551. 326. 85

FROZEN SLUSH ON LAKE ICE

BY

ERKKI PALOSUO

Institute of Marine Research, Helsinki

Abstract

Frozen slush will form in amounts varying very much from one winter to the next, and its thickness may even exceed the thickness of the normal lake ice.

The density of frozen slush in the case studied is about the same as that of normal lake ice. The ice crystals are usually small and larger crystals will mainly be found only where layers of water have intruded the snow. The crystal orientation is predominantly vertical, but horizontally oriented crystals do occur as well.

1. *Introduction*

Frozen slush (sometimes called snow-ice or white-ice) in this paper designates the uppermost layer of lake ice or sea ice formed during the winter out of thawed or moist snow or slush on the surface of the ice. In colour it is generally opaque and therefore clearly different from the ice beneath, which is formed directly out of the water and fairly clear, the so-called normal lake ice or sea ice [13].

Frozen slush is formed in two main ways: so much snow gathers on the ice that the ice sinks in the water, or during mild days the snow on the ice melts to sludge or water. When the cold grows sharper, this freezes again.

2. *Sinking of ice*

As mentioned by ZUBOV [14], the upper surface of the floating ice sinks below the level of the water as soon as

$$h_s \varrho_s = h_i (\varrho_w - \varrho_i) , \tag{1}$$

where h_s is the height of the snow cover, h_i the total thickness of the ice, ϱ_s the density of the snow, ϱ_w the density of water and ϱ_i the density of ice.

The density of fresh water at 0°C can be taken to be $\varrho_w = 1.0 \text{ g cm}^{-3}$. This applies approximately to the water of the Baltic as well, where the salinity is rather low. The density of the clear normal lake ice and sea ice can be said to be $\varrho_i = 0.9 \text{ g cm}^{-3}$ [7]. By using the approximate values mentioned above we get the load capacity of the ice

$$h_s \varrho_s = h_i \cdot 0.1 \text{ g cm}^{-3}$$

The density of fresh fallen snow varies between $\varrho_s = 0.10$ and 0.12 g cm^{-3}, that of slightly older snow $\varrho_s = 0.15$ to 0.16 g cm^{-3} and granular snow $\varrho_s = 0.20$ to 0.25 g cm^{-3}. So the critical value of h_s lies — very roughly — between h_i and a half of it.

In connection with the measurements, as will be explained later on, the height of the free water surface in relation to the upper surface of the ice was determined in an opened hole. Enclosed are some of these observations, which Hydrological Office kindly placed at my disposal. The density of the snow on the ice has been calculated from these as well. Unfortunately, it has not been measured with snow gauges.

Lake	Date	Thickness of ice h_i/cm	Thickness of snow h_s/cm	Water level — ice surface/cm	Density of snow calculated/ gcm^{-3}
Nellim	1962 XII 31	34	22	0	0.11
	1963 I 16	38	29	+1	sinks
	1963 II 1	42	27	0	0.14
Jormua	1962 XII 15	25	9	−1	0.11
	1962 XII 31	31	13	−1	0.12
	1963 I 15	38	29	+1	sinks
Tikkala	1963 I 15	35	21	0	0.16
	1963 I 31	42	26	+5	sinks

3. *Hardening of snow on the ice*

The transformation of snow is a very common problem in hydrology and in glaciology [2, 10]. The density and hardness of the snow on the lake ice were measured during the winter of 1963/64. But during this winter, as will be shown later on, only a small amount of frozen slush was formed. Therefore the melting and refreezing of snow will not be discussed in detail here. It will only be mentioned that in Finland in the early winter, when the radiation of the sun is slight, the melting of the snow depends mostly on the air temperature. During severe winters, when long cold periods occur more often, the melting of the snow is slight. In the later winter the melting of the snow is influenced by the air temperature, by direct radiation, by rain and by other factors. Therefore melting in the day-time can be considerable. An ice rind can form on the water surface on a cold night and later the water layer can freeze all through. So the largest amounts of frozen slush are often encountered in the spring.

