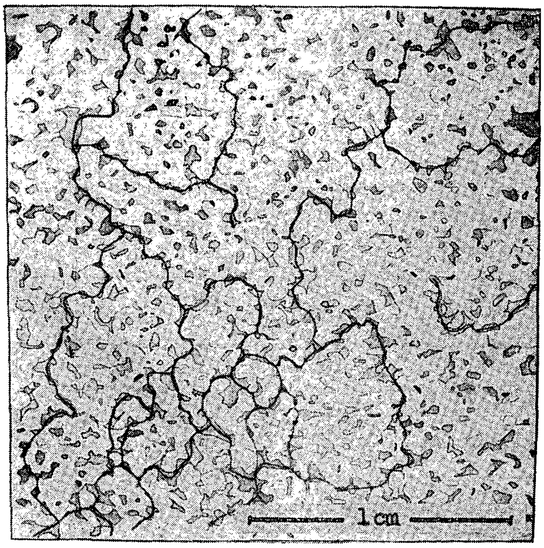


Fig. 2.

The phenomenon of sintering

The small particles composing clay, when burnt, unite themselves without melting to make ceramics. That phenomenon of sintering seems to have a close connection with the development of the above described ice network of snow. Ice grains produced by rubbing one block of snow against another were put in a box and left at a temperature below 0°C. The grains united themselves to make a strong block of snow indicating that they were joined by ice bonds. At intervals of a few days thin sections were cut out of the block and the diameter of the ice bonds was measured on them under a microscope. It was found that the bonds thickened as time went on in the manner predicted by the theory of sintering. Generally the phenomenon of sintering is studied by letting two small spheres or a sphere and a plane join together. Experiments of that sort were also made with ice. The photograph in Fig. 3 shows the joint made between an ice sphere and an ice plane. They were cut through vertically by means of the aniline method to show the joint clearly.

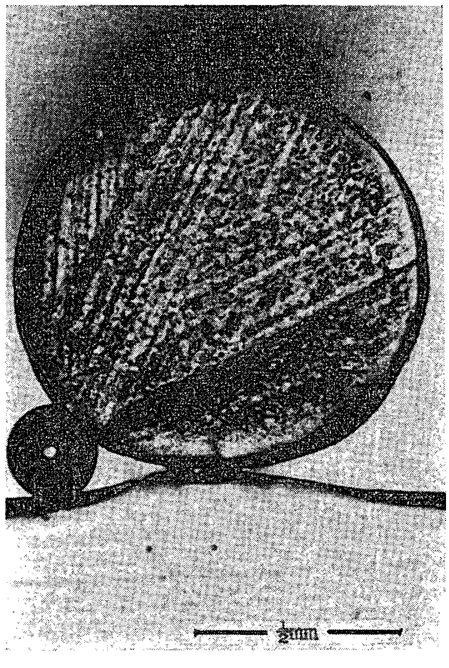


Fig. 3.

The contraction of snow layers composing a snow cover

A snow cover increases in thickness due to the layer by layer accumulation of the falling snow. But each of the snow layers composing the snow cover contracts under the weight of snow layers overlying it. After many observations on the contraction of snow layers a formula was found which relates the density ρ of a snow layer to the coefficient η of its contractive viscosity. Both ρ and η increase with time, keeping the relationship

$$\eta = \eta_0 e^{k\rho}$$

between them. Here k is a constant having the value 21.0 cm^3/gr common to all snow layers. η_0 is different from one snow layer to another within the range 0.6～1.6 gr-wt·day/cm^2, although it is a constant always for one and the same snow layer.

When the rate of accumulation of the falling snow is known, the increasing rate of the thickness of the snow cover as well as the degree of contraction occurring in each of the snow layers can be calculated by means of the above formula. Let a case be imagined in which snow keeps falling constantly. The thick curve marked HS in Fig. 4 shows how the snow cover will thicken when snow falls at a constant rate of 0.7 gr/cm^2 day. Positions of the snow layers deposited every ten days are indicated by the thin lines. The broken curves with decimals such as 0.1, 0.2 are lines of the same density; the decimals denote the value of density in the unit of gr/cm^3. In an actual case snow never falls constantly. But, on the average, it can be considered to be deposited at a constant rate. In that sense such diagrams as shown in Fig. 4 represent the general features of the change occurring in the internal structure of a snow cover.

