Studies on Depth Hoar*

By

Eizi AKITAYA
秋田谷 英次
The Institute of Low Temperature Science

Received December 1973

Abstract

A series of experiments were carried out on growing depth hoar in our laboratory and observations made on depth hoar in a natural snow cover. Depth hoar crystals grew in snow when the snow was subjected to a consistent negative temperature gradient for a considerably long period. Depth hoar crystals were classified into the two types: skeleton type and solid type.

Growth conditions of depth hoar crystals were studied in connection with the snow temperature, magnitude of negative temperature gradient, and size of an air space in snow. A description was given as to mechanical properties of depth hoar, change of hardness of snow as a result of the development of depth hoar, and relations between the density and hardness of depth hoar.

Finally, a possibility of occurrence of natural convection of air in a natural snow cover was studied by making use of heat flow measurement.

Contents

* Contribution No. 1294 from the Institute of Low Temperature Science.
北海道大学審査学位論文

I. Introduction

A snow cover has a layer structure, as a rule, according to the serial deposition of snowfalls. The original textures and properties of each layer are determined by "snowfall conditions": the amount and intensity of a snowfall, crystal shapes of the snow, air temperature, wind and other weather factors. The textures and properties of the snow layer are changed by metamorphism according to physical conditions (thermal and mechanical conditions caused by climatic and geographical factors) to which the layer has been subjected.

In 1858, an Englishman, J. Wolley, discovered a hoar crystal layer from a deep level in a snow cover in Lapland; he preferred to use it for making water to a lighter and fluffier surface snow. Reports on hoar layers in a snow cover were presented by E. Nordenskjold (1883) and other explorers (1885–1910) to Antarctica and Greenland.

Paulcke (1934) found the same hoar crystal layer as this in the Alps, and made precise observations of the shapes of hoar crystals, namely: hollow prism, solid six-sided plate, six-sided prism terminated by a pyramid and a basal plane, and six-sided prism closed at the top by a pyramid. He named the snow consisting of these crystals "Tiefenreif" or "Schwimmschnee", and warned that the development of the Schwimmschnee in a snow cover on a slope tended to increase avalanche hazard.

Seligman (1934) selected the name "depth hoar" for each crystal or an aggregate of these crystals in contrast with "surface hoar", and studied its growth, properties and contributions to an avalanche release. Experimental studies on the development of depth hoar and its properties were carried out by Bader, de Quervain, LaChapelle and others.

In 1941 Kinoshita and Okawa introduced Paulcke's book entitled "Praktische Shnee und Lawinenkunde" to this country, where depth hoar had been unfamiliar to the people.

Hirata (1941) made the first report of depth hoar in Japan; he found depth hoar crystals in an alpine snow cover in Honshū, Japan. "Kawaki-Zarame Yuki" (Kawaki means dry, Zarame granular, and Yuki snow, in Japanese) by his classification of deposited snow seems to correspond to "Kornschnee" by Paulcke, and to "solid-type depth hoar" by the present author.

Saito (1945) studied deposited snow in Hokkaido, and observed the process of growth of depth hoar in a natural snow cover. He chose a Japanese name, "Shimo-Zarame Yuki" (Shimo means hoar), for the depth hoar. This name has been adopted as the official name of depth hoar in the classification of deposited snow by Japanese Society of Snow and Ice (1967).

Yosida and Kojima (1950) studied the process of growth of depth hoar under a microscope in a laboratory: a temperature gradient was applied horizontally to a specially prepared sample of the snow grains scattered on a fine silk net. They observed that a hoar crystal developed through the following process: at first, water evaporates sublimatically from a snow grain; then, its vapour migrates in an air space; finally, the vapour reaches and sublimatically condenses on the colder side of the snow grain neighboring the first one. On the basis of the laboratory study, they considered two types of mechanisms of water vapour migration in real snow when a negative temperature gradient* existed vertically in it: the one, a long distance migration of water vapour through narrow air channels in snow, and the other a chain of micromigration of water vapour from a grain to the neighboring grain. They concluded that the latter mechanism, which they named a "hand to hand" mechanism, must have predominantly contributed to the actual transference of water vapour and the formation of depth hoar crystals in real snow, as compared with the former mechanism.

Afterwards, Kojima (1956) studied some mechanical properties of depth hoar. He obtained a result that cup-shaped depth hoar was mechanically much stronger than fine grained compact snow against a static force, while it was extremely fragile against a dynamic force.

On April 2, 1961, a number of large ground avalanches broke out almost all over the mountain district of the southern Hidaka Mountain Range, Hokkaido, during a period of only half the day; one of them assaulted a workmen's house and killed 33 and injured 12 persons. Immediately after the accident, Yosida's group (1963) made observations of structure of snow covers in that area, and found that the avalanches were caused by the collapsing of a fragile depth hoar layer with a thickness of 20 cm at the bottom of the snow cover averaging 90 cm in thickness in this area. Since then, special attention has been paid to relations between the development of a fragile depth hoar layer in a snow cover and avalanche hazard, in this country.

Chapter II gives a description of the growth of a depth hoar crystal in a laboratory and in a natural snow cover together with the classification of depth hoar crystals. In Chapter III the growth conditions of a depth hoar crystal is experimentally studied in connection with the air space in snow, snow temperature, magnitude of temperature gradient and original snow types (textures). In Chapter IV some mechanical properties of depth hoar and hardening of snow by metamorphism under a negative temperature gradient are experimentally studied. Finally, in Chapter V the transference of water vapour in snow under a negative

* Let us define the sign of a temperature gradient as negative, if the higher is a level in a snow cover, the lower the temperature of snow.

temperature gradient is studied. The occurrence of natural convection of air in snow is experimentally observed by the use of heat flow measurement, and the result is applied to examine a possibility of occurrence of natural convection of air in a natural snow cover in Hokkaido.

II. Growth of depth hoar

II. 1. *Classical Classification of Deposited Snow in Japan*

The first classification of deposited snow in Japan was made by the Deposited Snow Research Committee, Ministry of Agriculture, in 1937, and was practically used for about 10 years. In 1946–1947, active discussions were made on the classification of deposited snow on the basis of an up-to-date and wider source of information, resulting in a revised classification. However, depth hoar was still not adopted properly in it because of the lack of information and researches.

Until 1967, when the present classification of deposited snow was completed by Japanese Society of Snow and Ice (see Section II. 4), the following broad classification was practically used by snow researchers in this country.

i. New snow: Newly deposited fresh snow. Metamorphism has scarcely progressed; the crystal shape of fallen snow reserved; density ranges 0.05–0.15 g/cm^3.

ii. Fine grained compact snow: Hard and sturdy snow with a fine and complicated network of ice bonds connecting snow grains, after metamorphism and natural densification progressed sufficiently; density ranges 0.25–0.5 g/cm^3. Lightly compact snow was occasionally defined as snow in a transitional process from new to fine grained compact snow.

iii. Coarse grained granular snow: By a wet metamorphism, snow turns into coarse grained granular snow.

II. 2. *Artificial Growth of Depth Hoar*

The mechanism of growth of depth hoar crystals in snow is considered as follows. When a snow layer is subjected to a consistent negative temperature gradient for a long period, the top surface of the lower (warmer) snow grain evaporates sublimatically, and water vapour migrates upward by diffusion (caused by a gradient of saturated water vapour pressure according to a temperature distribution) in an air space among snow grains, then condenses sublimatically on the bottom surface of the upper (colder) snow grain, making a hoar crystal.

With due consideration for the foregoing a series of experiments of artificial growth of depth hoar crystals were carried out in the laboratory.

(1) *Experimental Mothod*

An experimental device used for the artificial growth of depth hoar crystals in snow is shown in Fig. 1. A snow block of 26 cm×26 cm×26 cm with a considerably uniform texture was used as a sample; it was placed in this thermally insulated box. A certain difference of temperature was applied between the top and the bottom surface of the sample by 2 sets of electric heaters H_1 and H_2 each with a thermo-regulator. A copper plate was inserted between the top/bottom surface of the sample and the heater, respectively, as a diffuser of heat source. This experimental device was set upright in the cold laboratory at −25°C, and a negative temperature gradient in a sub-freezing temperature range could be maintained in the snow sample, by keeping bottom heater H_1 warmer than top heater H_2. The temperature difference between the top and the bottom, i.e. the magnitude of temperature gradient, could be adjusted for an object of the experiment by the thermo-regulators. Snow temperatures at five levels in the sample were measured by five thermocouples T_1, $T_2 \ldots T_5$, and four local temperature gradients in the sample were obtained from them. By this way a snow sample was subjected to a constant temperature gradient of a desired magnitude for a desired period.

When the experiment was over, the sample was taken out so that a thin section was prepared for observations of the metamorphosed snow. A vertical fraction of the sample was occasionally cut out from the central part of the sample during the experiment to observe a degree of progress of metamorphosis of the sample

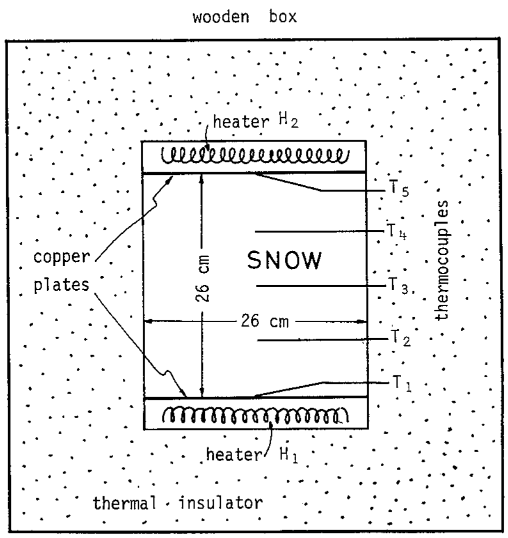
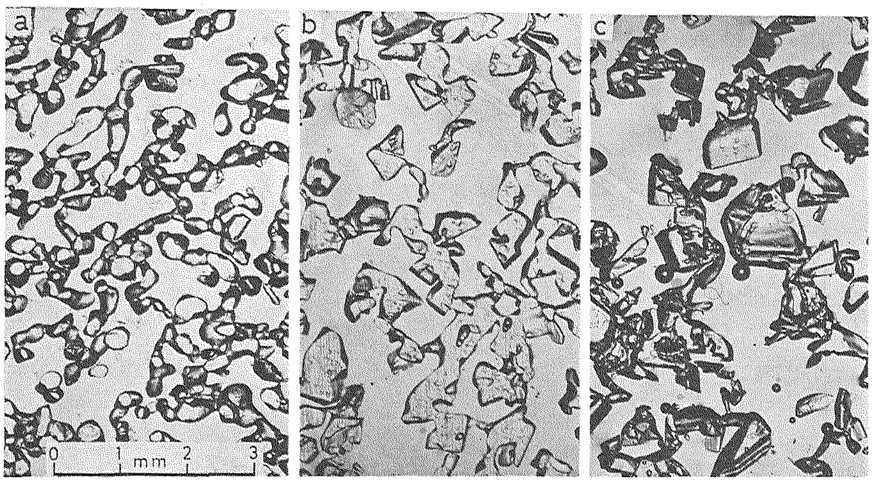


Fig. 1 Experimental device for growing artificial depth hoar

by lapse of time; the cavity left in the cabinet by the cutting out of the sample was filled with snow in an appropriate manner so that a thermal field was not disturbed in the cabinet; then the experiment was continued.

(2) *Growth of Depth Hoar in Fine Grained Compact Snow*

As the major part of a snow cover during the cold winter season in Hokkaido and in alpine districts of Honshū, Japan, is composed of fine grained compact snow, it was selected as the first samples for the experiments of metamorphism under a negative temperatue gradient. Two samples A and B were prepared from a snow block of fine grained compact snow, 0.35 g/cm³ in density. Sample A was subjected to a negative temperature gradient of –0.17°C/cm, at the average snow temperature of –0.7°C, for 10 days, then sample B to a negative temperature gradient of –0.33°C/cm, at –0.9°C, for 6 days. Figure 2 shows the vertical thin sections: (a) the original snow, (b) metamorphosed sample A, (c) metamorphosed sample B. From these experiments it became clear that the texture of fine grained compact snow was considerably changed by a dry metamorphism under a negative temperature gradient, that is, fine and rounded snow grains connected with each other by ice bonds in complicated ways in the original snow, turned into large and sharply edged hoar grains connected by thin ice joints in simpler ways than the original. These are developments of depth hoar.



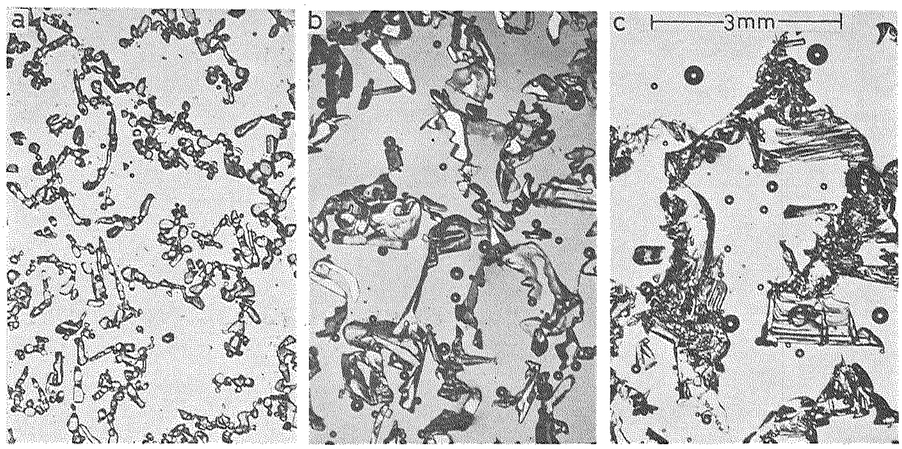
Original snow 0.35 g/cm³ –0.17°C/cm at –0.7°C, 10 days –0.33°C/cm at –0.9°C, 6 days

Fig. 2 Growth of depth hoar in fine grained compact snow (experiment). Vertical thin sections of:
(a) Original snow, (b), (c) Depth hoar crystals

Samples A and B showed considerably different textures after individual metamorphoses. Hoar grains of metamorphosed sample A were generally small solid crystals with sharp edges, corners and flat crystal surfaces; these were named "solid-type depth hoar". On the other hand, many of hoar grains grown in sample B were large crystals with rugged surfaces, and were namea "skeleton-type depth hoar".

(3) *Growth of Depth Hoar in New Snow*

As the second samples of the experiment, two samples of new snow A and B, 0.15 g/cm^3 in density, were chosen. Samples A and B were subjected to temperature gradients of −0.22°C/cm and −1.20°C/cm respectively, for 16 days. Figure 3 shows the vertical thin sections of the original snow and metamorphosed samples A and B. In the case of sample A (Fig. 3 (b)) which was subjected to a small negative temperature gradient, fractional numbers of skeleton-type and solid-type depth hoar crystals were 68% and 32% with the average crystal size of 1.3 mm and 0.8 mm, respectively. On the contrary, in the case of a large negative temperature gradient (sample B, Fig. 3 (c)), all the depth hoar crystals appeared were the skeleton type with the average size of 2.8 mm, which was approximately twice as large as that of the skeleton-type crystals in sample A. However, cup-shaped depth hoar crystals,well-known crystal shape as the typical depth hoar, were scarcely observed in both samples A and B.

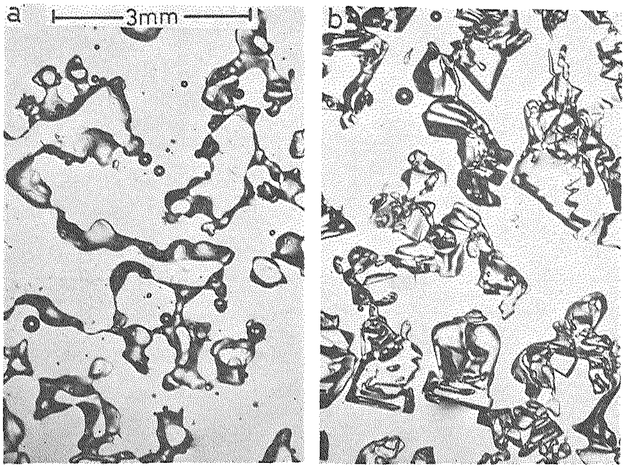


Original snow 0.15 g/cm^3 −0.22°C/cm at −2.0°C, 16 days −1.2°C/cm at −4.3°C, 16 days

Fig. 3 Growth of depth hoar in new snow (experiment).
Vertical thin sections of:
(a) Original snow, (b), (c) Depth hoar crystals

(4) *Growth of Depth Hoar in Coarse Grained Granular Snow*

To cover all kinds of textures of deposited snow for the experiment, coarse grained granular snow was finally selected. Coarse grained granular snow, 0.3 g/cm^3 in density, was subjected to a temperature gradient of $-0.32°C/cm$ at the mean temperature of $-1.3°C$ for 12 days. Figure 4 shows the vertical thin sections of the original and metamorphosed samples. Both the skeleton-type and solid-type depth hoar crystals were observed, and their crystal sizes were considerably larger than those of the previous cases.



Original snow 0.30 g/cm^3 $-0.32°C/cm$ at $-1.3°C$, 12 days

Fig. 4 Growth of depth hoar in coarse grained granular snow (experiment). Vertical thin sections of:
(a) Original snow, (b) Depth hoar crystals

II. 3. *Growth of Depth Hoar in a Natural Snow Cover*

In Hokkaido the temperature of the ground surface beneath a snow cover more than 50 cm in thickness is maintained constantly at 0°C through the snow season of a year. As the snow surface is exposed to the cold air above, generally lower than 0°C, during the cold winter season, a vertical negative temperature gradient appears as a whole in the snow cover. A vertical profile of temperature in a snow cover is not monotonic. Near the surface of a snow cover, snow temperature varies rapidly from time to time according to the change of air temperature and of snow surface radiation due to the quick conduction of heat from/to the surface. On the other hand, snow temperature hardly changes at a deep level of a snow cover, as there are a constant heat source in the vicinity, namely the ground, as

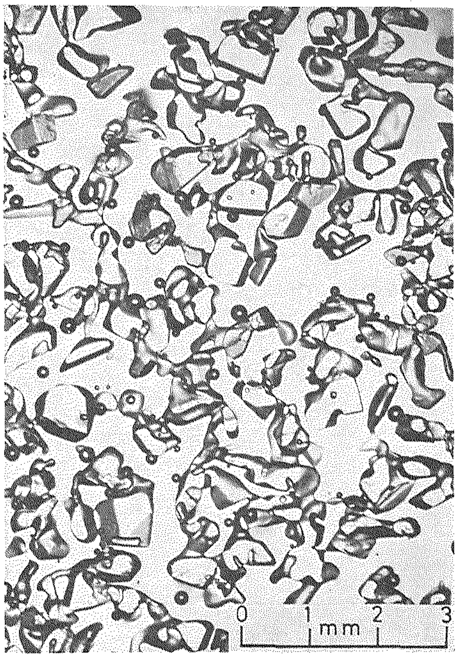


Fig. 5 Vertical thin section of solid-type depth hoar formed in a natural snow cover

well as the slow and attenuated conduction of heat from/to the surface. As the result, the temperature gradient in a snow cover varies its magnitude and even its sign from time to time at a shallower level in a snow cover, while both the magnitude and the sign of the temperature gradient are considerably constant at a deeper level. A snow layer near the surface is subjected to a consistent large negative temperature gradient when air temperature is maintained very cold continuously for a long period. On the other hand, in a snow layer near the bottom of a snow cover, a very small negative temperature gradient is constantly maintained through a winter season after the snow cover gets a sufficient thickness, although a large negative temperature gradient appears occasionally in the beginning of winter when the snow cover is still thin. From these considerations, it would reasonably be presumed that depth hoar would grow at various times in various layers of the snow cover when growth conditions were satisfied.

From field observations it was found likely that a climatic factor and the conditions of deposited snow in the northern Hokkaido were appropriate for the growth of solid-type depth hoar in a snow cover. Figure 5 shows a vertical thin section of a solid-type depth hoar layer developed in a natural snow cover, which is very common in the northern Hokkaido.

Figure 6 shows an example of a depth hoar layer acted as a sliding plane of a surface avalanche. On February 11, 1966, a dry slab avalanche occurred at the Karikachi Pass in the central Hokkaido. Next day, observations of a snow cover was made at the avalanche site. At the starting point of the avalanche, the broken plane of the snow cover and the sliding plane of the avalanche were very clearly observed, as shown in Fig. 6 (a). Both planes were almost perpendicular to each other. From the observations on the vertical section of the natural snow cover in the vicinity of the starting point of the avalanche, it became clear that

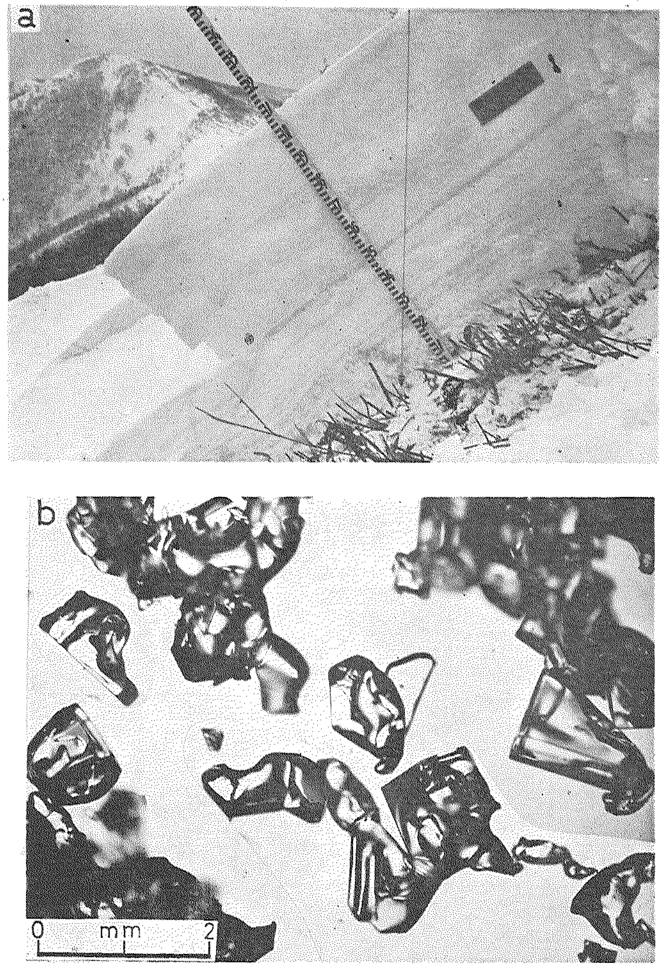


Fig. 6

(a) Vertical section of a snow cover at the starting point of an avalanche, Karikachi Pass, central Hokkaido. The sliding plane was a thin layer at a level of 47 cm level marked on the scale.

(b) Hoar crystals in the sliding plane

the sliding plane of the avalanche was a thin layer of very fragile coarse grained solid-type depth hoar. All other layers of the snow cover were composed of fine grained compact snow and very sturdy fine grained solid-type depth hoar, while skeleton-type depth hoar was observed in the bottom layer of the snow cover. Figure 6 (b) shows hoar crystals of the sliding layer.

In 1965, an avalanche research station of the Institute of Low Temperature

Science, Hokkaido University, was established at Toikanbetsu, Teshio Mountain Range in the northern Hokkaido. In this district, the average thickness of snow covers in the normal winter comes up to 1 m or so and depth hoar grows fairly actively in it; besides, a number of ground avalanches break out all over the south slopes of the mountain ridges in spring.

Through the winter of 1967–1968, observations of a snow cover was carried out every 2 weeks at 4 sites in the vicinity of the station: sites A and B were on the south slope, while C and D on the north slope of on one of the mountain ridges. The change of textures and properties (snow type, grain size, density and hardness) of each layers of a snow cover were traced by lapse of time. The progress of metamorphosis of snow grains was directly observed in the field by a magnifier and later in the cold laboratory of the station by a microscopic analysis of their thin sections. Figure 7 shows the daily mean air temperature at the station on the mountain ridge, and the change of thickness of a snow cover at site A on the south slope.

The change of heights and textures of each layers of a snow cover at 4 sites A, B, C and D are given in Fig. 8. Each layer of the snow cover at the 4 sites was

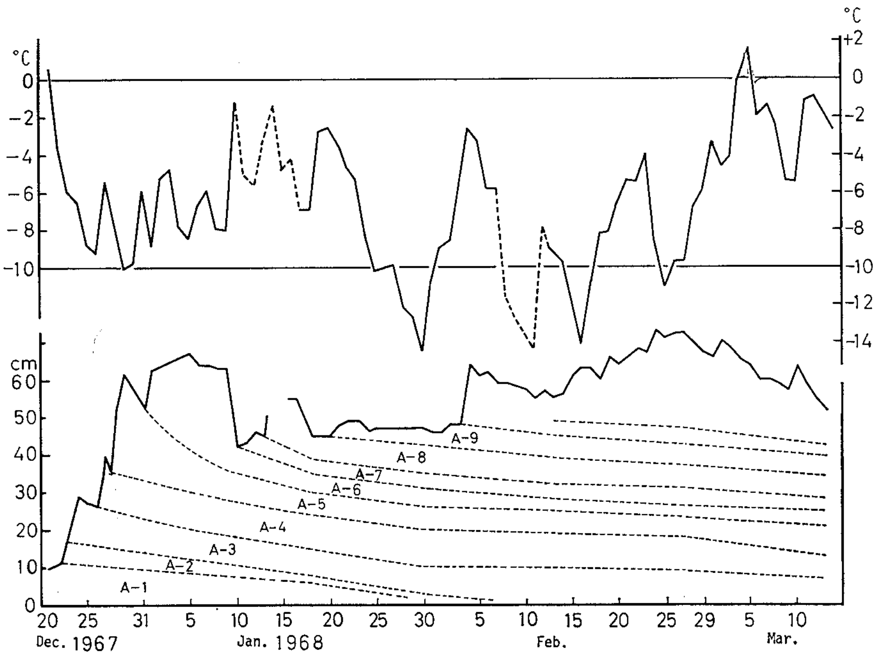


Fig. 7 Daily mean air temperature at the Avalanche Research Station (upper), and the variation of snow depth and position of snow layers at observation site A (lower), Toikanbetsu, northern Hokkaido

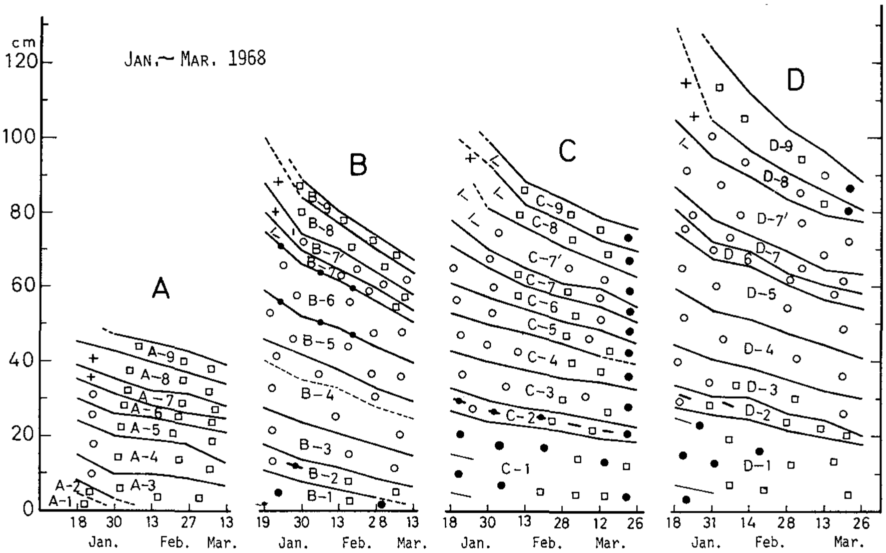


Fig. 8 Change of positions and types of snow layers at the 4 observation sites, Toikanbetsu, northern Hokkaido.
Sites A, B: on the south slope,
Sites C, D: on the north slope,
The uppermost boundary of each diagram was not necessarily the actual surface of the snow cover

designated as shown in Fig. 8: the Roman letter indicates the site, and the numeral the serial numbers of the layers in the snow cover; individual layer with the same serial number at the 4 sites had been formed at the same time. From these observations, metamorphoses of snow by the end of February in this district were classified into five types as follows:

Type i. New snow→Fine grained compact snow, and remained same.

Type ii. Fine grained compact snow→Solid-type depth hoar.

Type iii. Coarse grained granular snow→Solid-type depth hoar.

Type iv. New snow→Solid-type depth hoar.

Type v. Fine grained compact snow→Solid-type depth hoar→Skeleton-type depth hoar.

Typical crystal shapes of snow which underwent the above-mentioned types of metamorphoses are shown in Fig. 9, and the change of density and hardness of snow in Fig. 10 by types of metamorphosis. The hardness of snow was measured by Kinosita's gauge. The progress of metamorphoses and changes of properties of snow by the types of metamorphosis are described hereunder in more detail.

Type. i. New snow→Fine grained compact snow, and remained same (Layers

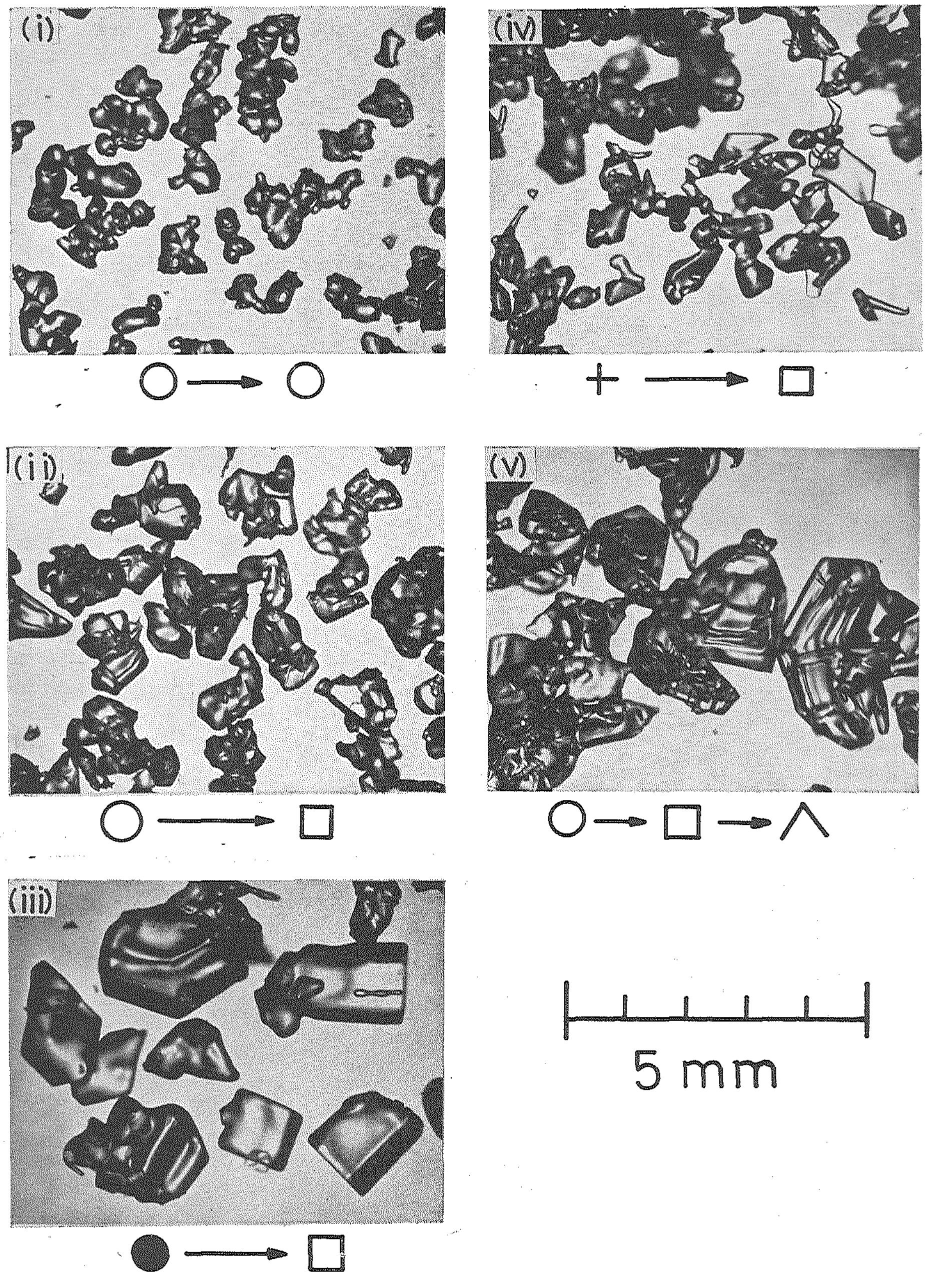


Fig. 9 Typical crystal shapes of snow which underwent metamorphoses, Types i. ii...... V. (As for the graphic symbols, see Table 1: Classification of deposited snow by Japanese Society of Snow and Ice. 1967)

B-3, B-4, D-4 and D-7′, Fig. 10 (i): Layers B-3, B-4 and D-4 were deposited on December 23, 1968, by falling snow, while D-7′ on January 15, 1969, by drifting snow. All these layers remained as fine grained compact snow until the snow melt season. Densities of these snow layers ranged 0.32–0.35 g/cm^3 on January 18, and increased fairly monotonically up to 0.40–0.45 g/cm^3 by March 13. Hardnesses of these layers in January and February were 1–5 kg/cm^2, which were the hardest snow in this area. As the snow melt began in spring, hardnesses of these snow layers decreased rapidly. The decrease of hardness of snow began in the beginning of March on the south slope, and in the middle of March on the north slope.

Type ii. Fine grained compact snow→Solid-type depth hoar (Layers A-3, A-5, A-6, C-3, C-4 and D-3, Fig. 10 (ii)): This type of metamorphosis of snow was most commonly observed on the top of the mountain ridge where a snow cover could not become so thick because of the strong wind. Densities of these snow layers increased almost linearly, but more gradually than type i with elapse

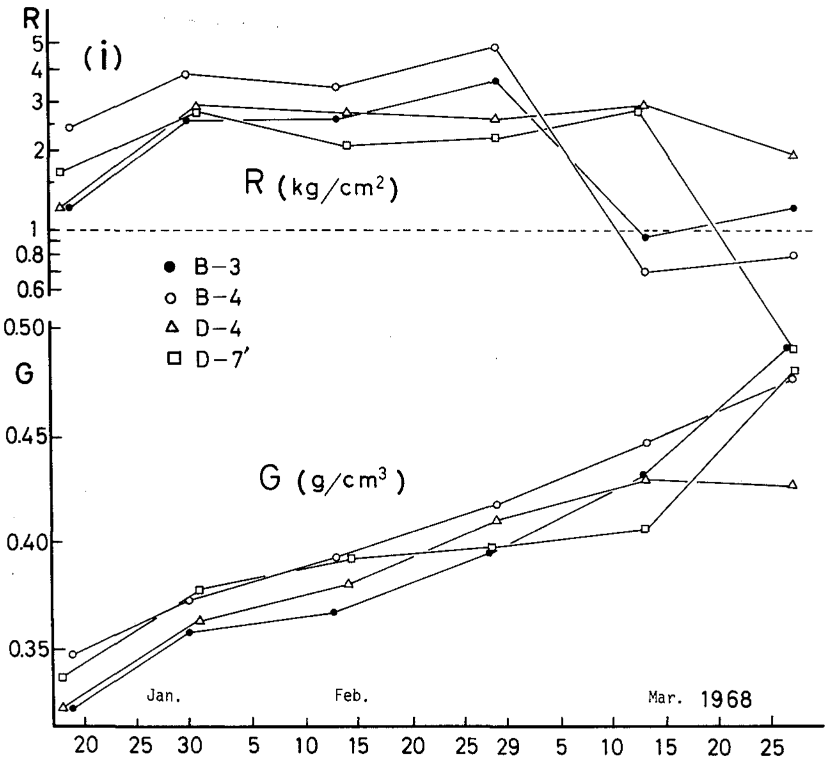
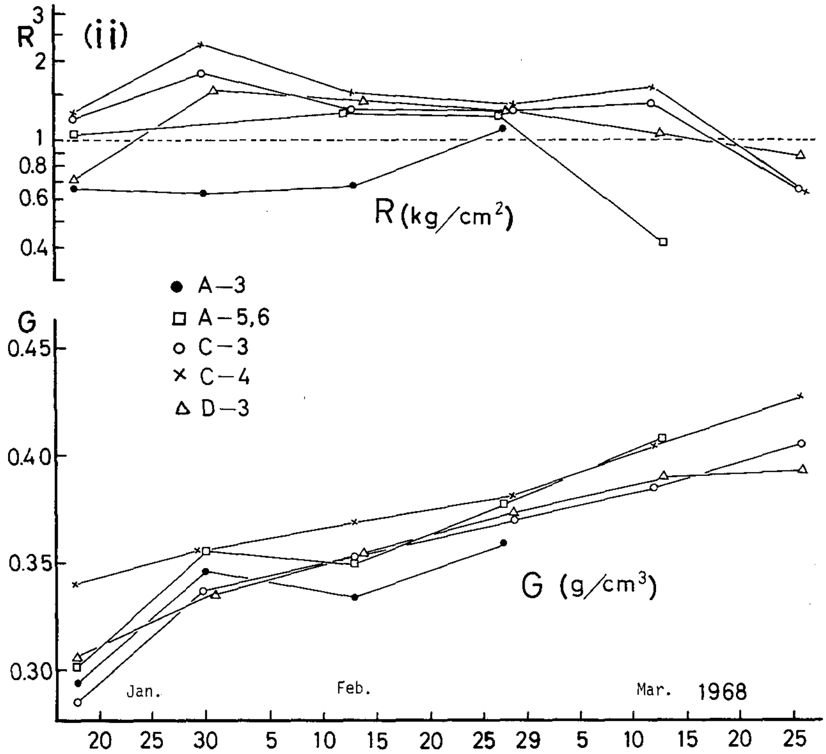


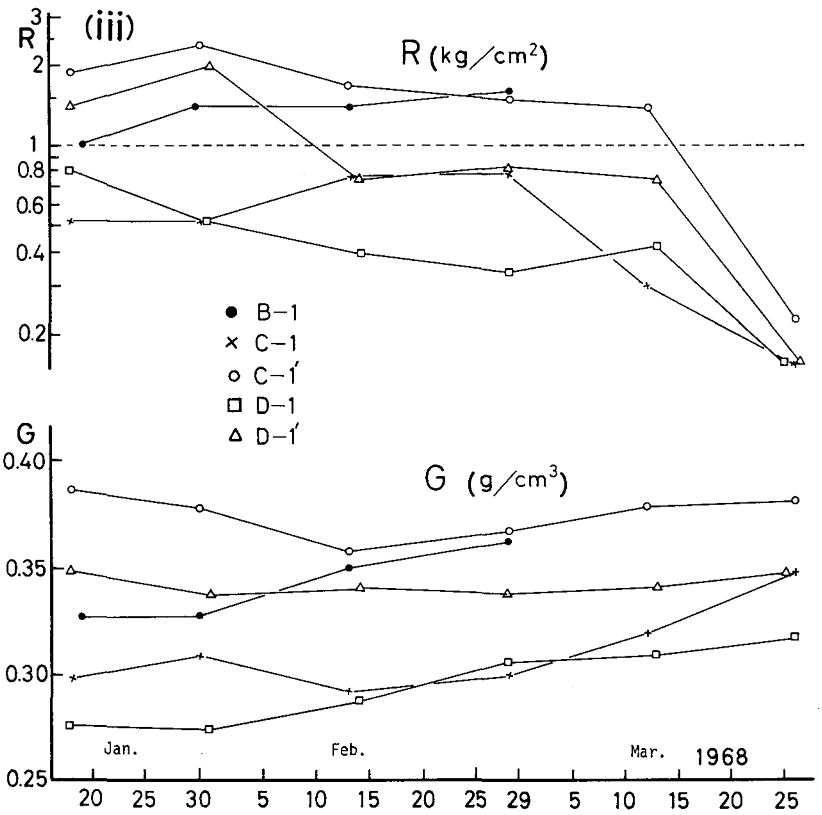
Fig. 10 Change of density G and hardness R of a snow layer, by lapse of time, which underwent metamorphoses, Types i, ii. . . .v



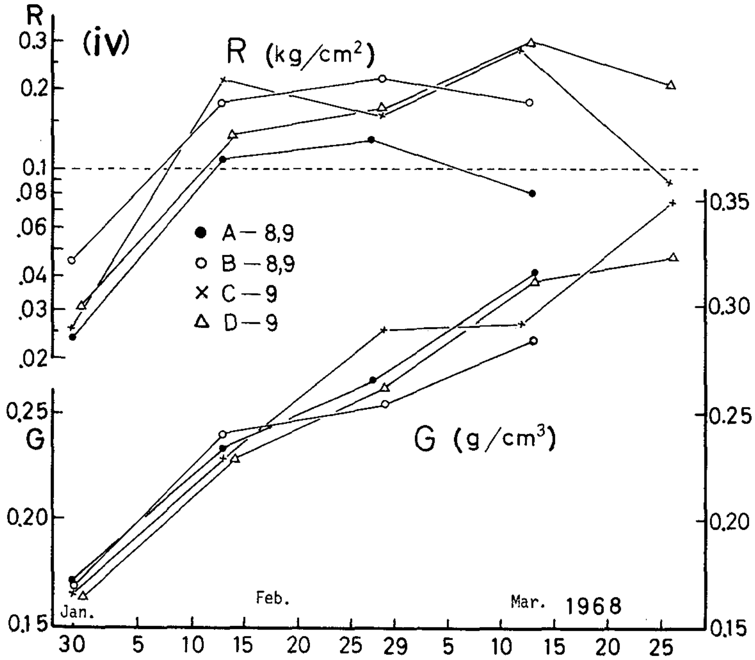
of time until the snow melt season, up to 0.4 g/cm^3. Hardnesses of these layers were around 1 kg/cm^2 without remarkable change through the winter, while slight tendencies of increasing were observed in the early winter and those of decreasing in the snow melt season.

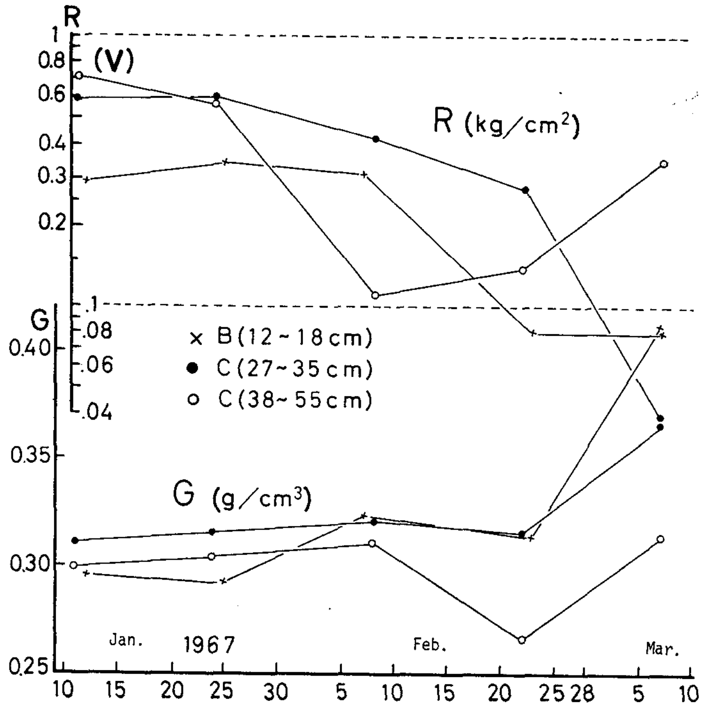
Type iii. Coarse grained granular snow→Solid-type depth hoar (Layers B-1, C-1, C-1′ and D-1, D-1′, Fig. 10 (iii)): This type of metamorphosis of snow took place in the bottom layer of a snow cover on the ground. Crystal shapes of metamorphosed snow, namely of solid-type depth hoar, were column or plate, and the crystal size was much larger than that of type ii. Both the density and hardness of these original layers had ranged considerably widely, 0.27–0.39 g/cm^3 in density and 0.5–2.0 kg/cm^2 in hardness, and those of individual layers showed very small changes through the winter, although a common tendency of decrease of hardness was observed in the snow melt season.