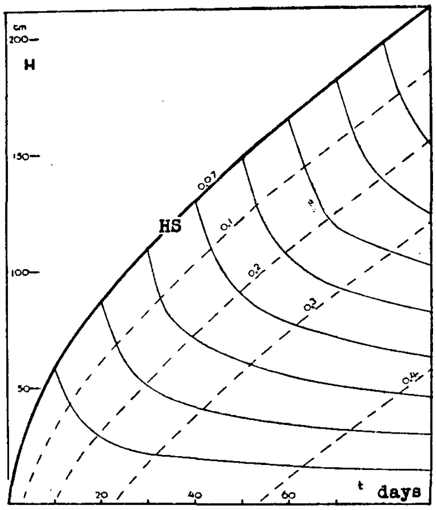


Fig. 4.

The internal melting of the snow cover by penetrating sunlight

Sunlight penetrates some distance into the snow cover and heats its inner layers. The poor conductivity of snow keeps the heat from escaping with the result that the inner layers sometimes melt even though the air temperature remains below 0°C. Under what conditions such an internal melting should occur can be predicted by the theory of heat conduction. Let u denote the temperature of snow, x the distance downwards from the snow surface, c the specific heat of ice, k the heat conductivity of snow. The intensity of the penetrating sunlight decreases with x in proportion to $e^{-\alpha x}$. The heat evolved in a unit time in a unit volume of snow is then given by $Ae^{-\alpha x}$, where A represents $\alpha(1-r)I_0$, I_0 and r being the intensity of the original sunlight and the albedo of the snow surface respectively. With those notations the equation of heat conduction is written as

$$c\rho\frac{\partial u}{\partial t}=k\frac{\partial^2 u}{\partial x^2}+Ae^{-\alpha x}.$$

The change of variables $\frac{\alpha^2 k}{A}u\to v$, $\alpha x\to\xi$, $\frac{\alpha^2 k}{c\rho}t\to\tau$ turns the above equation into a simpler one

$$\frac{\partial v}{\partial \tau}=\frac{\partial^2 v}{\partial \xi^2}+e^{-\xi}.$$

Under the conditions that $(v)_{\tau=0}=0$ and $(v)_{\xi=0}=0$, the solution is known to be

$$v=(1-e^{-\xi})-\Phi(\xi/2\sqrt{\tau})+(e^{\tau-\xi}/2)\{1-\Phi(\sqrt{\tau}-\xi/2\sqrt{\tau})\}$$
$$-(e^{\tau+\xi}/2)\{1-\Phi(\sqrt{\tau}+\xi/2\sqrt{\tau})\},$$

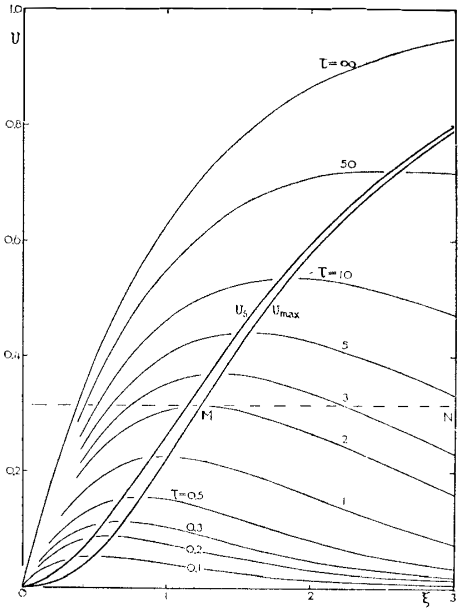


Fig. 5.

where Φ represents the error integral. In Fig. 5, v is plotted against ξ for different values of τ. The zero of v means the initial temperature of snow which is below 0°C. Let, for instance, the melting point of ice (0°C) be at the height of the horizontal broken line in Fig. 5. Then the snow reaches the melting point at point M for the first time at $\tau=2$ after the sunlight has begun to penetrate. After that the snow melts both upwards and downwards with the level of M as the center. The curve marked v_{max} runs through the maximum points of $v-\xi$ curves. Point M lies upon it. This shows that the lower the temperature of snow initially is, the more time is needed for the snow to begin melting and the deeper the level lies where the melting begins. (A numerical example: for $I_0=50$ cal/cm^2·hr, $\rho=0.35$ gr/cc and the initial temperature of snow$=-4.3$°C, snow begins to melt at the level 2 cm below its surface 23 min after the penetration of sunlight.) The internal melting enhances the change which should occur to the texture of the snow. It may play some role also in developing the *puddles* on the Antarctic snow fields.