Type iv. New snow→Solid-type depth hoar (Layers A-8, A-9, B-8, B-9, C-9 and D-9, Fig. 10 (iv)): In this category, the metamorphosis of lightly compact snow into solid-type depth hoar is included. Both the density and



hardness of the these snow layers were so small in the original stage that, even in the final stage, they remained, in spite of the steep increase, small as a whole, as compared with the density and hardness of snow layers subjected to other types of metamorphoses. The solid-type depth hoar metamorphosed from new snow comprised small plate-type crystals. From January 18 to 23, new snow deposited calmly on the old snow cover, then it was exposed to low temperatures down to −14.5°C for one week without a further snowfall. Then it was found that major part of the surface new snow had metamorphosed into solid-type depth hoar, but not into lightly compact snow as usual. Even the largest hardness of these snow layers did not exceed 0.3 kg/cm^2 in the middle of March. The density and hardness of snow layers deposited on these layers later and metamorphosed into fine grained compact snow were much larger than those of these layers, even under a smaller load than for these layers.


(iv)
R (kg/cm²)
G (g/cm³)
A — 8,9
B — 8,9
C — 9
D — 9
Jan.
Feb.
Mar.
1968
30 5 10 15 20 25 29 5 10 15 20 25


(V)
R (kg/cm²)
G (g/cm³)
B (12 ~ 18 cm)
C (27 ~ 35 cm)
C (38 ~ 55 cm)
Jan.
1967
Feb.
Mar.
10 15 20 25 30 5 10 15 20 25 28 5 10

Type v. Fine grained compact snow→Solid-type depth hoar→Skeleton-type depth hoar (Layers B (12–18 cm above the ground), C (27–35 cm) and C (38–55 cm), Fig. 10 (v): these layers were observed during the previous winter): This type of metamorphosis of snow was occasionally observed in the layer near the ground, and the crystal of the depth hoar in the final stage had a shape of skeleton-type cup. Densities of these layers were fairly constant during the cold winter season, while hardnesses decreased gradually according to progress of metamorphosis. It was presumed that the development of such a layer in a snow cover on a slope might increase avalanche hazard.

II. 4. *Classification of Snow*

(1) *Classification of Depth Hoar Crystals*

Definition of depth hoar can be given as follows: Depth hoar is a deposit of hoar crystals grown by internal sublimatic evaporation and condensation of water from/onto snow grains in a snow cover, which occurs when a snow layer was subjected to a consistent temperature gradient (generally a negative gradient). From a number of observations both in the laboratory and in the field, depth hoar crystals were classified into two types, "Solid-type depth hoar crystal" and "Skeleton-type depth hoar crystal".

A solid-type depth hoar crystal is generally a small solid crystal with sharp edges, corners and flat crystal surfaces. It takes shapes of plate and column, occasionally with piramidal surfaces. A solid-type depth hoar layer is frequently misread as a fine grained compact snow layer. Sometimes, a solid-type depth hoar layer is hard and sturdy like a fine grained compact snow layer. If we observe the layer carefully, however, a solid-type depth hoar layer is easily detected by sharply edged grains in it and at times by glistening crystal surfaces even with naked eyes. Further, if one takes several snow grains on a black paper card and observes them under a magnifier, a solid-type depth hoar can be identified more clearly (Fig. 11 (a)).

On the contrary, a skeleton-type depth hoar grain is very easily detected. It is a large skeleton crystal with rugged surfaces: cup-, sheath-, needle-, plate- or sector-shaped. A cup-shaped skeleton-type depth hoar crystal is shown in Fig. 11 (b). As seen in the picture, this type of crystal has a large crystal body and thin joints at the crystal base, and a layer consisting of this type of depth hoar is extremely fragile against a dynamic force.

Figure 11 (c) shows a vertical thin section of a depth hoar layer: A solid-type depth hoar; B skeleton-type depth hoar. The present author gave a Japanese name "KO-SHIMO-ZARAME-YUKI" (KO means tiny, SHIMO hoar, ZARAME granular, and YUKI snow) to solid-type depth hoar, and used "SHIMO-

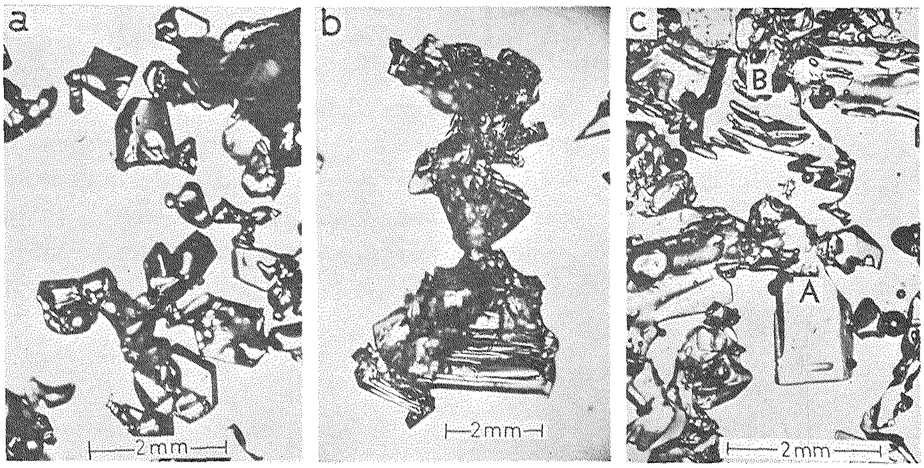


Fig. 11 Classification of depth hoar crystals.
(a) Solid-type depth hoar (plate and column)
(b) Skeleton-type depth hoar (cup)
(c) Vertical thin section of a depth hoar layer (A: solid-type crystal, B: skeleton-type crystal)

ZARAME-YUKI (Saito's designation)" for skeleton-type depth hoar.

(2) *Classification of Deposited Snow by Japanese Society of Snow and Ice (1967)*

Studies on deposited snow have actively progressed since 1950 in this country. As a result, depth hoar was recognized as an interesting and important snow from a standpoint of snow science.

In 1967, the Committee of Classification of Deposited Snow, Japanese Society of Snow and Ice, completed a new classification of deposited snow after two years of work, as shown in Table 1. Classification was made on the basis of metamorphism of snow, as follows:

i. New snow (SHIN-SETSU: SHIN means new, SETSU snow):
Newly deposited fresh snow which is very soft and light, reserving the crystal shape of falling snow in it. Density ranges 0.05–0.15 g/cm³.

ii. Lightly compact snow (KO-SHIMARI-YUKI: KO means lightly or slightly, and SHIMARI compact or densified):
A few days after a snowfall, the crystal shape of the original snow has disappeared completely by a dry metamorphosis, even without snow melt, and the texture of the snow layer has turned into a simple network of fine ice bonds. Densification has progressed lightly. Such snow is named lightly compact snow. Density ranges approximately 0.15–0.25 g/cm³.

Table 1 Classification of deposited snow by Japanese Society of Snow and Ice (1967)

denomination of deposited snow	graphic symbol	
New snow	+	+
Lightly compact snow	<	<
Fine grained compact snow	○	○
Coarse grained granular snow	●	●
Solid-type depth hoar	□	□
Skeleton-type depth hoar	∧	∧

iii. Fine grained compact snow (SHIMARI-YUKI):
As metamorphosis and densification progress, lightly compact snow turns into fine grained compact snow, the texture of which is a complicated network of sturdy ice bonds. As the result, fine grained compact snow is mechanically hard and sturdy. Major part of snow covers in Hokkaido and in alpine districts of Honshū in cold winter is composed of fine grained compact snow. Density ranges 0.2–0.5 g/cm.^{3}

iv. Coarse grained granular snow (ZARAME-YUKI: ZARAME means coarse grained granular particle):
By a wet metamorphism, a small snow grain or assembly of small snow grains turn into a coarse polycrystal grain. This is named coarse grained granular snow, and commonly exists at the bottom layer of a snow cover through winter. In the active snow melt season, the whole snow cover turns into coarse grained granular snow. Density ranges 0.3–0.5 g/cm^3.

v. Solid-type depth hoar (KO-SHIMO-ZARAME-YUKI):
Solid-type depth hoar is formed by a dry metamorphosis under a small negative temperature gradient in a snow cover, as will be described later. The hoar grain, with a colummar or plate shape, is a sharply edged solid crystal with flat crystal surface. Density ranges 0.2–0.4 g/cm^3.

vi. Skeleton-type depth hoar (SHIMO-ZARAME-YUKI):
Skeleton-type depth hoar is formed by a dry metamorphosis under a large negative temperature gradient in a snow cover, as will be described later. A hoar grain is a large-skeleton, rugged-surface crystal with thin joints at its base; it has cup, plate, needle, sheath, or sector shapes. Generally, this type of depth hoar layer is extremely fragile against a dynamic force. Density ranges 0.25–0.4 g/cm^3.

Further, each of these 6 types of deposited snow is classified into dry type and wet type. Classifications of deposited snow and graphic symbols of each of them are given in Table 1.

(3) *Metamorphism of Deposited Snow*

A block diagram of metamorphism of snow was given in Fig. 12, from all the results of the experiments on the growth of depth hoar in the laboratory as well as the observations on metamorphoses of snow in natural snow covers. A solid arrows in this diagram indicates a possible metamorphosis to depth hoar, while a broken arrow to other snow types. That is, depth hoar can grow in any kinds of snow layers if they are subjected to an appropriate condition; the only metamorphosis which has not been confirmed either in the laboratory or in natural snow is a metamorphosis from skeleton-type depth hoar to solid type.

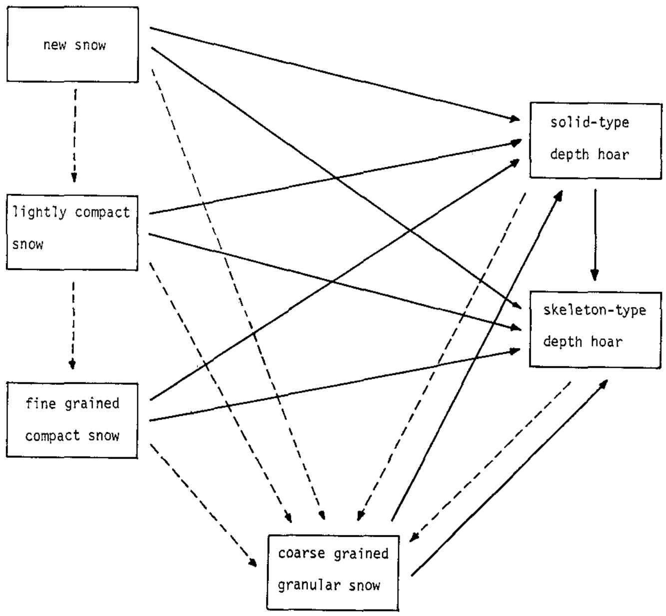


Fig. 12 A block diagram of metamorphism of snow. A solid arrow indicates a possible metamorphism to depth hoar

III. Growth conditions of depth hoar

III. 1. *Effects of Snow Temperature and Magnitude of Negative Temperature Gradient on the Growth of Depth Hoar*

The results of the experiments of growth of depth hoar in the laboratory, described in Section II. 2, suggested strongly that a strong relation between the magnitude of negative temperature gradient in snow and the type of depth hoar grown must have existed. A series of experiments of the growth of depth hoar in the laboratory were carried out in an effort to find out a possible relation.

(1) *Effect of Magnitude of Negative Temperature Gradient on the Type of Depth Hoar* (1)

A sample of fine grained compact snow, 0.32 g/cm^3 in density, was subjected to a constant negative temperature gradient for 42 days, by the use of the experimental device described in Section II. 2. 1 (Fig. 1). As the top surface and the bottom surface of the sample were maintained at constant temperatures of –12.2°C and –3.7°C, respectively, the mean temperature gradient in the snow sample was –0.32°C/cm through the experiment. However, the temperature gradient in the sample was actually not uniform: about –0.20°C/cm in upper part, –0.30°C/cm in middle part, and –0.37°C/cm in lower part of the sample. Microphotographic observations of vertical thin sections of the sample were made every 7 days from the start of the experiment. Figure 13 gives a graphical description of the series of observations of thin sections of the sample; each frame gives a thin section, with serial No. and magnitude of temperature gradient, and the vertical position of each frame gives the vertical position of the thin section in the sample, and the horizontal position the day when the thin section was made. Thin section No. 7, for example, was sampled from the bottom part of the snow block which was subjected to –0.32°C/cm of temperature gradient consistently for 21 days beginning the start of the experiment. Microphotographs of three vertical thin sections of the sample are shown in Fig. 14: (a) is the original snow; (b) and (c) respectively

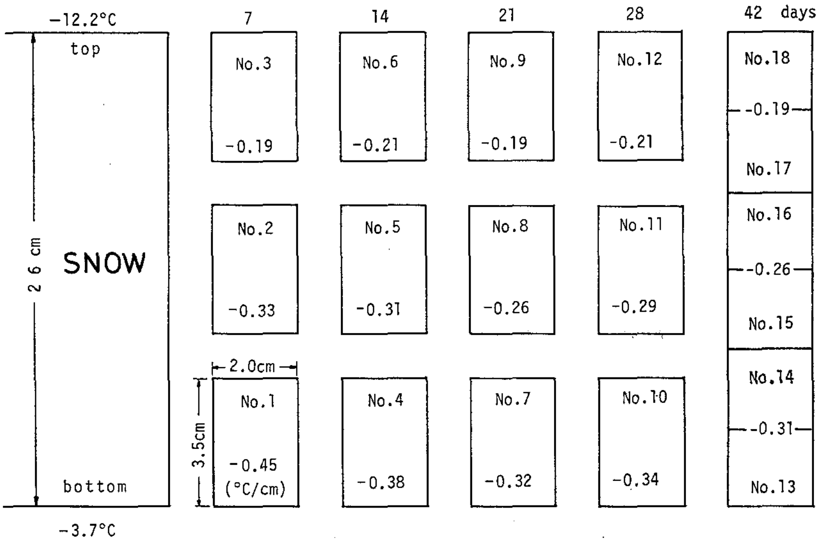


Fig. 13 Location and experimental data of a vertical thin section: time lapse (in day after the start of experiment), serial number of the thin section, and magnitude of temperature gradient applied

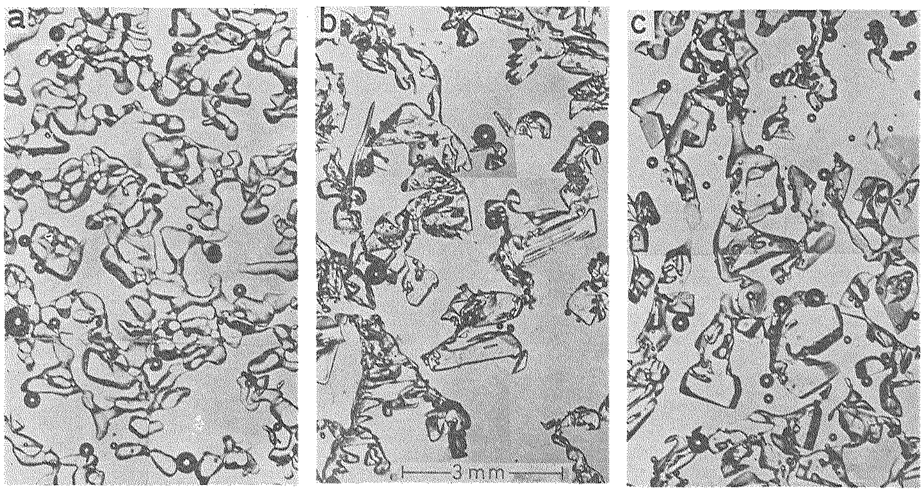


Fig. 14 Vertical thin sections of:
(a) Original snow, density 0.32 g/cm^3
(b) No. 13: the bottom part of the sample, 42 days after the start.
(c) No. 18: the top part of the sample, 42 days after the start.

thin sections No. 13 and No. 18 are metamorphosed snow 42 days after the start. The vertical thin sections in the pictures are placed in the same way as real snow, namely, the top is upward and the bottom is downward. Therefore, it is presumed that a snow grain in an upper level in each of the pictures was colder than that in a lower level, and water vapour was transfered upward. Figure 14 shows that fine grained compact snow was metamorphosed into coarse grained depth hoar during 42 days under a temperature gradient, increasing the grain size and decreasing the number of grains.

Table 2 gives the number, type and average size of the depth hoar crystals grown in the snow block during the experiment: the number of depth hoar crystals was counted on a thin section of the sample, 7 cm^2 in area.

In the upper part of the sample, 50 crystals/7 cm^2 of depth hoar grew during 14 days after the start of the experiment, then a total number of depth hoar crystals increased slightly: most of the crystals were solid type, and the diameter averaged 0.7 mm 14 days after the start, then grew up to 1.2 mm during the following 28 days. The average snow temperature of this upper part was −12°C, and temperature gradient −0.20°C/cm. On the other hand, in the lower part of the sample, the average snow temperature was −4°C, and temperature gradient −0.31 – −0.45°C/cm. And 89 crystals/7 cm^2 of depth hoar grew during the first 7 days of the experiment, then the total number of depth hoar crystal decreased gradually, increasing the size of crystals of survived depth hoar. Although the

Table 2 The number, type and average size of depth hoar crystals grown in snow by lapse of time under artificial negative temperatue gradients. (see Fig. 13)

		Top part of the sample					Bottom part of the sample				
Sample No.		3	6	9	12	18	1	4	7	10	13
Time lapse (day)		7	14	21	28	42	7	14	21	28	42
Total number of depth hoar crystals		0	50	51	57	61	89	65	45	46	37
Solid type	Fractional number (%)	–	100	98	85	95	79	76	29	42	32
	Crystal size (mm)	–	0.7	0.8	1.0	1.2	0.7	0.7	1.0	1.0	1.1
Skeleton type	Fractional Number (%)	–	0	2	15	5	21	24	71	58	68
	Crystal size (mm)	–	–	–	–	–	0.9	0.9	1.6	1.4	1.7

fractional number of skeleton-type depth hoar was 1/4 smaller than that of solid-type depth hoar 7 days after the start, it increased up to more than twice that of solid-type depth hoar during the next 14 days, then a remarkable change disappeared; the average crystal size of skeleton-type depth hoar increased up to 1.6 mm during the first 21 days, but no more remarkable growth took place afterwards.

As the result of this experiment, the following were summarized:

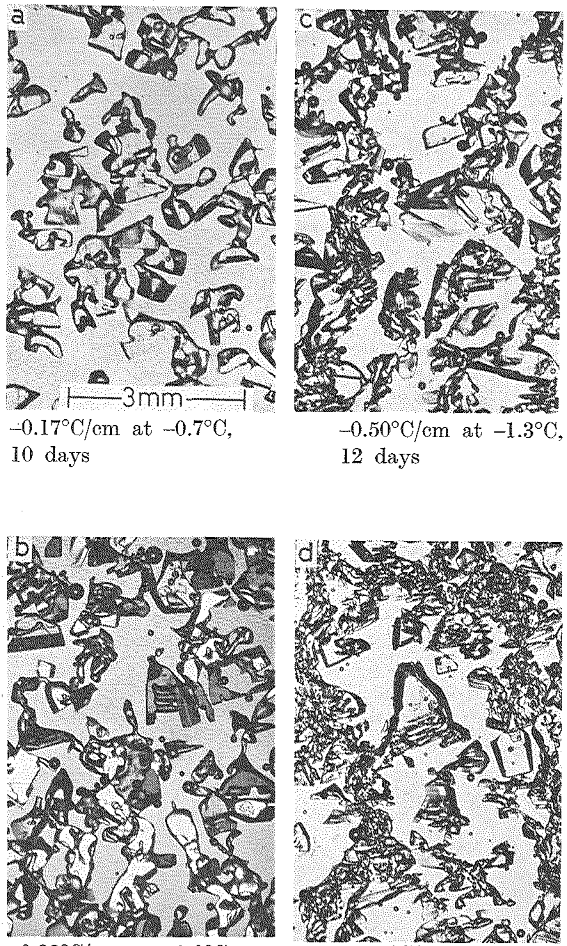
i. Solid-type depth hoar predominantly grew in fine grained compact snow, when the magnitude of negative temperature gradient was about –0.20°C/cm at the mean snow temperature of –12°C.

ii. When the magnitude of negative temperature gradient was about –0.32°C/cm at the mean snow temperature of –4°C, skeleton-type depth hoar grew in number predominantly, about twice as much as solid-type depth hoar.

iii. In both cases, 2 types of depth hoar, solid type and skeleton type, grew simultaneously: either type of the two grew predominantly according to conditions to which the snow was subjected.

(2) *Effect of Magnitude of Negative Temperature Gradient on the Type of Depth Hoar (2)*

Four samples A, B, C and D of fine grained compact snow, 0.35 g/cm^3 in density, were subjected to temperature gradients of –0.17°C/cm, –0.20°C/cm, –0.50 °C/cm and –0.89°C/cm respectively, for 10–16 days. Thin sections of the 4 samples were prepared, when the individual experiment was over; they are shown in Fig. 15. It could be seen that skeleton-type depth hoar grew when the temperature gradient was fairly large, while solid-type did only when the temperature gradient was small. Also, there could not be found any remarkable change in density of the



−0.17°C/cm at −0.7°C, 10 days

−0.50°C/cm at −1.3°C, 12 days

−0.22°C/cm at −2.0°C, 16 days

−0.89°C/cm at −3.6°C, 16 days

Fig. 15 Magnitude of negative temperature gradient and type of depth hoar crystals grown from fine grained compact snow.
(a) Sample A (solid type only)
(b) Sample B (solid type predominates)
(c) Sample C (skeleton type predominates)
(d) Sample D (skeleton type predominates)

snow sample through the experiment. In the case of sample D, the sample was subjected to the largest temperature gradient of the series, −0.89°C/cm, and a number of micro-crystals grew simultaneously filling up the narrow space in between large depth hoar crystals. It was also found that the mechanical strength of sample D increased greatly through metamorphosis; discussions will be made later on this problem.

(3) *Effects of Snow Temperature and Magnitude of Negative Temperature Gradient on the Type of Depth Hoar*

Form the results of the previous experiments described in Sections II. 2, III. 1. 1 and III. 1. 2, it was confirmed that solid-type depth hoar developed under a small temperature gradient, and skeleton-type under a large temperature gradient. In the field of cloud physics, it has been made clear that a crystal habit of snow in growth is controlled by air temperature and the degree of super-saturation of water in the field of crystal growing, as Nakaya's Diagram shows. In the case of depth hoar crystals, the degree of super-saturation of water in an air space in snow can be considered to depend upon the magnitude of temperature gradient in a snow cover: the larger is the temperature gradient in the snow, the higher is the degree of supersaturation of water.

To study a dependence of the crystal habit of depth hoar on the snow temperature and temperature gradient in snow, all the results of the previous experiments in the laboratory and observations in the field were put in order, and further a series of complementary experiments were carried out. The results are as follows, as also shown in a diagram in Fig. 16.

i. For the most cases, two types of depth hoar, solid type and skeleton type, grew simultaneously, while either of the two types grew predominantly according to the magnitude of negative temperature gradient. Therefore, the definition of the type of a depth hoar layer was made on the basis of the predominant type in the shape of hoar crystals.

ii. Solid-type depth hoar comprising short-column and thick-plate grains grew predominantly under a negative temperature gradient smaller than about $-0.25°C/cm$, regardless of snow temperature.

iii. Skeleton-type depth hoar grew predominantly under a negative temperature gradient larger than about $-0.25°C/cm$, and a crystal habit had a dependence on snow temperature, as shown by the pictures of depth hoar crystals on the middle row in Fig. 16; the skeleton cup ranged $-4\sim-10°C$ in snow temperature; the malformed cups or plates are found at both sides of the cup area.

In a large air space (hole, cavity and gap) in snow, a fairly large hoar crystal grew under a large magnitude of negative temperature gradient. A crystal habit of this case was also controlled by snow temperature, as shown on the uppermost row of crystal pictures in Fig. 16; the crystals are placed in the order of skeleton plate, needle, sheath and sector, as the temperature lowers.

iv. A dependence of the crystal habit of depth hoar on snow temperature

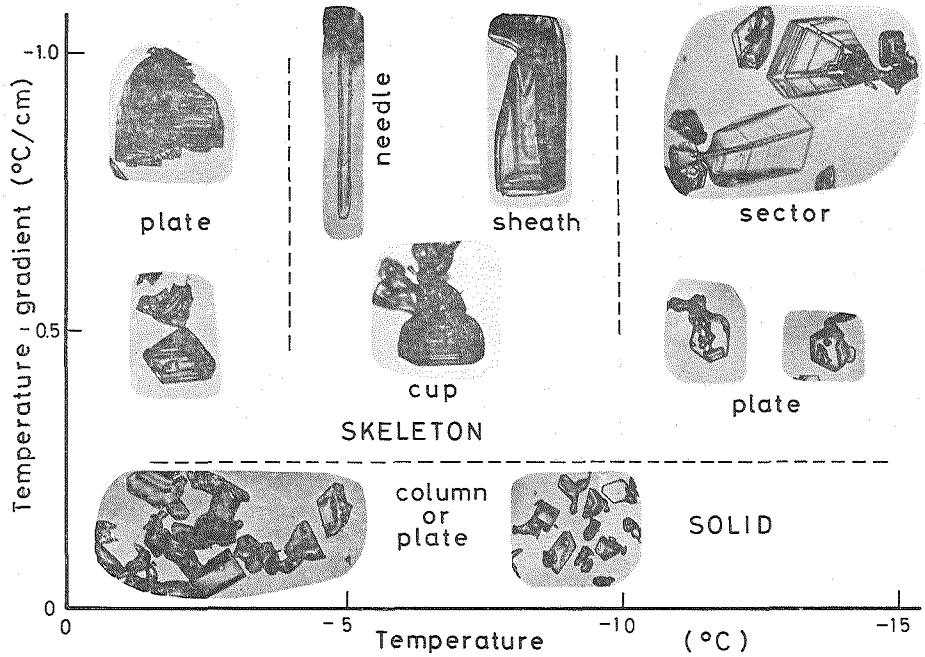


Fig. 16 Dependence of shapes of depth hoar crystals on temperature and temperature gradient. Growth of depth hoar crystals shown in the uppermost row of the diagram was observed only in special cases: in large hole and cavity in a snow cover.

showed an agreement with those of snow crystals in Nakaya's diagram.

III. 2. *Effect of An Air Space in Snow on the Growth of Depth Hoar*

The previous experiments of growth of depth hoar in the laboratory and the field observations of depth hoar in a natural snow cover showed that the development of depth hoar was affected not only by snow temperature and temperature gradient, but also by textures of snow, especially the size of an air space in snow. Seligman has pointed out that large crystals of depth hoar developed in snow with a large air space in it. A series of experiments were carried out to investigate this.

(1) *Growth of Depth Hoar in Different Snow Under Same Magnitude of Negative Temperature Gradient*

Four snow samples A, B, C and D were prepared and subjected to the same magnitude of temperature gradient of –0.37°C/cm at the mean temperature of –2.0°C for 11 days, respectively.

Sample A: Fine grained compact snow, 0.25 g/cm³ in density, with the mean grain size of less than 0.5 mm.

Sample B: snow of sample A was artificially compressed until the density reached 0.37 g/cm^3.

Sample C: coarse grained granular snow, 0.37 g/cm^3 in density, (same density as to sample B) with the grain size of 1–3 mm.

Sample D: snow of sample C was artificially compressed until the density reached 0.45 g/cm^3.

A vertical thin section of each sample prepared after the experiment is given in Fig. 17; the data of the metamorphosed snow including fractional number and grain size of solid-type and skeleton-type depth hoars are given in Table 3.

Table 3 Effect of an air space on the development of depth hoar (see Fig. 17)

Sample	Snow type	Treatment	Density	Depth hoar crystals developed			
				solid type		skeleton type	
			g/cm^3	%	size	%	size
A	fine grained compact snow	natural	0.25	75	0.8^{mm}	25	0.9^{mm}
B		compressed	0.37	90	0.6	10	0.9
C	coarse grained glanular snow	natural	0.37	49	1.0	51	2.0
D		compressed	0.45	84	0.8	16	1.3

From the result of the experiment, it can be seen that the growth in terms of fractional number of crystals (%) of solid-type depth hoar is 3–9 times larger than that of skeleton-type, under such a condition, except the case of sample C. Comparing two snow samples with the same grain size but different densities, i.e. samples A and B, and samples C and D, the smaller is the air space in the snow (caused by densification), the larger is the fractional number of solid-type crystals grown. Comparing two samples with different grain sizes but the same density, i.e. samples B and C, on the contrary, the smaller is the air space (even with the same porosity) in the snow, the larger is the fractional number of solid-type crystals grown. It can also be seen that the largest hoar crystals both of solid type and skeleton type grew in sample C which had had the largest air space between the grains in original snow of the 4 samples. As the result, the following were concluded:

i. A few number of large crystals of depth hoar, both of solid type and skeleton type, grow in snow with a large air space between snow grains.

ii. A large number of minute crystals of solid-type depth hoar grow in snow with a narrow air space between snow grains.

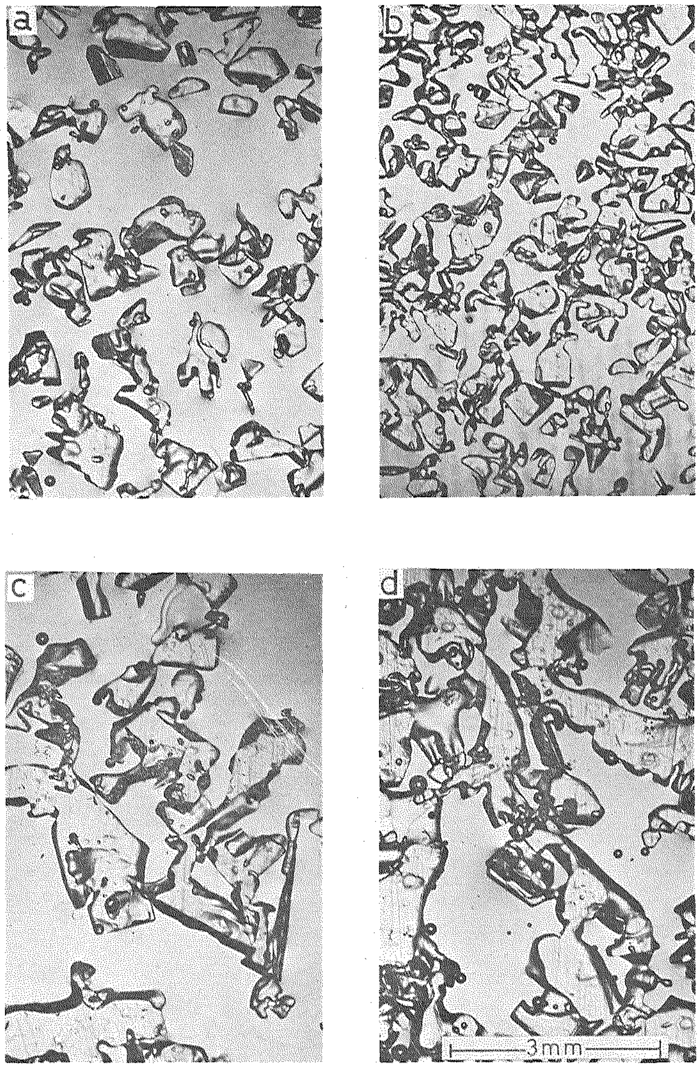


Fig. 17 Effect of an air space between snow grains on the growth of the depth hoar; each sample was subjected to a negative temperature gradient of $-0.37°C/cm$ at $-2.0°C$ for 11 days.

(a) Sample A, fine grained compact snow, $0.25\ g/cm^3$
(b) Sample B, artificially compressed fine grained compact snow, $0.37\ g/cm^3$
(c) Sample C, coarse grained granular snow, $0.37\ g/cm^3$
(d) Sample D, artificially compressed coarse grained granular snow, $0.45\ g/cm^3$

(2) *Growth of Depth Hoar in a Hole in Snow*

To investigate further the effect of size of an air space in snow on the growth of a depth hoar crystal, another series of experiments were carried out. Several cylindrical holes, 8 mm in diameter, were horizontally bored in a sample of fine grained compact snow, 0.36 g/cm^3 in density, and 0.5–1.0 mm in grain size. A negative vertical temperature gradient, –0.92°C/cm in the mean magnitude, was applied to the sample, keeping the top and the bottom side of the sample at –5.6°C and –1.0°C, respectively. Nine days after the start of the experiment, it was foud that extraordinarily large hoar crystals had grown downward at the upper wall of the horizontal cylindrical holes, as shown in the picture in the upper left side in Fig. 18. Although temperatures in the holes were not actually measured, they were estimated as –5.1, –3.9 and –2.2°C at A, B and C respectively from the interpolated snow temperatures at each level of the holes, on an assumption that the temperature gradient in the snow was uniform.

Hoar crystals grown in holes A, B and C are shown in Fig. 18: needle and sheath crystals in A, cup crystals in B, and plate crystals in C; all were skeleton-tye depth hoar. Growth conditions of individual hoar crystals corresponded with Nakaya's diagram (T_a-S diagram), in a temperature range.

A vertical thin section of the snow sample around the wall of hole B is shown in Fig. 19; the approximate position of the wall is indicated by a broken line. Large skeleton-type hoar crystals grown are noted in the space of the original hole, while a number of minute hoar crystals are seen in the original fine grained compact snow around the hole where snow had been considerably densified by the penetration of a rod to make the hole. This fact can be considered as an experimental confirmation of conclusions i and ii in the previous Section III. 2. (1).

The next experiment was carried out under a positive temperature gradient to investigate the effect of the sign of temperature gradient on the growth of hoar crystals. Several cylindrical holes, 7 mm in diameter, were bored in the same way as the previous experiment in a sample of fine grained compact snow, 0.34 g/cm^3 in density, whereby a positive vertical temperature gradient, +0.72°C/cm, was applied to the sample for 11 days. Figure 20 shows the hoar crystals grown upward from the bottom surface in the hole which was kept approximately at –6°C in the sample. The result means that vapour was not transfered by a convectional current of air, but by diffusion through an air space in the hole. (Under the positive temperature gradient the air in the hole is stable, and natural convection does not occur in it. See V. 1. (2))

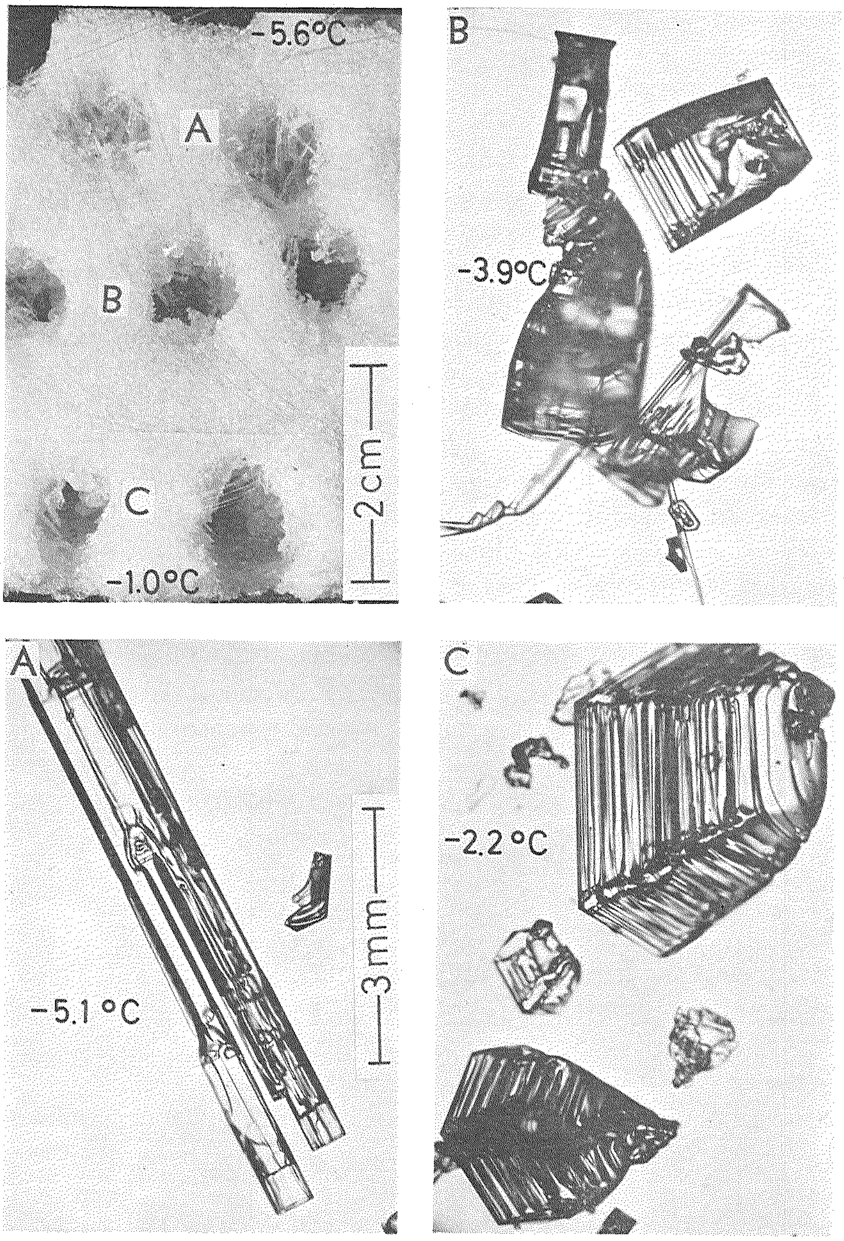


Fig. 18 Large skeleton-type hoar crystals grown in horizontal holes A, B and C in snow, during 9 days.
A: Needle and sheath crystals,
B: Cup crystals,
C: Plate crystals

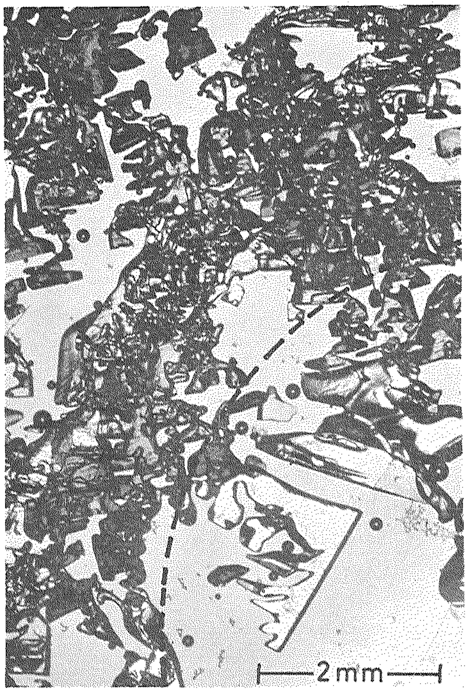


Fig. 19 Vertical thin section of artificially boared snow (a broken line shows the approximate position of the wall of hole B)

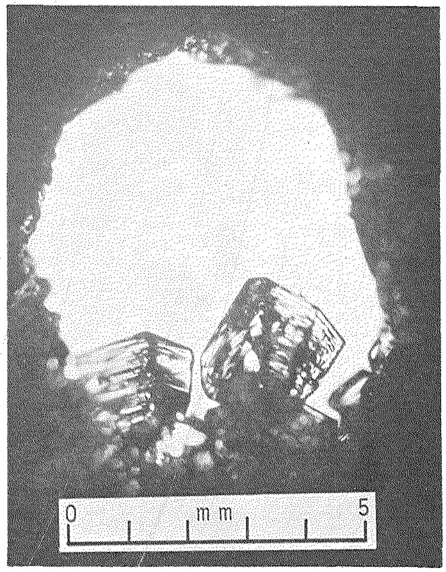


Fig. 20 Large hoar crystals grown in a hole under a positive temperature gradient of +0.72°C/cm, during 11 days

(3) *Natural Growth of Depth Hoar in a Snow Cover with a Large Air Space*

i. Growth of depth hoar in a surface new snow layer: Growth of depth hoar in a surface new snow layer was observed at Toikanbetsu, in the northern Hokkaido as was described in the previous section (metamorphosis Type iv, Section II. 3), when calm and cold weather lasted for 10 days without a snowfall. In that case, depth hoar comprised minute solid-type crystals even in fresh snow with a large air space probably because of an insufficient continuation of the conditions needed to grow up into a large crystal.

Another similar but extreme case occurred in Sapporo. During December 22–24, 1968, a new snow layer, 10 cm thick, deposited on an old snow cover, 3 cm thick. This thin snow cover, 13 cm thick, was exposed to calm and cold weather for 13 days without a snowfall, during which the minimum air temperature was −13°C, average minimum air temperature −10°C, and average air temperature −5°C. On January 6, 1969, large skeleton-type depth hoar grew in the surface

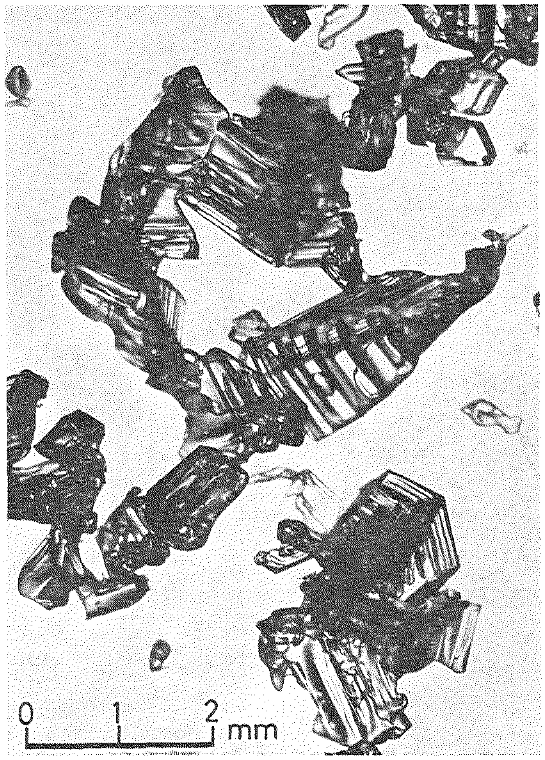


Fig. 21 Large skeleton-type depth hoar crystals grown in a new snow layer of natural snow cover

layer of this thin snow cover (Fig. 21); the snow cover had been thinned down to 9 cm by natural densification, and the ground beneath the snow cover frozen.

ii. Growth of depth hoar in coarse grained granular snow: Figure 22 shows an example of depth hoar growth in a coarse grained granular snow layer. Figure 22 (a) is a macroscopic feature of a vertical section of a snow cover in which depth hoar has grown. The uppermost white part repesents a fine grained compact snow layer, while the dark part directly beneath it was originally a coarse grained granular snow layer and has turned into a skeleton-type depth hoar layer. This layer has had a large air space, and the depth hoar developed in this layer consisted of large skeleton-type cup crystals, 2–3 mm in diameter, and solid-type crystals, 1 mm, as shown in Fig. 22 (b).

iii. Growth of depth hoar in a cavity: On March 13, 1968, active snow melt took place at the surface of a snow cover during the daytime at Toikanbetsu in the northern Hokkaido. At night weather was fine, and air temperature rapidly dropped down to $-12°C$. Next morning, it was observed that a large number of

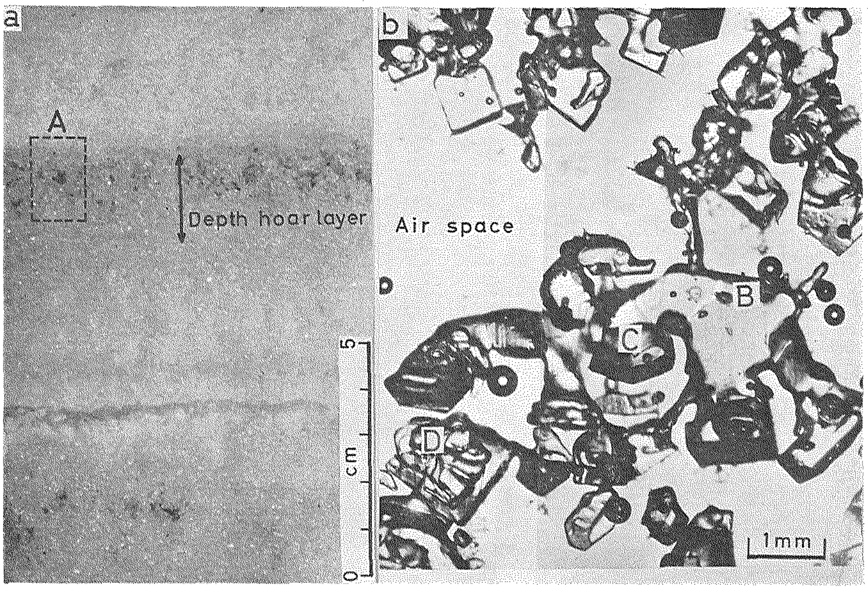


Fig. 22 Depth hoar crystals in a natural snow cover.
(a) A vertical section of snow layers in which depth hoar developed.
(b) A vertical thin section of the part A in (a).
B: A grain of original granular snow,
C: Solid-type depth hoar,
D: Skeleton-type depth hoar

tiny skeleton-type depth hoar crystals with the shapes of cup and plate had grown downward on the underside of the surface crust of the snow cover. Fig. 23 (a) and (b) are respectively a view of the depth hoar of the crust which was looked at upward from beneath and looked at sideways horizontally. These crystals had developed in a large cavity right beneath the icy surface of the crust as short as over-night under a large negative temperature gradient, obtaining a sufficient supply of water vapour from wet and warm snow at a deeper level, which had been metamorphosed into coarse grained granular snow fully down to the bottom.

iv. Growth of depth hoar in a graupel layer in a snow cover: On January 25, 1968, a layer of graupels, 5 cm thick, was deposited on a snow cover by precipitation. On March 6 the solid-type depth hoar growth was observed only in a graupel layer; at that time, the graupel layer was found at a depth of 40 cm beneath the surface of the snow cover by successive snow deposition since January 25. The original texture of the graupel layer had had a large air space, several mm in diameter between graupels, and thick plate solid-type crystals grew on the bottom surface of the graupels downward, as shown in Fig. 24. These depth hoar

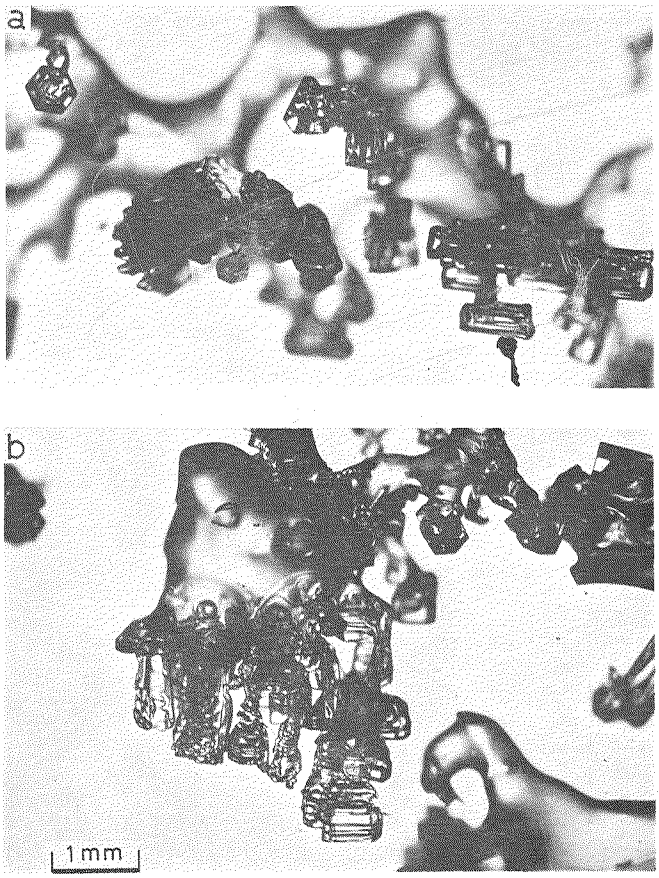


Fig. 23 Depth hoar crystals grown downward on the underside of the surfce crust of a snow cover, only by one night.
(a) Viewed upward from beneath,
(b) Viewed sideways horizontally

crystals were developed in 40 days under a small negative temperature gradient. The graupel layer had a fairly large air space in it, and was fragile mechanically even 40 days after deposition.

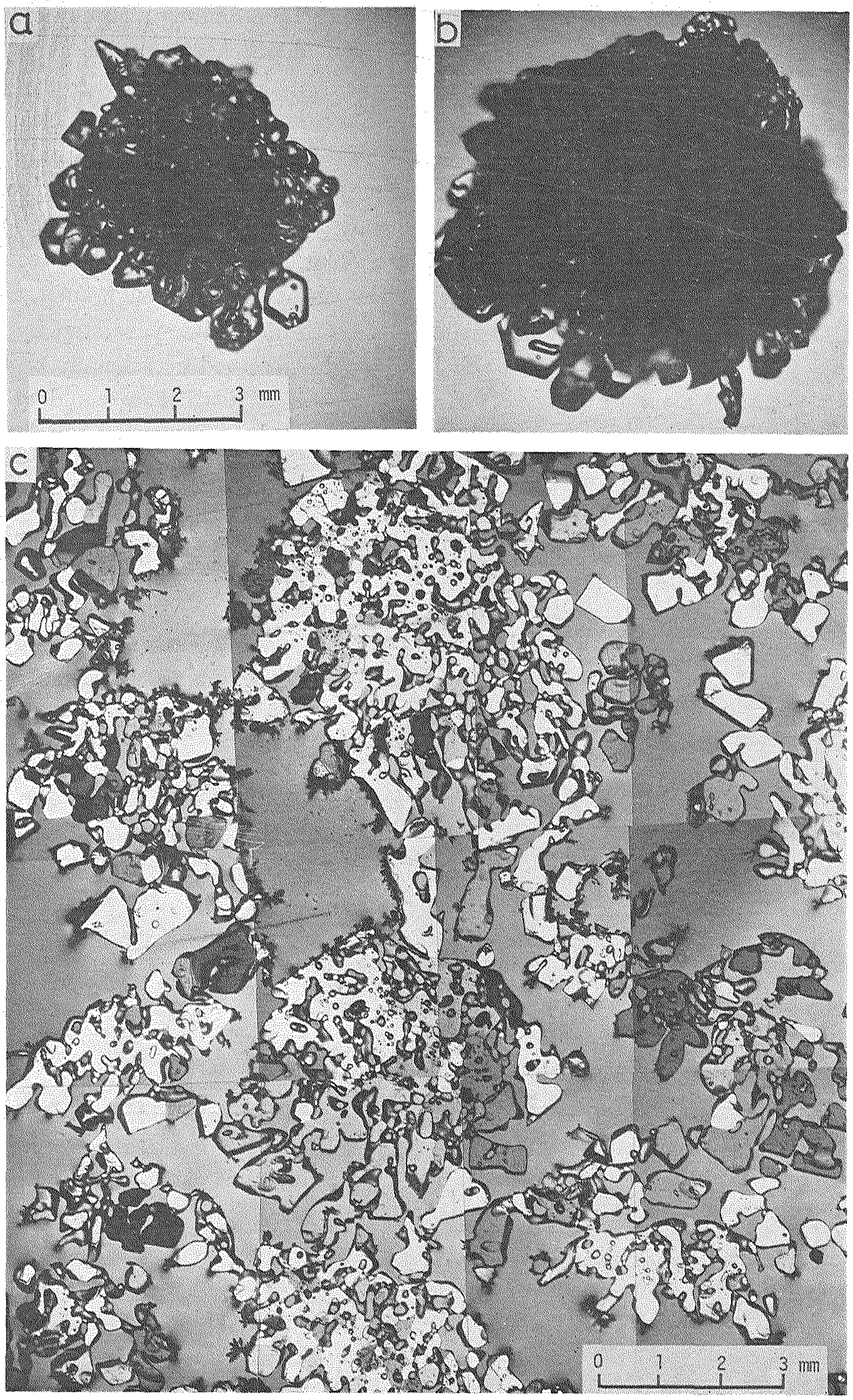
III. 3. *Relation Between Texture of Original Snow and Metamorphosis to Depth Hoar*

Depth hoar crystals grow in a snow cover under a negative temperature gradient in snow through sublimatic evaporation, diffusional migration and sublimatic condensation of water from/onto snow grains. A general tendency of development of depth hoar is as follows:

If the growth conditions were maintained constantly, a number of minute

---

Fig. 24 Hoar crystals grown in a graupel layer in a snow cover.
(a), (b) A graupel and hoar crystals grown on the graupel's bottom surface.
(c) Vertical thin section of a graupel layer with depth hoar grown


a
0 1 2 3 mm
b
c
0 1 2 3 mm

depth hoar grow in snow at the first process. Then, they grow to larger crystals by lapse of time, decreasing the number of crystals by obtaining a supply of water vapour from warmer snow grains and even from depth hoar crystals at a lower level in the snow.

From the previous experiments and field observations, it became clear that a relation existed between the texture of the original snow and the crystal size of depth hoar. The control factor of the relation was "the size of an air space" of the original snow, namely, large crystals could grow in a large air space, while small crystals in a small air space. (In the Polar region where a snow cover is preserved for more than several years near the surface without snow melt, repetition of growth of depth hoar may enlarge the size of an air space step by step; finally, very large skeleton-type depth hoar can be observed occasionally.) In an ordinary case of a natural snow cover, large crystals of depth hoar could grow in new snow, lightly compact snow, some of fine grained compact snow and coarse grained granular snow of low density, all with a large air space in them. Let us define this group of snow as A. On the contrary, in most of fine grained compact snow and coarse grained granular snow of medium and high density with a small air space, only minute crystals could grow. Let us name this group C. Group B consisted of some of fine grained compact snow and coarse grained granualr snow of medium density, with the medium size of an air space. A qualitative graphical expression of this relation is given by Fig. 25 (a). The grain size was measured

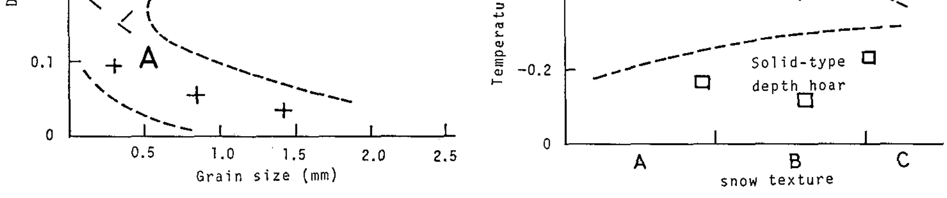


Fig. 25 Relation between texture of original snow and metamorphism under a negative temperature gradient.
(a) Relation between the types of metamorphosed snow A, B and C, and properties (grain size and density) of original snow.
(b) Relation between the crystal shape of depth hoar, texture of original snow, and temperature gradient

by the diameter of an equi-areal circle for round-shaped grains, by the longest axis for bar-shaped grains, and by the diameter of an envelope circle for new snow crystals. The grain size can be an index indicating the size of an air space in snow. There is no real snow corresponding to the blank areas in Fig. 25 (a).

A dependence of crystal shapes of the depth hoar metamorphosed from each group of snow (A, B and C) on the temperature gradient is also qualitatively given by a graphic expression in Fig. 25 (b). In the upper right area of the diagram, a peculiar-type depth hoar of extremely complicated fine structure (as shown in Fig. 32 (c), Section IV. 2) was observed, which was tentatively named "hard depth hoar" as it was very hard. "Hard depth hoar" developed in a small air space generally, under a fairly large magnitude of negative temperature gradient. It might be an assembly of minute skeleton-type or solid-type depth hoar, or the third type of depth hoar which was basically different from either of them. A further investigation is necessary to shed light on it.

IV. Mechanical properties of depth hore

IV. 1. *Relation Between Density and Hardness of Depth Hoar*

As mentioned previously, a solid-type depth hoar layer looks very similar to a fine grained compact snow layer, while a skeleton-type depth hoar layer has its own unique feature. Such a difference of the shapes between the two types of depth hoar crystals is reflected on their mechanical properties, as a matter of course. Mechanical properties of a solid-type depth hoar are generally represented by those of the original snow.

On the contrary, skeleton-type depth hoar has particular mechanical properties. Figure 26 shows a microstructure of cup crystals of skeleton-type depth hoar. It can be seen that cup crystals, having a large crystal body and a thin joint at the base individually, are linked vertically forming a column. Kojima (1956) derived a conclusion on mechanical properties of (skeleton-type) depth hoar from his experiment, namely, "Coefficients of vertical compressive viscosity of (skeleton-type) depth hoar are larger than those of fine grained compact snow, but the mechanical strength of the depth hoar against a large dynamic force or a static force is much smaller than that of fine grained compact snow". Kojima's conclusion may be explained by the microstructure of skeleton-type depth hoar shown in Fig. 26, as a vertical columnar structure of skeleton-type depth hoar shows a larger strength against a vertical force than fine grained compact snow which has a complicated network of ice bonds but not a paticular vertical structure. At the same time, it can be said that even for a vertical force, if the force exceeded a certain value which produced a stress larger than the yield stress of ice in the ice

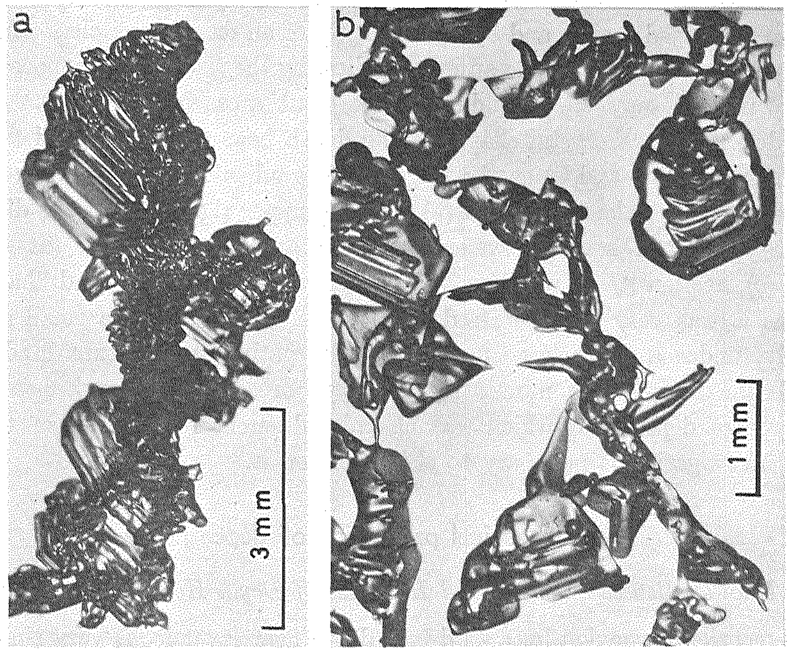


Fig. 26 Microstructure of a skeleton-type depth hoar crystal
(a) Hoar crystals linked vertically,
(b) Vertical thin section of a skeleton-type depth hoar layer: structure of a cup crystal is seen in the upper-right corner

joint of the depth hoar, the destruction of the vertical column, which has no other support, proceeds very quickly. And further, it is clear that skeleton-type depth hoar is very fragile especially against a lateral force, because it scarcely has a structure supporting itself horizontally, while the network of ice bonds of fine grained compact snow is fairly isotropic. Such peculiar mechanical properties of a skeleton-type depth hoar layer may occasionally trigger off an avalanche.

As it was considered that an increase of ice in a depth hoar deposit might increase its mechanical strength (by an increase of a vertical structure in size, in number, or in other ways), a relation between density and hardness of skeleton-type depth hoar was investigated by the use of as many kinds of samples as possible, including polar depth hoar from Alaska and Antarctica. The hardness was measured by Kinosita's gauge. The result is given in Fig. 27, where white circles represent depth hoar of Hokkaido, and solid circles that from Alaska and Antarctica. A solid line in the diagram shows a relation between density and hardness of natural fine grained compact snow of Hokkaido derived by Kinosita (1960).

A curve showing a relation between these two parameters of skeleton-type

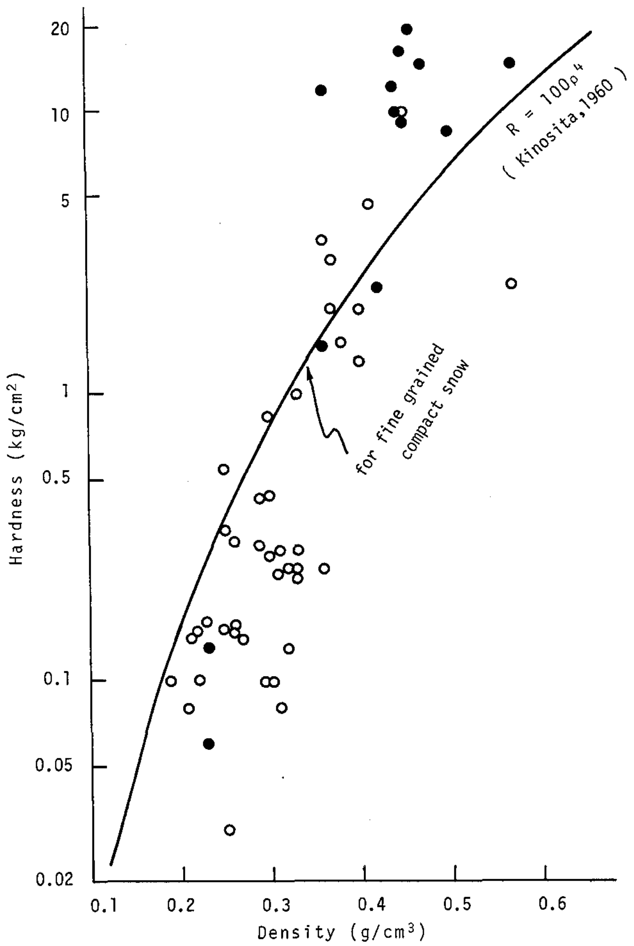


Fig. 27 Relation between density and hardness of natural depth hoar (mostly of the skeleton type)
○: Depth hoar of Hokkaido
●: Polar depth hoar (Alaska and Antarctica)

depth hoar is steeper than that of fine grained compact snow, making an intersection at a density value of 0.35 g/cm³ approximately. This means that the hardness of a common depth hoar, the density of which is generally less than 0.35 g/cm³, is less than that of fine grained compact snow with the same density, while the hardnesses of some special kinds of depth hoar such as polar depth hoar and others, the densities of which are more than 0.35 g/cm³ approximately, are larger than the hardnesses of fine grained compact snow with the same density.

IV. 2. *Change of Hardness of Snow by Development of Depth Hoar*

(1) *Sintering of Snow and Development of Depth Hoar*

In the previous experiments of depth hoar growth, it was noticed that metamorphosed snow occasionally had become harder than the original. Two reasons for the hardening of snow were considered as follows:

i. Sintering of ice: When two ice particles contact with each other at a point, an ice bond connecting these two particles grows thicker by lapse of time. Such thickening of a ice neck is called sintering of ice, and its mechanism is considered in four ways: by plastic flow of ice, by evaporation — diffusion — condensation of water vapour, by volume diffusion or by surface diffusion of a water molecule to the neck of the ice bond to make the surface energy of the new ice particle minimum. Sintering of ice increases the mechanical strength of snow, as well known by Peter-snow.

ii. Development of depth hoar: Although correct mechanisms are still not clear, it is experimentally presumed that the development of depth hoar may increase the hardness of snow depending on a case.

An experiment was carried out to confirm the contribution of these two mechanisms to the hardening of snow. An experimental device used was a thermally insulated box with 3 sections, A, B, and C, as shown in Fig. 28. Each section of the box was filled uniformly with seived snow comprising grains smaller than 2 mm in diameter; the box was stored in a cold room at −7°C until snow temperature became in equilibrium to room temperature. Then, section B was covered with a thick lid made of foam-stylene (thermal insulator), and section C with a thin foam-stylene lid; and the box was put in another cold room at −20°C for 7 hours. Snow temperature was measured by six thermocouples continuously at the top surface and at 1.8 cm below the surface in each section. Under such an experimental condition, temperature gradients occurred in snow immediately beneath the top surface of the samples which are given in Table 4. The original

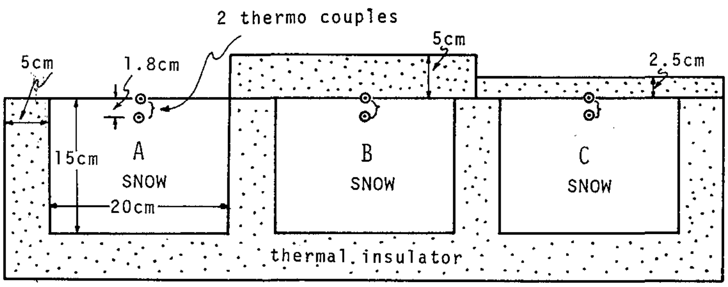


Fig. 28 Experimental device (Effect of temperature gradient on hardening of snow)

Table 4 Hardening of snow (see Figs. 28, 29)

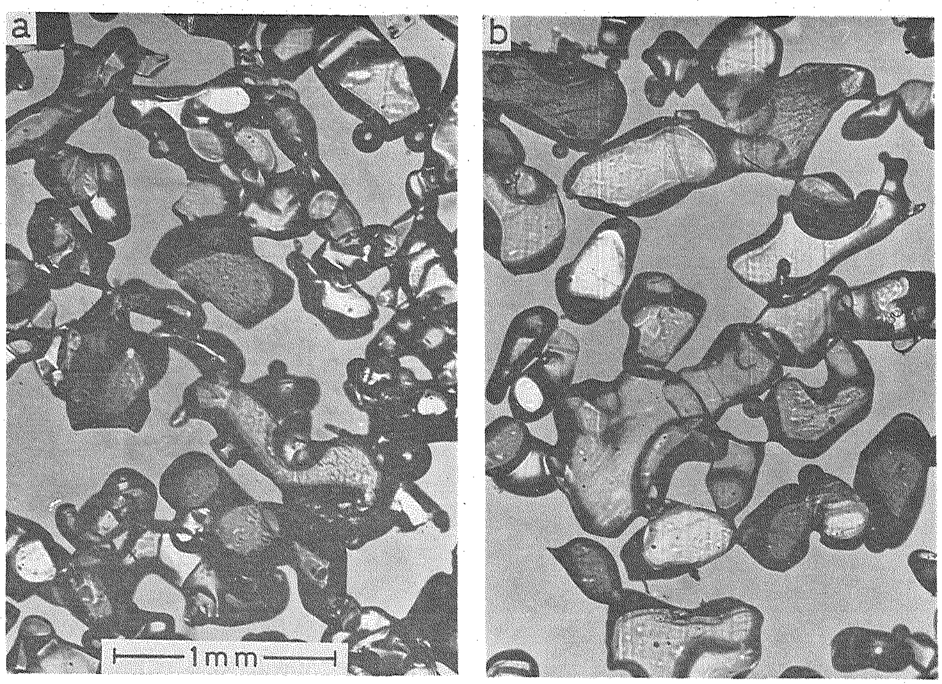
Sample	Metamorphosed in a thermal insulation box	Original density g/cm³	Temperature gradient : °C/cm		R : kg/cm² after 7 hrs.	Original density g/cm³	R : kg/cm² after 63 hrs.
			Start (of the experiment)	after 7 hrs.			
A	without lid	0.43	-1.9	-0.4	4.6	0.40	5.8
B	with a thick lid	0.42	extremely small		1.1	0.39	2.7
C	with a thin lid	0.43	-0.3	-0.1	1.4	0.40	3.0

snow density and the final hardness of snow at the top surface of the sample are also given in Table 4. Although the original hardnesses of the surface snow of the samples were not actually measured, it is reasonably presumed that they were almost the same as at the start of the experiment, as the samples were prepared uniformly by a single procedure of seiving, and as the original surface snow densities of the samples were almost the same, 0.42–0.43 g/cm³. When the experiment was over, the surface hardness of Sample A was about 3 times that of Sample C, and more than 4 times that of Sample B.

It may be considered that Sample B was maintained, as a matter of fact, almost at −7° uniformly, without a remarkable temperature gradient inside, and was metamorphosed only by sintering, while the other two Samples A and C were metamorphosed both by sintering and by development of depth hoar, more or less, during 7 hours under negative temperature gradients. Figure 29 shows the microstructure of metamorphosed snow, (a) Sample A and (b) Sample B. A very clear difference in structure between Samples A and B is not observed from these pictures, probably because the experiment was too short for remarkable depth hoar crystals to grow. But some trace of growth of solid-type depth hoar can be observed in Sample A, as shown in Fig. 29 (a), while no trace of growth of depth hoar was observed but some progress of sintering was detected in Sample B, as shown in Fig. 29(b). Therefore, we are compelled to ascribe the reason for the difference of hardness of the metamorphosed snow samples, given in Table 4, to the development of depth hoar.

Another experiment was carried out by the same procedure for 63 hours. The result is also given in Table 4. In this case, the surface hardness of Sample A was only up to twice or less that of Samples B and C, when the experiment lasting 63 hours was over.

From these two experiments, it may be concluded as follows. A large difference of hardness among metamorphosed snow samples in the beginning process of the experiment (6 hours) was caused by the fact that Sample A was hardened



Sample A Sample B

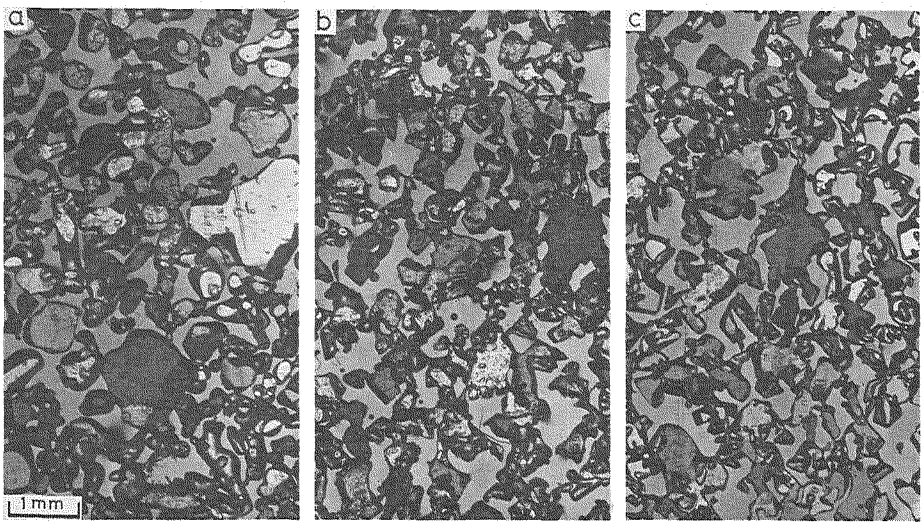
Fig. 29 Metamorphoses of seived snow (7 hours)

both by sintering and by growth of depth hoar due to the existence of a large negative temperature gradient near the exposed surface, while Sample B was hardened only by sintering due to almost a uniform temperature distribution in snow. On the contrary, a decrease of difference of hardness between samples A and B in the final stage of the experiment (63 hours) was caused by the fact that the hardening of Sample A proceeded only by sintering at –20°C, after snow temperature became in equilibrium to room temperature (–20°C), while the hardening of Sample B proceeded by sintering at a higher temperature than Sample A due to the thermal insulation of the sample*, and perhaps also by some development of depth hoar due to a small temperature gradient by the insufficient insulation of heat.

The third experiment was carried out to confirm the contributions of sintering and development of depth hoar to the hardening of snow. Three samples A, B and C taken from a uniform deposit of seived snow consisting of grains smaller than 2 mm in diameter were prepared in each individual box. Sample A was

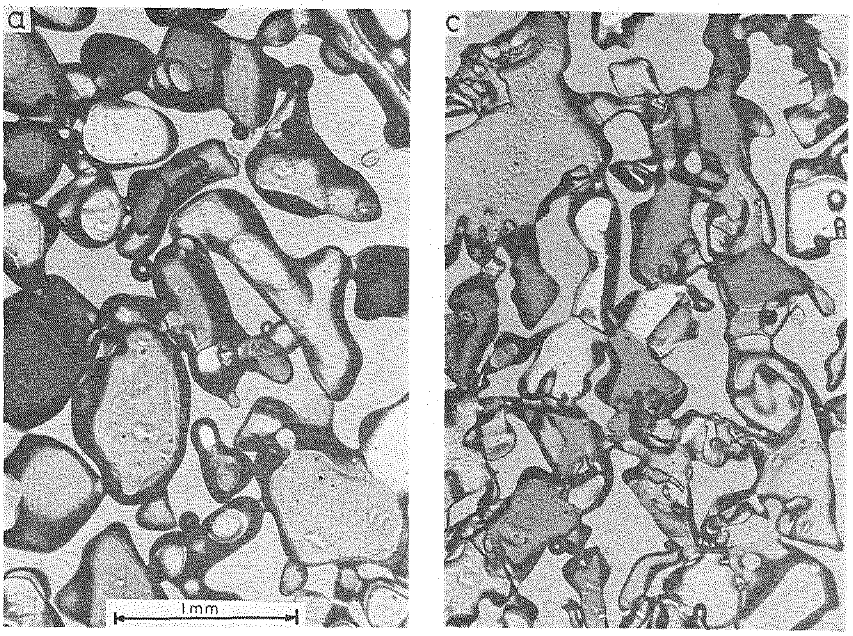
* Progress of sintering decreases exponentially, as the temperature decreases.

stored in a cold room at -7°C without applying an artificial temperature gradient, while Samples B and C were subjected to negative verical temperature gradients of -0.39°C/cm and -0.50°C/cm respectively for 5 days; snow temperature near the top surface of Samples B and C were constantly maintained at -9.5°C and -8.7°C respectively. Five days later Samples B and C were moved to the cold room at -7°C, where Sample A had been stored, and stored there until the snow temperature of the samples became in equilibrium to room temperature. Then hardnesses of the samples were measured by Kinosita's gauge. The results of the measurements and the microstructure of each sample are given in Fig. 30. The hardness of Sample A, hardened only by sintering of ice, was 1/6 smaller than that of Sample B and 1/8 smaller than that of Sample C, active development of depth hoar took place in both samples, as shown in the pictures of Fig. 30. Fig. 31 shows the microstructure of metamorphosed snow of Samples A and C in more detail. In Fig. 31 (a), only the progress of sintering of ice through the thickening of ice bonds connecting snow grains can be seen, while the active development of solid-type depth hoar can be seen in Fig. 31(c) together with the progress of sintering.



Sample A	Sample B	Sample C
Original density 0.50 g/cm^3, uniform temperature of -7°C, 5 days, R: 3 kg/cm^2 (Kinosita's hardness)	0.45 g/cm^3, -0.39°C/cm at -9.5°C, 5 days, R: 18.4 kg/cm^2	0.50 g/cm^3, -0.50°C/cm at -8.7°C, 5 days, R: 24.0 kg/cm^2

Fig. 30 Metamorphoses of seived snow (5 days)



Sample A Sample C

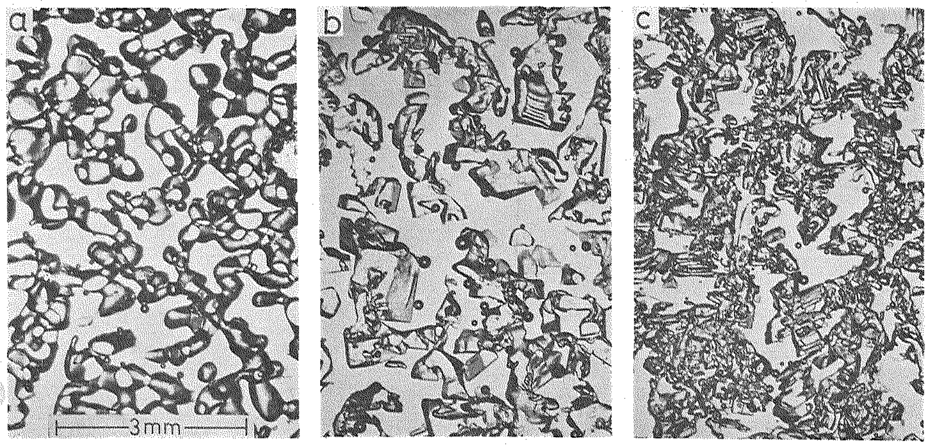
Fig. 31 Detail of samples A and C of Fig. 30

(2) *Change of Hardness of Snow by Development of Depth Hoar*

Negative temperature gratients of –0.33°C/cm at –7.1°C and –0.90°C/cm at –6.5°C were applied to two snow samples A and B, prepared from the same block of fine grained compact snow, 0.36 g/cm^3 in density and 2.3 kg/cm^2 in hardness, respectively. Ten days after the start, the hardness of Sample A had decreased down to 1.8 kg/cm^2, while that of Sample B had increased up to 6.9 kg/cm^2 which was 3 times the original value. Such a remarkable difference of mechanical property between these two samples seem to be explained by the difference of their textures. As is seen in Fig. 32 (b), metamorphosed snow of Sample A has a scanty connection among snow grains, mostly depth hoar crystals. On the contrary, Fig. 32 (c) shows that skeleton-type depth hoar has been well developed in Sample B, and moreover a large number of minute crystals have cemented them.

Summarizing the results of the experiments in both the previous section (Fig. 30, Section Ⅳ. 2. 1.) and this section mentioned above, it can be concluded that change (increase or decrease) of hardness of snow by the development of depth hoar is controlled not only by the magnitude of negative temperature gradients applied but also by the density (texture) of the original snow.

A series of experiments were carried out to investigate a relation between



Original snow 0.36 g/cm^3, R: 2.3 kg/cm^2, (Kinosita's hardness).

Sample A
−0.33°C/cm at −7.1°C, 10 days, R: 1.8 kg/cm^2

Sample B
−0.90°C/cm at −6.5°C, 10 days, R: 6.9 kg/cm^2

Fig. 32 Change of hardness by development of depth hoar

these parameters. Thirty-six snow samples were subjected to individual negative temperature gradients for 1–10 days; some of the samples were subjected to a temperature gradient for a long period (10 days) when the magnitude of temperature gradient was small, to emphasize the effect of the development of depth hoar. The hardnesses and densities of both the original and the metamorphosed snow were measured, whereby the mean value of hardness obtained from 5 measurements was taken as the hardness of each sample. The density of snow hardly showed any remarkable change by metamorphism. The results were plotted in a diagram in terms of density of the original snow vs. magnitude of negative temperature gradient in Fig. 33. Graphic symbols used in the diagram are:

○: Hardness increased,

⊕: Hardness did not change (including change less than 10% of the original value),

+: Hardness decreased, through metamorphisim (development of depth hoar).

The modes of changes in hardness subsequent to metamorphosis of snow are distributed roughly in three divisions: A represents a division for an increase in hardness, B for no or marginal change, and C for a decrease. The modes of change in hardness of the metamorphosed snow are looked at from a standpoint of the original snow as follows:

i. Hardness of snow (with the original density less than 0.26 g/cm^3) decreases by metamorphosis, regardless of the magnitude of negative temperature gradient.

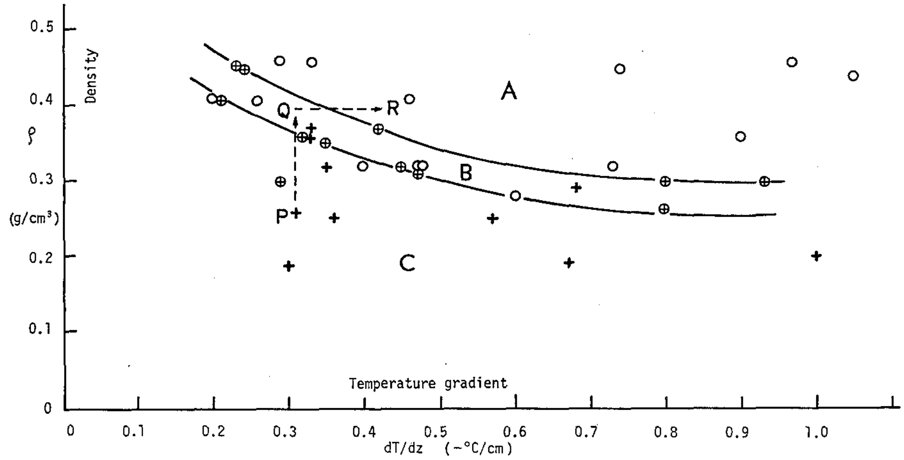


Fig. 33 Change of hardness of snow by metamorphism under negative temperature gradients.
○: Hardness of snow increased through metamorphism,
⊕: Hardness changed scarcely,
+: Hardness decreased

ii. Hardness of snow (with the original density more than 0.26 g/cm^3) decreases, changes scarcely, or increases, according to the magnitude of negative temperature gradient.

iii. As a special case, when snow was subjected to a magnitude of negative temperature gradient larger than -0.5°C/cm (which is fairly a large value in natural conditions, and occurs only in a special case) for example, hardness of snow (with the original density more than 0.35 g/cm^3) increases greatly in a layer near the surface of a snow cover, when the surface temperature drops rapidly under conditions including a sudden visit of cold weather, an active surface radiation from the snow surface, and a strong cold wind. Since the hardness of polar depth hoar and foot-packed snow for a ski race course exceeded that of fine grained compact snow, it is considered that these cases may correspond to this special case mentioned above, whereby the polar depth hoar, so-called "hard depth hoar" (Section III. 3.) may be comparable with the "hard snow of mt. Daisetsu" by Aburakawa (1972).

If a snow deposit with a density less than 0.26 g/cm^3, for example, the snow at point P in division C of Fig. 33, is subjected to a negative temperature gradient of any magnitude, large or small, it is metamorphosed to a "fragile" depth hoar with a hardness less than the original, which increases avalanche hazard and causes inconvenience to race skiing. If we artificially densify snow P (0.25 g/cm^3 in density as it is) up to say point Q (0.4 g/cm^3 in density) in division B by foot packing or by any other mechanical ways, the densified snow will be subjected to such a larger temperature gradient, say as at point R in division A, than original situation P even under the same air temperature because of a decrease of its thickness. Such a consideration will lead to a procedure to make soft and light snow into hard and sturdy depth hoar.

Without a correct understanding about the mechanism of the foregoing process, it has been tried properly to prevent an avalanche release by making a number of snow step lines, by foot packing, along the contours of slopes near highways, rail roads and workmen's houses in mountaneous terrains of Hokkaido. Further, active efforts were concentrated to harden snow at ski race courses in Mt. Eniwa and Mt. Teine, Hokkaido, in preparation for downhill, giant slalom and slalom competitions in the XI Olympic Winter Games, Sapporo, 1972. The artificial densification of snow by over-snow vehicles and by foot packing was applied almost everyday during the period of the preparations. As the results, very hard and sturdy ski race courses, mainly composed of "hard depth hoar", were completed; very thick fragile depth hoar layers have been observed to grow in a snow cover in the Mt. Eniwa area. These are practical examples of the hardening of snow by the aid of growth of hard depth hoar; of course, a contribution of progress of sintering to the hardening of snow should also be noticed.

V. Transference of water vapour in snow

V. 1. *Mechanism of Transference of Water Vapour and Heat in Snow*

(1) *Transference of Water Vapour and Heat in Snow*

The rate of water vapour supply upward from lower and warmer part of a snow cover controls the growth rate of depth hoar in snow. The present author has developed his investigation on the growth of depth hoar with a viewpoint of transference mechanism of water vapour by a evaporation-diffusion-condensation process between neighbouring grains; this mechanism is concerned with "Hand to hand delivery by diffusion of water vapour" as was mentioned by Yosida.

Seligman in the past and de Quervain and Benson recently suggested that natural convection of air occur in a snow cover when it is subjected to a large negative temperature gradient, and it accelerates the growth of depth hoar with water vapour carried by it, in addition to the diffusion of water vapour. If a natural convection occurs in snow, it transfers water vapour together with heat upward. A natural convection of fluid takes place in a layer, when the temperature difference in the fluid between the top and the bottom of the layer reached a certain magnitude which was determined by the thickness of the layer. The present author intended to find the occurrence of natural convection of air by observations of heat flow in snow.

(2) *Transference of Heat in a Snow Cover*

During the cold winter season, a snow cover on the ground is subjected to a negative temperature gradient, as a whole, and heat flows from the ground into a snow upward. Direct measurements by a heat meter told us that the quantity of heat flowed from the ground upward into a snow cover was several cal/cm^2·day in the cold winter season on the mountain ridge of the Avalanche Research Station, Toikanbetsu. Transference of heat in a snow cover can be divided into 3 mechanisms, as shown by a model in Fig. 34 (a).

i. Thermal conduction through an ice network and an air space of a snow cover: Thermal conductivity of air is negligibly small, about one hundredth smaller than that of ice. Heat flow by thermal conduction through ice is indicated by bold broken arrows in the schema.

ii. Diffusion of water vapour through an air space: Due to the existence of a negative temperature gradient in snow, water vapour migrates upward, from a lower and warmer grain to an upper and colder grain through a process of evaporation — diffusion — condensation: water vapour takes the laten heat of evaporation away from the lower grain, and releases the same amount of the

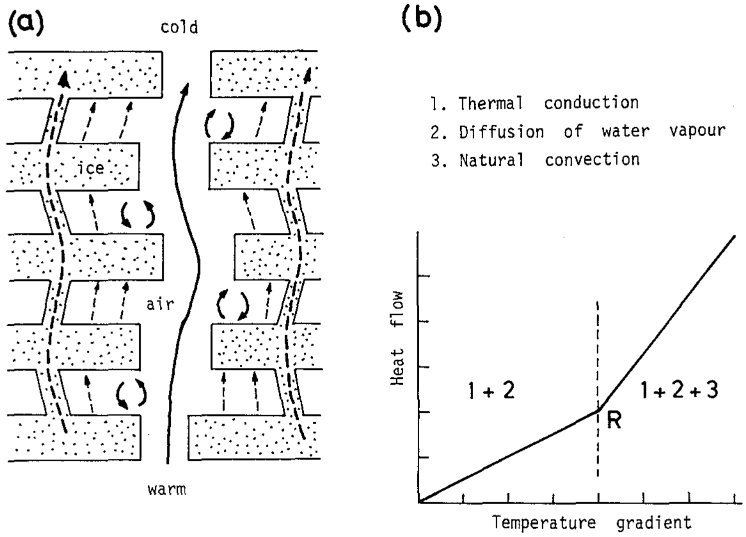


Fig. 34 Heat flow in a snow cover
(a) Schema of mechanism of heat flow in snow
(b) Heat flow vs. temperature gradient in snow

latent heat of condensation at the upper grain. The heat flow by diffusion of water vapour is indicated by fine broken arrows.

iii. Natural convection of air in an air space: When the temperature difference between the top and the bottom of a certain layer of snow reached a critical value, referring to the thickness of the layer, natural convection of air occurs by the difference of density of air between the top and the bottom. Water vapour is transferred upward by a convectional current, accompanying heat. Two types of convection can be considered as indicated by solid arrows in the schema: Small-scale convection occurring in a small air space between snow grains, and large-scale convection in a certain snow layer through channels of networks of air spaces.

A schematic diagram of heat flow rate in snow against a temperature gradient is shown in Fig. 34 (b). Heat flow rate in snow increases proportionally to a temperature gradient in the region of small temperature gradients where only thermal conduction through ice and diffusion of water vapour through the air space contribute to the transference of heat. If natural convection occurres at critical point R, heat flow rate in snow increases abruptly with an increase of a temperature gradient from point R, getting a contribution to transference of heat by a convectional current in addition to those by thermal conduction and diffusion of water vapour, mentioned above.

V. 2. *Natural Convection of Air in Snow*

(1) *Experimental Method*

In consideration of the account described above, a series of experiments of heat flow measurement in snow was carried out to investigate the occurrence of natural convection of air in snow.

An experimental device is shown in Fig. 35. This is a kind of improved one of the previous device (Fig. 1, Section II. 2. 1.). A wooden box was divided into three sections, top, middle and bottom sections. Both in the top and bottom sections, a set of an electric heater with a thermo-regulator and an electric fan was installed respectively, and only 4 lateral sides were thermally insulated by foam-stylene boards 10 cm in thickness. A snow sample (20 cm$\times$20 cm$\times$15 cm) was set in the central cabinet, and was subjected to a temperature gradient, either positive or negative. By aid of heat diffuser A (a copper plate 1 cm thick), and an electric fan to stir the hot air in the heat source section, temperature distribution at the top and the bottom surface of the sample could be maintained very uniformly at the proper temperature. Snow temperatures at 5 levels in the sample were measured by five sets of thermo-couples, and heat flow rates in a steady state by heat meter B (a set of thermo-pile, 20 cm$\times$20 cm$\times$1 cm), set immediately

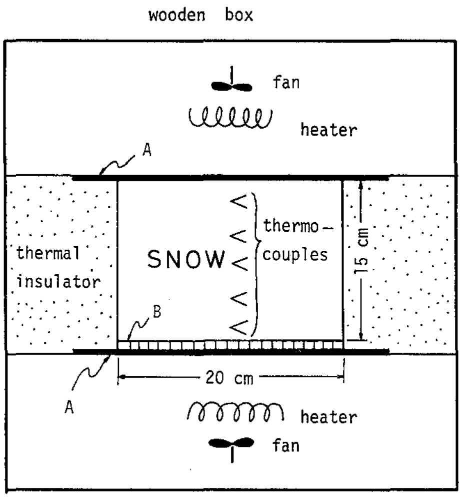


Fig. 35 Experimental device (heat flow in snow)
A: Copper plates (diffuser of heat)
B: Heat meter

beneath the bottom of the sample. Calibration of the heat meter had been made by a standard ceramic specimen. The relation between heat flow rate Q (10^{-3} cal/cm^2·sec) and electromotive force E (mV) derived from the heat meter, obtained by the calibration, was

$$Q = 0.31\,E\,.$$

This relation was also valid for the reverse flow of heat.

(2) *Thermal Conductivity of Snow*

Thermal conductivity of fine grained compact snow of 0.46 g/cm^3 in density was measured by the use of this device. The result was plotted in a diagram of heat flow rate vs. temperature gradient, in Fig. 36: graphic symbol ○ is for upward heat flow by a negative temperature gradient; + for downward heat flow by a positive temperature gradient. Relations between these two parameters for the upward and the downward flow of heat shows a good agreement, on the same straight line; this means that natural convection of air in the snow did not occur under such a condition.

One can calculate the thermal conductivity of snow, by the relation,

$$Q = \mu_s \frac{dT}{dz}$$

where, Q : heat flow rate (cal/cm^2·s),

$\frac{dT}{dz}$: temperature gradient (°C/cm),

μ_s : coefficient of thermal conductivity (cal/cm·s·°C).

The coefficient of thermal conductivity of this sample was 2.15×10^{-3} cal/cm·s·°C, which was independent of the magnitude and sign of temperature gradient in this experimental region.

Coefficients of thermal conductivity of various snow* were also measured by

* Samples covered various kinds of snow, new snow (0.12 g/cm^3 in density)→fine grained compact snow→artificially compacted high density snow→commercial ice.

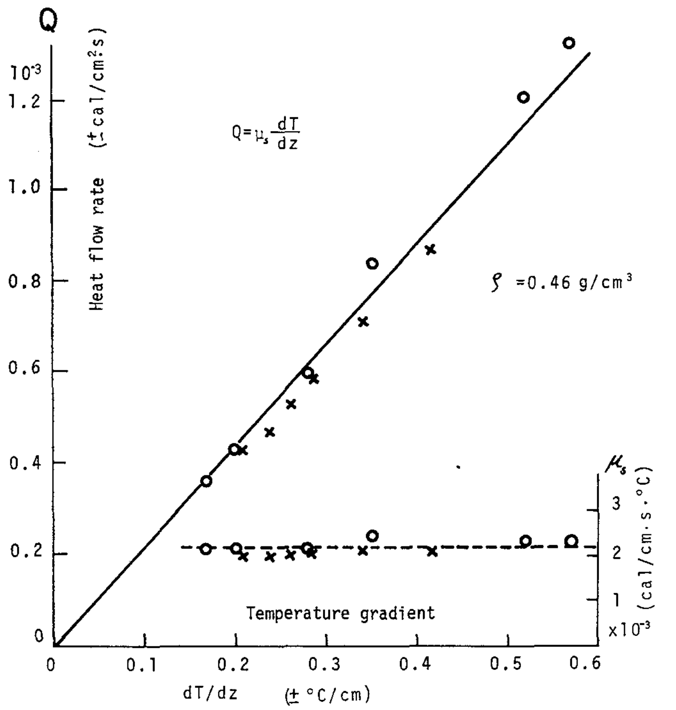


Fig. 36 Heat flow rate (Q) and thermal conductivity (μ_s) against temperature gradient (dT/dz),
○: Upward heat flow in snow,
×: Downward heat flow in snow

this device, under temperature gradients of -0.2∼-1.0°C/cm, at 0∼-15°C, and without occurrence of natural convection of air in the sample.

The results were plotted in a diagram of thermal conductivity vs. snow density in Fig. 37. From these results, the following two experimental formulae were derived:

$$\log_{10} \mu_s = -3.6 + 1.8\, \rho_s$$

for snow of density smaller than 0.65 g/cm³,

$$\log_{10} \mu_s = -3.0 + 0.9\, \rho_s$$

for snow of density larger than 0.65 g/cm³,

where ρ_s is density in g/cm³, and μ_s thermal conductivity in cal/cm·s·°C. A broken line in the diagram shows the relation between these two parameters experimentally obtained by Yosida (1947). Such a disagreement between these two results, Yosida's and the present author's, might have been resulted from the difference of devices and procedures.

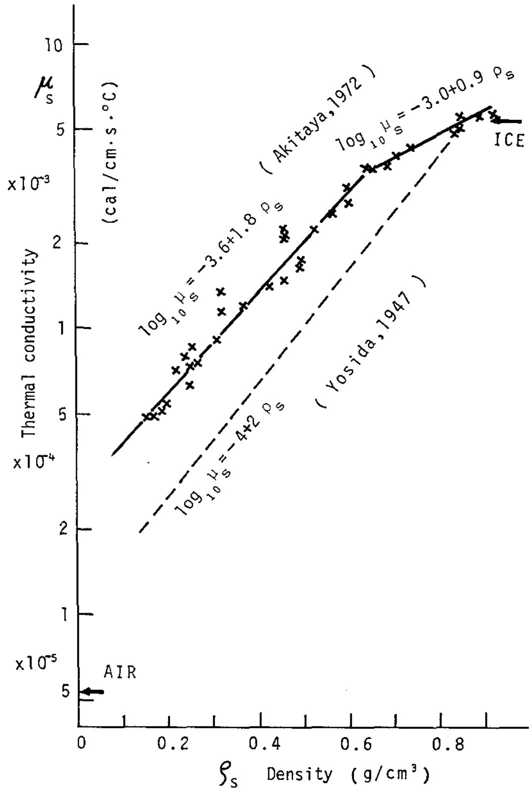


Fig. 37 Density and thermal conductivity of snow

(3) *Natural Convection of Air in Snow*

When a vertical negative temperature gradient is generated in a layer of fluid, the equilibrium of the fluid in the layer becomes unstable: the higher is a level in the layer, the colder and the heavier is the fluid. However, natural convection does not occur under the smaller magnitude of negative temperature gradient than the critical value, because the flow of fluid upward and downward is prevented by viscosity and thermal conductivity of the fluid; the latter acts as to uniformalize temperature distribution. In the case of convection of air in snow, the texture of snow (a pack of snow grains) prevents an air flow, moreover.

As it was considered that the less is the resistence to an air flow (the more the air permeability) of snow, the easier is the occurrence of natural convection of air in the snow, the following experiments were carried out.

A series of negative temperature gradients down to $-2.0°C/cm$ was applied to three different kinds of natural snow samples (20 cm×20 cm and 15 cm thick):

new snow, lightly compact snow and fine grained compact snow with densities of 0.12, 0.17 and 0.27 g/cm^3, respectively. The resultant relation between temperature gradient and heat flow rate were given in Fig. 38: natural convection of air did not occur in the snow samples under such a condition.

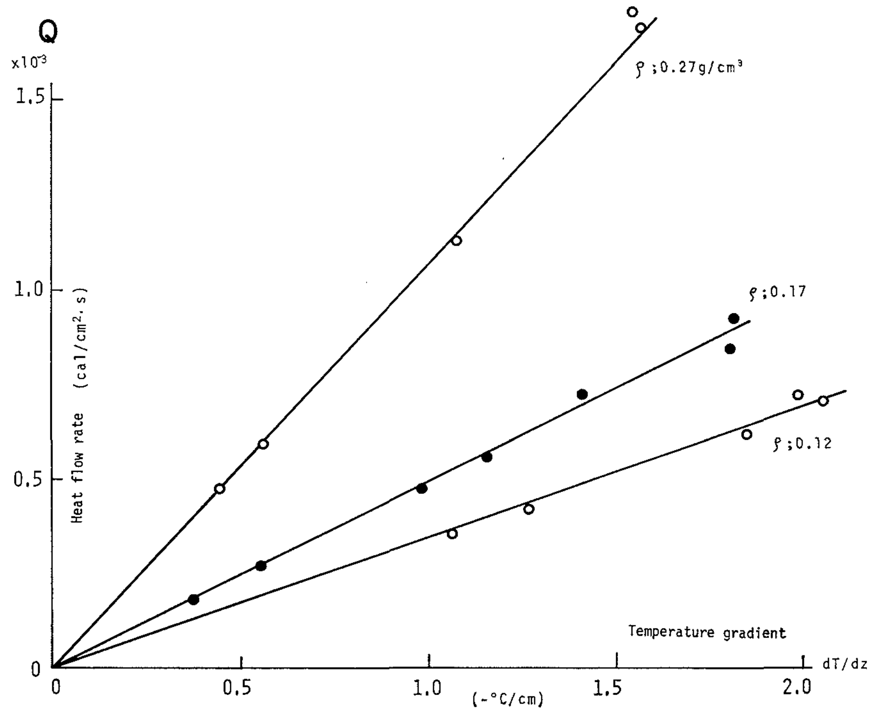
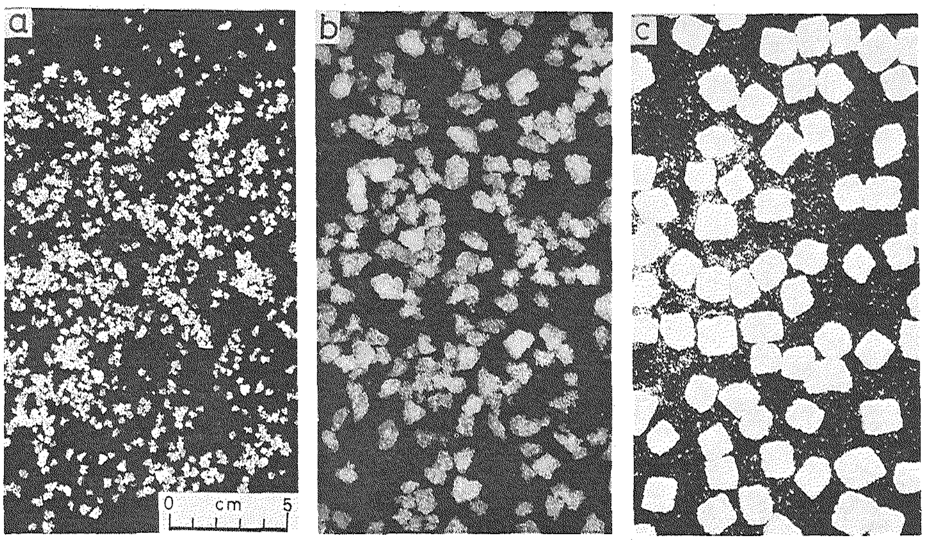


Fig. 38 Temperature gradient and heat flow rate

The second experiment was carried out by seived snow samples with large air permeabilities. A block of coarse grained granular snow was crushed, and two kinds of seived snow samples were prepared: grains of Sample A (2–5 mm in diameter, 0.33 g/cm^3 in density) and Sample B (5–10 mm, 0.28 g/cm^3), are shown in Fig. 39 (a) and (b). The results were straight lines down to –1.7°C/cm of temperature gradient, as shown in Fig. 40: natural convection of air still did not occur in the samples of such seived snow.

The final experiment was carried out by specially prepared artificial samples of snow, with a very large air space (accordingly large air permeability). A number of snow cubes (15 mm$\times$15 mm$\times$15 mm) were cut out of a block of fine grained compact snow, as shown in Fig. 39 (c). Three samples C, D and E were



D: 2~5 mm
Sample A

D: 5~10 mm
Sample B

D: 15 mm
Sample C, D and E

Fig. 39 Grains of the sample for experiments on natural convection of air in snow:
(a), (b) Seived snow of coarse grained granular snow,
(c) Snow cubes (15 mm×15 mm×15 mm) of fine grained compact snow

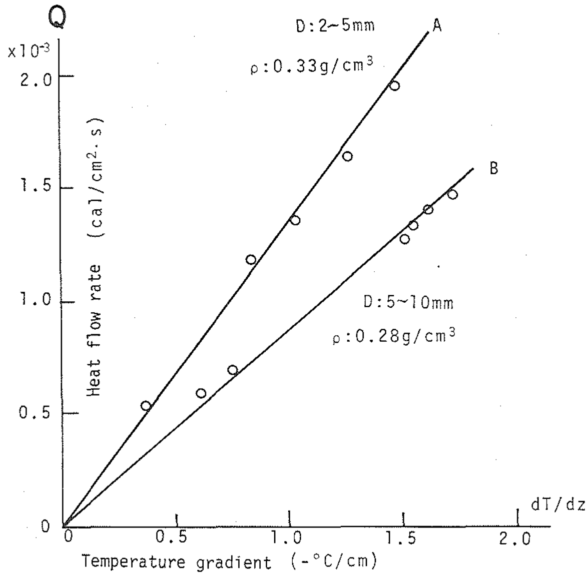


Fig. 40 Temperature gradient and heat flow rate (see Fig. 39 (a) and (b) as for grains of the sample)

prepared by random packing of the snow cubes in a space of 20 cm×20 cm with a height of 15 cm (a height of 23 cm only for Sample E); bulk density of Samples C, D and E were 0.23, 0.15 and 0.16 g/cm³, respectively. The results were given in Fig. 41; finally, natural convection of air occured in artificial samples C, D and E, at points C′ (–1.3°C/cm of temperature gradient), D′ (–1.1°C/cm) and E′ (–0.7°C/cm), respectively.

A series of positive temperature gradients were applied to Sample D afterwards; the result was a straight line, the beginning half part of which showed a complete agreement with that of the case of negative temperature gradients, as shown by OD* in Fig. 41. This fact is a positive proof to conclude that natural convection of air actually occurred at points C′, D′ and E′ when the magnitude of temperature gradient increased, because natural convection can not occur under positive temperature gradients.

The following can be concluded from the results mentioned above:

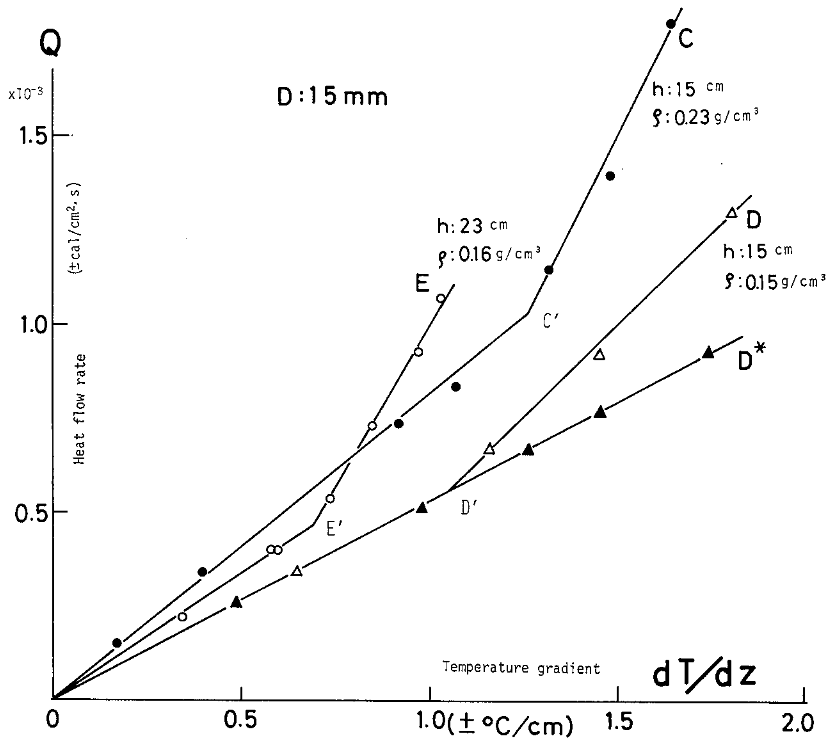


Fig. 41 Temperature gradient and heat flow rate: convection occurred at points C′, D′ and E′ (see Fig. 39 (c), as for grains of the sample)

Natural convection of air in snow is apt to occur,

i. in a snow layer of less density (or higher porosity), if the thickness of snow layers is same, and

ii. in a thicker snow layer, if the density (or porosity) is same.

The results of these experiments also indicate that small-scale convection of air in an air space between snow grains in a snow cover cannot occur, while there may remain some possibility of occurrence of large-scale natural convection of air in a natural snow cover under some particular conditions.

Upward flow rates Q in snow in a steady state under a negative temperature gradient are given as follows:

$$Q=\mu_s \frac{\mathrm{d}T}{\mathrm{d}z} \qquad \text{(only by conduction and diffusion without convection)},$$

$$Q=(\mu_s+\lambda)\frac{\mathrm{d}T}{\mathrm{d}z} \qquad \text{(by conduction, diffusion and convection)},$$

where μ_s is the coefficient of thermal conductivity by conduction through ice and by diffusion of water vapour, and λ the coefficient of heat transfer by convection.

The coefficients μ_s and λ of samples C, D and E were experimentally calculated from the slope of the relation of temperature gradient vs. heat flow rate. The value of λ appeared almost the same as μ_s, as shown in Table 5. This means that the quantity of heat transfered by thermal conduction through ice and by diffusion of water vapour is almost equal to that by natural convection of air, if convection occurs. Further, it may be concluded that, when natural convection of air occurs in snow, the growth rate of depth hoar, which is controlled by the supplying rate of water vapour from the lower part of snow, would be controled by convection for a fairly large portion, because about a half amount of total heat transfer under such a condition is brought by convection as the previous result indicates, while thermal conduction through an ice network cannot act as a carrier of water.

Table 5 Coefficient of thermal conductivity by conduction through ice and by diffusion of water vapour (μ_s), and coefficient of heat transfer by natural convection of air in snow (λ)

Sample	Density (g/cm^3)	μ_s	$\mu_s+\lambda$	λ
		(cal/cm·s·°C)		
C	0.23	0.8×10^{-3}	1.9×10^{-3}	1.1×10^{-3}
D	0.15	0.5	1.0	0.5
E	0.16	0.7	1.8	1.1

V. 3. *Discussion on Natural Convection of Air in Snow*

To begin with, let us consider a horizontal layer of a fluid with a thickness of ζ, and a fixed rectangular coordinate axes, x and y horizontally, and z vertically, in it; a temperature gradient β exists only in the direction z in the layer. The equilibrium of the fluid layer is stable, if β is positive; while unstable, if β is negative. Suppose that the temperature of the fluid at a level in the layer, in which natural convection occurred, was deviated by θ from the equilibrium temperature Θ at the level, as shown in Fig. 42.

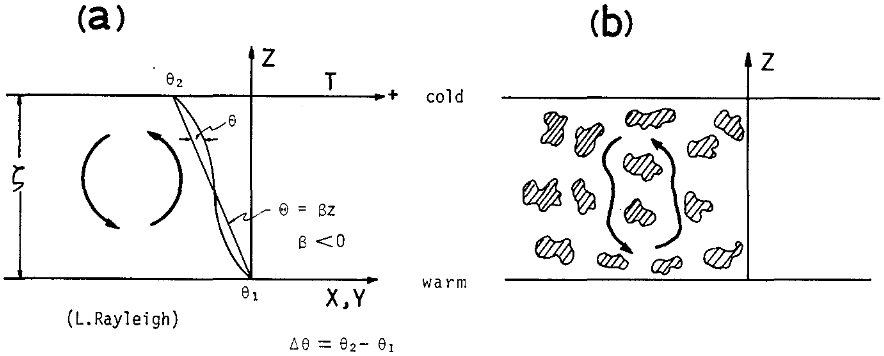


Fig. 42 Schema of natural convection
(a) Horizontal layer of fluid
(b) Horizontal layer of snow

Rayleigh derived the following equations of motion of viscous fluid,

$$\begin{aligned} \frac{\partial u}{\partial t} &= -\frac{1}{\rho}\frac{\partial \omega}{\partial x} + \nu \nabla^2 u , \\ \frac{\partial v}{\partial t} &= -\frac{1}{\rho}\frac{\partial \omega}{\partial y} + \nu \nabla^2 v , \\ \frac{\partial w}{\partial t} &= -\frac{1}{\rho}\frac{\partial \omega}{\partial z} + \alpha g\theta + \nu \nabla^2 w , \end{aligned} \tag{1}$$

where $\omega = p + g\int_0^z \rho_0 (1-\alpha\Theta)\, dz$; u, v, and w are velocity component to x, y, z direction, and ρ, ν are density and kinematic viscosity of air, respectively.

He also derived equation (2) as the critical condition for the occurrence of natural convection in a horizontal layer of fluid, from the equations of motion of viscous fluid, the energy equation, and the equation of continuity, with the boundary conditions of $w=0$, $\theta=0$ when $z=0$ and $z=\zeta$,

$$a g \rho \Delta\theta \zeta^3 / \kappa\nu = 27\,\pi^4/4 \ , \tag{2}$$

where α: the coefficient of thermal expansion of the fluid,
g: gravity,
κ: thermal diffusivity of air,
ν: coefficient of kinematic viscosity,
$\Delta\theta$: temperatue difference between the top and bottom surface of the layer.

The left side of equation (2) is called Rayleigh Number of the fluid layer.

Now we apply the Rayleigh's theory to the natural convection of air in a snow layer. In this case, the motion of air is impeded not only by the viscosity of air, but also by the structural resistance of a snow deposit to an air flow. Therefore, equations (1) can be reformed as follows:

$$\begin{aligned}
\frac{\partial u}{\partial t} &= -\frac{1}{\rho}\frac{\partial \omega}{\partial x} - \frac{R}{\rho} u \ , \\
\frac{\partial v}{\partial t} &= -\frac{1}{\rho}\frac{\partial \omega}{\partial y} - \frac{R}{\rho} v \ , \\
\frac{\partial w}{\partial t} &= -\frac{1}{\rho}\frac{\partial \omega}{\partial z} + a\,g\,\theta - \frac{R}{\rho} w \ ,
\end{aligned} \tag{3}$$

where R is resistance of snow, by its texture, to the air flow. As the viscous resistance of the air flow is negligibly small as compared with the resistance of snow to the air flow, the final term of each equation of equations (1) was eliminated, and a new term referred to the resistance of snow to the air flow was added in equations (3) for the natural convection of air in snow. The critical condition for occurrence of natural convection of air in a snow layer was derived from equations (3), by Rayleigh's way, as

$$a g \rho \Delta\theta \zeta / \kappa_s R = 4\pi^2 \ , \tag{4}$$

where κ_s is thermal diffusivity of snow. This could be named "Reyleigh's number for air in a snow layer." Equations (2) and (4) can be transformed into a form to define the critical temperature gradient for occurrence of natural convection, respectively, as follows:

$$\beta^* = \frac{27\,\pi^4}{4}\,\frac{\kappa\eta}{a\rho g \zeta^{*4}} \quad \text{(for a horizontal fluid layer),} \tag{5}$$

$$\beta_s^* = 4\pi^2 \frac{\kappa_s R}{\alpha\rho g \zeta_s^{*2}} \qquad \text{(for air in a snow layer)}, \tag{6}$$

$$= 4\pi^2 \frac{\kappa_s}{\alpha\rho g \zeta_s^{*2} B}\,, \tag{7}$$

where, β^*, β_s^*: the critical temperature gradient for a horizontal fluid layer of ζ^* in thickness, and for a snow layer of ζ_s^* in thickness, respectively,

ζ^*, ζ_s^*: the critical thickness of the horizontal layers for occurrence of natural convection of the fluid, and of air in snow, under negative temperature gradients of β^* and β_s^*, respectively,

η $(=\rho\nu)$: the viscosity of air,

B $(=1/R)$: the air permeability of snow.

From equations (5) and (6), it can be seen that β_s^* is larger than β^* for the same thickness of a snow layer and horizontal fluid layer, and reversely, ζ_s^* is larger than ζ^* for the same magnitude of temperature gradient in the layers. Equation (7) was practically used for the numerical calculation of the critical temperature gradient of a snow layer. Critical temperature gradients β_s^* of new snow, fine grained compact snow, and coarse grained granular snow were calculated; κ_s (thermal diffusivity of snow) was determined from μ_s (thermal conductivity of snow), by a relation of $\kappa_s = \mu_s / c\rho_s$, where c is the specific heat of ice, and B (air permeability of snow) by the result of Shimizu (1970) shown in Fig. 43.

Theoretical relations between β_s^* and ζ_s^* for new snow, fine grained compact snow and coarse grained granular snow, with maximum and minimum air permeabilities for each snow, were given by solid curves in Fig. 44. As most of the samples of the experiments on occurrence of natural convection of air in snow were 15 cm in thickness, a horizontal broken line was drawn at the level of $\zeta_s^* = 15$ cm; the critical temperature gradient should exist between points A and B, in Fig. 44, for each snow type of a snow layer with a thickness of 15 cm. (The hatched

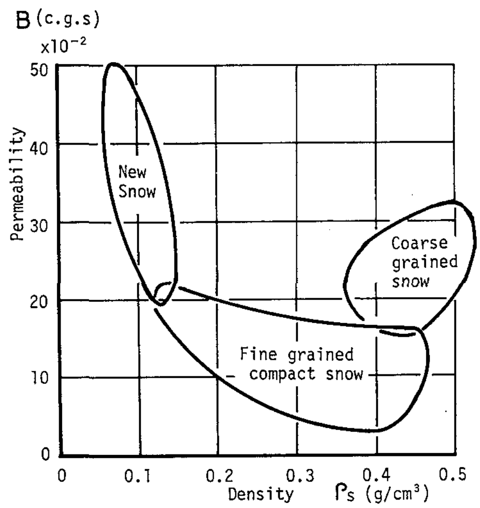


Fig. 43 Distribution of air permeability of snow (Shimizu, 1970)

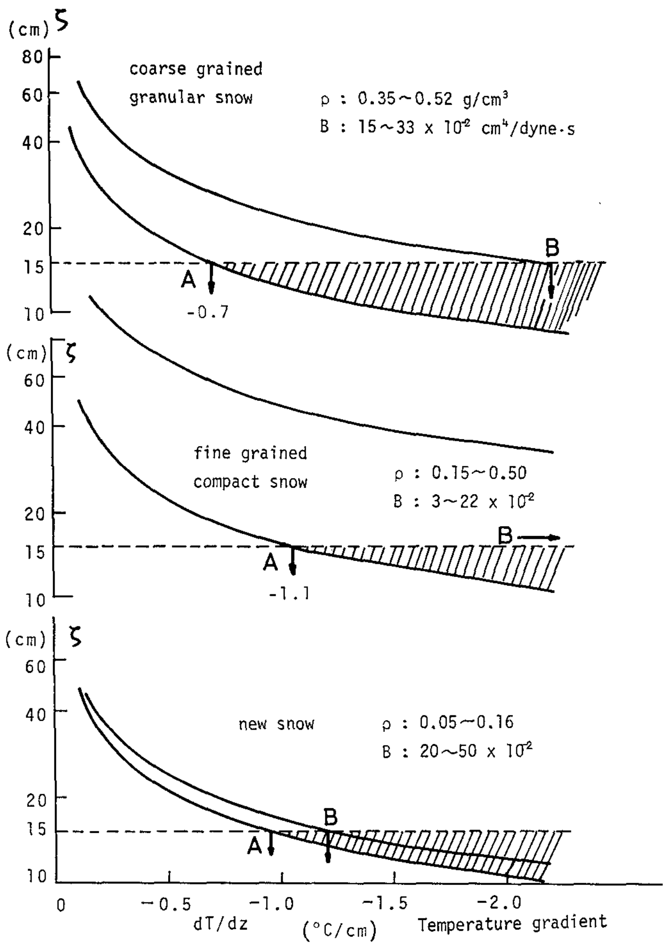


Fig. 44 Critical thickness (ζ) of natural convection in a snow cover.
Temperature gradient, thickness of a snow layer (ζ), and occurrence of natural convection of air in snow

areas in Fig. 44 show the theoretically probable area in which natural convection of air can occur in a snow layer, as a snow layer in a snow cover is thinner than 15 cm generally.) It can be seen from the diagrams that natural convection of air in snow occurs most easily in the coarse grained granular snow layer (starts to occur at −0.7°C/cm for a thickness of 15 cm), and most hardly in the fine grained compact snow layer (starts at −1.1°C/cm for the same thickness).

However, actually, convection did not occur in a sample of new snow of 0.12 g/cm³ in density with a thickness of 15 cm, even under a temperature gradient of

-2.0°C/cm. As one of the reason for this disagreement between the theoretical result and the experimental result, it may be considered that the top and bottom surface of the sample for experiment had been completely confined by copper plates, while they should be free in the Rayleigh's theory. And, by any reason, the theoretical critical condition for occurrence of natural convection of air in snow, based on the Rayleigh's theory, appeared much smaller than the real experimental result.

V. 4. *Possibility of Occurrence of Natural Convection of Air in a Snow Cover in Hokkaido*

Finally, the possibility of occurrence of natural convection of air in a snow cover in Hokkaido was investigated by use of the meteorological data of 5 weather stations, given in Fig. 45; station No. 1 is in the northern Hokkaido, where the climatic condition is cold with much snow in winter, while No.'s 2 ~5 are in mountaneous regions in the central and eastern Hokkaido where a climatic condition is cold with snow less than 1 m in thickness. It was learned by experiences that

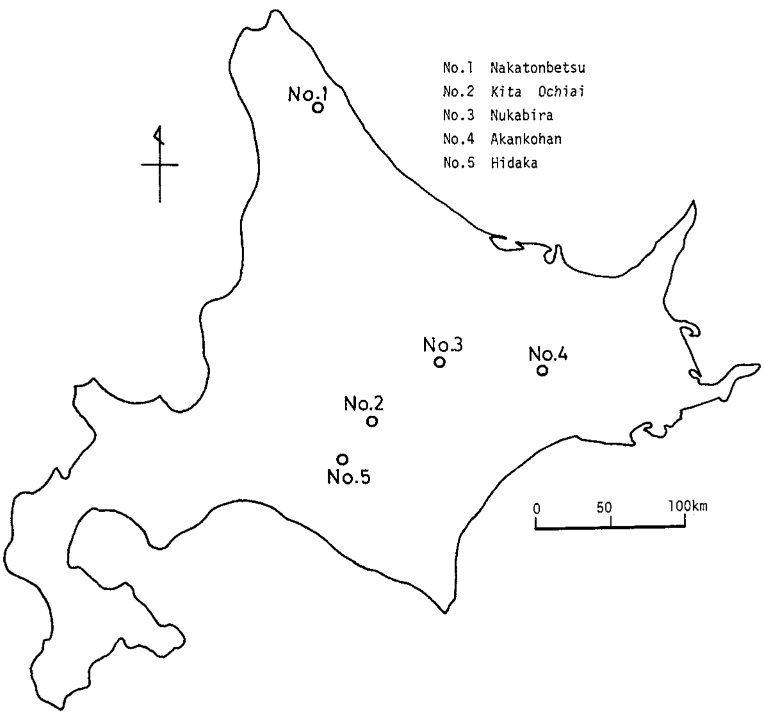


Fig. 45 Five weather stations where temperature gradients in snow covers were estimated

depth hoar developed actively in a snow cover, and larger avalanches caused by depth hoar broke out frequently in the central Hokkaido. Also from our experiences, the ground surface does not freeze even during the cold winter season, if it is covered by a snow cover of more than 50 cm in thickness in Hokkaido.

When we consider the monthly mean magnitude of temperature gradient in a snow cover, we may take the monthly mean air temperature as the surface temperature, and the monthly mean snow depth as the thickness of a snow cover. We estimated the monthly mean negative temperature gradient in a snow cover from the meteorological data, given in Table 6, by the following formulae:

$$\begin{pmatrix}\text{Montly mean}\\ \text{temperature gradient}\end{pmatrix} = \frac{(\text{Monthly mean air temperature})}{(\text{Monthly mean snow depth})}$$

$$\begin{pmatrix}\text{Monthly mean max.}\\ \text{temperature gradient}\end{pmatrix} = \frac{(\text{Monthly mean daily min. air temperature})}{(\text{Monthly mean snow depth})}$$

Table 6 Air temperature and depth of snow at five weather stations.

Station	Item	1966		1967		1968		1969		1970	
		Jan.	Feb.	Jan.	Feb.	Jan.	Feb.	Jan.	Feb.	Jam.	Feb.
No. 1 Nakatonbetsu h: 40 m	mean	-9.5	-9.9	-10.6	-9.8	-10.2	-13.3	-11.4	-11.7	-11.5	-9.3
	min.	-15.4	-16.7	-16.6	-15.7	-17.6	-20.0	-17.3	-18.2	-18.4	-15.1
	H	142	171	84	87	109	118	116	126	115	168
No. 2 Kita Ochiai h: 550 m	mean	-9.9	-9.5	-11.1	-9.5	-8.2	-11.1	-11.1	-9.9	-11.9	-8.1
	min.	-13.4	-13.9	-15.3	-14.1	-11.6	-16.9	-15.6	-13.6	-16.6	-11.2
	H	110	155	78	138	68	140	33	53	59	94
No. 3 Nukabira h: 540 m	mean	-11.2	-9.9	-12.2	-10.4	-9.2	-11.8	-11.8	-11.2	-13.0	-9.6
	min.	-18.3	-16.6	-18.6	-17.8	-15.3	-20.3	-18.2	-17.8	-20.7	-15.9
	H	61	79	35	33	48	57	25	80	60	115
No. 4 Akankohan h: 430 m	mean	-10.7	-10.5	-11.7	-10.3	-9.4	-11.5	-13.0	-13.0	-13.9	-9.9
	min.	-18.1	-18.9	-18.9	-18.2	-15.1	-18.8	-21.6	-21.5	-22.7	-16.2
	H	78	87	31	31	29	62	26	95	53	121
No. 5 Hidaka h: 280 m	mean	-8.9	-7.3	-9.2	-7.7	-7.3	-8.2	-9.9	-9.1	-10.6	-6.9
	min.	-14.9	-14.1	-15.5	-14.5	-13.3	-15.3	-16.2	-15.2	-17.8	-12.5
	H	54	74	20	24	42	55	24	73	60	90

h: altitude (above sea level),
mean: monthly mean air temperature (°C),
min.: monthly mean daily minimum air temperature (°C),
H: monthly mean snow depth (cm)

These formulae were applied as they were, as the 1st approximation, even for the case of a snow depth was less than 50 cm where the ground surface might have been frozen and the temperature there lower than 0°C. The result is given in Table 7.

In ordinary cases, the thickness of a depth hoar layer is less than 15 cm, in Hokkaido. Therefore, the thickness of an individual layer in which convection might occur was supposed to be 15 cm at most. The minimum values of theoretical "critical temperature gradient β_s*" for the occurrence of natural convection of air in a snow layer of 15 cm thickness are −0.9°, −1.1 and −0.7°C/cm for new snow, fine grained compact snow and coarse grained granular snow, respectively,

Table 7 Magnitude of temperature gradient (−°C/cm) in snow covers, estimated from the meteorological data.

Station	Item	1966		1967		1968		1969		1970	
		Jan.	Feb.	Jan.	Feb.	Jan.	Feb.	Jan.	Feb.	Jan.	Feb.
No. 1 Nakatonbetsu	mean	0.07	0.06	0.13	0.11	0.09	0.11	0.10	0.09	0.10	0.06
	max.	0.11	0.10	0.20	0.18	0.16	0.17	0.15	0.14	0.16	0.09
No. 2 Kita Ochiai	mean	0.09	0.06	0.14	0.07	0.12	0.08	(0.34)	0.19	0.20	0.09
	max.	0.12	0.09	0.20	0.10	0.17	0.12	(0.47)	0.26	0.28	0.12
No. 3 Nukabira	mean	0.18	0.13	(0.35)	(0.32)	(0.19)	0.21	(0.47)	0.14	0.22	0.08
	max.	0.30	0.21	(0.53)	(0.54)	(0.32)	0.36	(0.73)	0.22	0.35	0.14
No. 4 Akankohan	mean	0.14	0.12	(0.38)	(0.33)	(0.32)	0.19	(0.50)	0.14	0.26	0.08
	max.	0.23	0.22	(0.61)	(0.59)	(0.52)	0.30	(0.83)	0.23	0.42	0.13
No. 5 Hidaka	mean	0.16	0.10	(0.46)	(0.32)	(0.17)	0.15	(0.41)	0.12	0.18	0.08
	max.	0.28	0.19	(0.78)	(0.60)	(0.32)	0.28	(0.68)	0.21	0.30	0.14

mean: Magnitude of monthly mean temperature gradient in snow covers,
max.: Magnitude of monthly mean maximum temperature gradient in snow covers.
All the values were calculated on the supposition that the temperature of the ground surface was 0°C, even for the case of the snow depth less than 50 cm; the values in ( ) show temperature gradients at places where the ground surface might have been frozen

which are much smaller values than the experimental results. Most of the temperature gradient in snow given in Table 7 were much smaller even than the minimum theoretical β_s^* (−0.7°C/cm, for coarse grained granular snow); only 3 examples exceeded it slightly. Even on the supposition that a particular snow layer of 15 cm in thickness in a snow cover was subjected to twice the magnitude of the mean temperature gradient in the snow cover, because of an ununiform vertical distribution of temperature gradient, they would be still much less than real β_s^* as was suggested by the experiments described in the previous section; convection did not occur in natural new snow even under a large temperature gradient of −2.0°C/cm, and finally occurred at −1.0°C/cm or larger in the artificially prepared special samples which had a spacious air space in them, and are far different from real natural snow. From these considerations, it was concluded that natural convection of air in a snow cover does not occur even under the severest climatic conditions in Hokkaido.

IV. Concluding remarks

Growth of depth hoar, growth conditions of depth hoar, mechanical properties of depth hoar, and transference of water vapour in snow were investigated by experiments in the laboratory and observations in the field.

It was shown that depth hoar could grow in any kinds of snow, if the snow was subjected to a negative temperature gradient for an appropriate period. Depth hoar crystals were classified into two types, skeleton type and solid type, while a further investigation is necessary to make a correct definition of "hard depth hoar." Solid-type depth hoar developed under a small temperature gradient, while skeleton-type depth hoar predominated under a large temperature gradient; a crystal habit was affected by snow temperature only for skeleton-type depth hoar. Large crystals could grow only in snow having a large air space. Hardness of snow was changed by metamorphism, namely it increased, decreased or changed scarcely, according to the textures of the original snow and the magnitude of negative temperature gradient.

Finally, the occurrence of natural convection of air in snow was investigated, which transfers water vapour in snow and contributes significantly to the development of depth hoar, if occurred. But the results of both the experiments and observations in the field were negative for the occurrence of convection, and it was concluded that natural convection of air in a natural snow cover does not occur even under the severest climatic conditions in Hokkaido.

Acknowledgements

This work was carried out at the Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan, and on mountain slopes at the Snow Avalanche Research Station of the Institute of Low Temperature Science in the Teshio Experimental Forest of Hokkaido University. The author would like to express his sincere gratitude to Dr. T. Huzioka, Dr. H. Shimizu and Dr. Z. Yosida for every encouragement and valuable advice accorded in preparation for this paper.

References

ABURAKAWA, H. 1972 Studies of hard snow on Mt. Daisetsu II. *Low Temp. Sci.*, **A 30**, 129–143.

AKITAYA, E. 1964 Studies of depth hoar I. *Low Temp. Sci.*, **A 23**, 67–74.

AKITAYA, E. 1967 Some experiments on the growth of depth hoar. *In* Physics of Snow and Ice, Part II (H. Ōura *ed.*), Inst. Low Temp. Sci., Sapporo, 713–723.

AKITAYA, E. 1967 Studies of depth hoar II. *Low Temp. Sci.*, **A 25**, 37–47.

BADER, H. 1939 Mineralogische und Strukturelle Charakterisierung des Schnee und seiner Metamorphose. Beiträge zur Geologie der Schweiz, Geolechn. *Ser. Hydrol.*, **3**, 1–61.

de QUERVAIN, M. 1958 On metamorphism and hardening of snow under constant pressure and temperature gradient. IUGG, Intern. Assoc. Sci., Hydrol., Publ **46**, 225–239.

de QUERVAIN, M. 1963 On the metamorphism of snow, *In* Ice and Snow (W.D. Kingery, *ed.*) M.I.T. Press. Cambridge, Mass., 377–390.

HUZIOKA, T., SHIMIZU, H., AKITAYA, E. and NARITA, H. 1968 Properties of snow cover at avalanche research station, Toikanbetsu, Northern Hokkaido. *Low Temp. Sci.*, **A 26**, 169–185.

KOJIMA, K. 1956 Viscous compression of natural snow-layer II. *Low Temp. Sci.*, A **15**, 117–135.

KOJIMA, K. 1959 The influence of temperature gradient upon the grain texture, settling rate and brittleness of snow. *Low Temp. Sci.*, A **18**, 29–45.

LACHAPELLE, E. 1963 The chemical modification of depth hoar, *In* Ice and Snow (W.D. Kingery, *ed.*) 586–593.

NAKAYA, U. 1954 Snow Crystals, Natural and Artificial. Harvard Univ. Press. 510 pp.

PAULCKE, W. 1934 Der Schnee und seine Diagenesse. Zeitschrift für Gletscherkunde, XXI, 259–282.

RAYLEIGH, L. 1916 On convection currents in a horizontal layer of fluid, when the higher temperature is on the under side. *Phil. Mag.* S.6. **32**, No. **192**, 529–546.

SAITO, R. 1945 Struktur der Schneekörner und ihre mechanischen Eigenschaften, *J. Meteor. Soc. Japan*, 1–34.

SELIGMAN, G. 1936 Snow Structure and Ski Field. McMillan and Co., Ltd. London, 555 pp.

SHIMIZU, H. 1970 Air permeability of snow. *Contr. Inst. Low Temp. Sci.*, A **22**, 1–32.

WAKAHAMA, G. and TAKAHASHI, T. 1969 Field studies for snow and ice in Alaska, February-March, 1968. *Low Temp. Sci.*, A **27**, 195–212.

YAMADA, T. 1970 Studies of hard snow on Mt. Daisetsu. *Low Temp. Sci.*, A **28**, 155–164.

YOSIDA, Z. 1955 Physical studies on deposited snow I. Thermal properties. *Contr. Inst. Low Temp. Sci.*, **7**, 19–74.

YOSIDA, Z., HUZIOKA, T., KINOSITA, S. and WAKAHAMA, G. 1963 Snow avalanches in Hidaka-District, Hokkaido. *Low Temp. Sci.*, A **21**, 75–94.