4. *Observation methods*

In making observations we followed a common method [3]. A stake about one metre long was provided with a centimetre scale and painted white. In early winter, when the ice had reached a thickness just sufficient to support a walking man, the stake was taken to the site of the measurements and allowed to freeze in the ice so that its zero-point was level with the surface of the ice (Fig. 1). To prevent the stake from falling or floating in the late spring, a plate or cross-tree was attached to its lower end.

At least once a week the position of the surface of the snow (k) was read off on the stake. Then the thickness of the snow (h_s) was measured with a separate thin blunt stick (the handle end of the ice thickness meter). The difference of these two readings gave the amount of frozen slush. It will be mentioned that as a control the thickness of the snow was measured at two points close to the stake and at another place, where a hole was opened. During winter 1963/64 the density of the snow was measured at the same time.

For measuring the total thickness of the ice we prepared an ice gauge of a type similar to that used on the Drifting Stations at the North Pole [12], but the prototype did not function satisfactorily. Therefore every time a hole was drilled in the vicinity of the stake, although not within

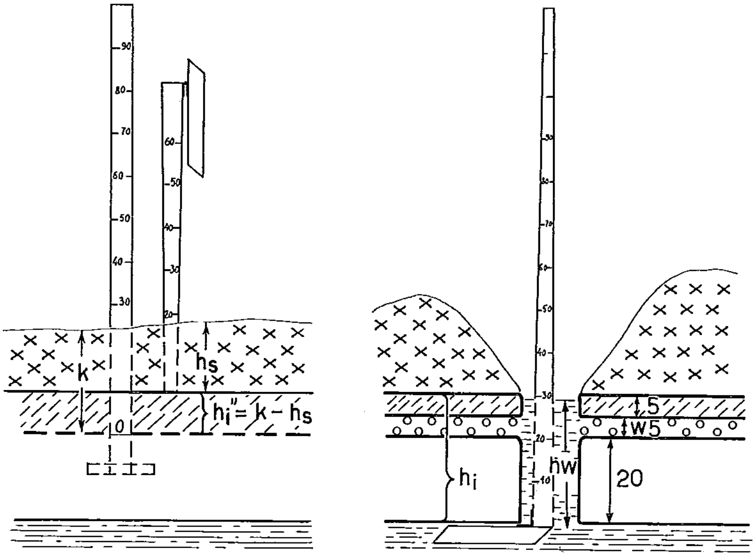


Fig. 1. Measurement of thickness of the ice as recommended by the Hydrological Office in Finland.

two metres of it. The total thickness of the ice (h_i) was measured with a special folding-L measuring stick copied from the model used by Hydrological Office in Finland. Besides the thickness of the ice, the surface of the free layer (h_w) was read as well from the cale on the gauge.

The drilling was done with a normal CRREL coring auger, operated by hand. As the ice core is rotated when taken up, the horizontal orientation could not be ascertained. Therefore an ice sample was sawn out. This was best done by drilling two holes about 20 cm apart and sawing two cuts between them. A side view of this block was drawn and all the visible boundaries, the density of air bubbles, etc., drawn in. In the case of sea ice the ice block was then cut to pieces and the pieces melted for the titration of salinity, etc. [9].

5. *The winter of 1962/63*

During the winter of 1962/63 observations of frozen slush were made on six lakes and at ten separate places in the Baltic [8]. At all lakes very similar results were obtained, and therefore here only the measurements on Sääksjärvi, in the area of the Geophysical Observatory, will be presented.

Sääksjärvi is a relatively shallow lake, which in the autumn of 1962 froze on November 29. At the same time there was a fall of snow, which remained on the ice and was seen in the observations of December 5 as a layer 5 cm thick (Fig. 2). The thin ice could not support such a weight and sank. On December 14 the water on the ice had formed 2 cm of moist slush. In the middle of December there was plenty of rain and in late December the slush froze to ice. The amount of frozen slush on January 4 was 8 cm.

In the middle of January so much snow fell that the ice sank a second time. As the cold grew stronger, the surface of the water on the ice began to freeze, but it had not time to freeze throughout before a new layer of water was formed on the ice because of the mild weather in early

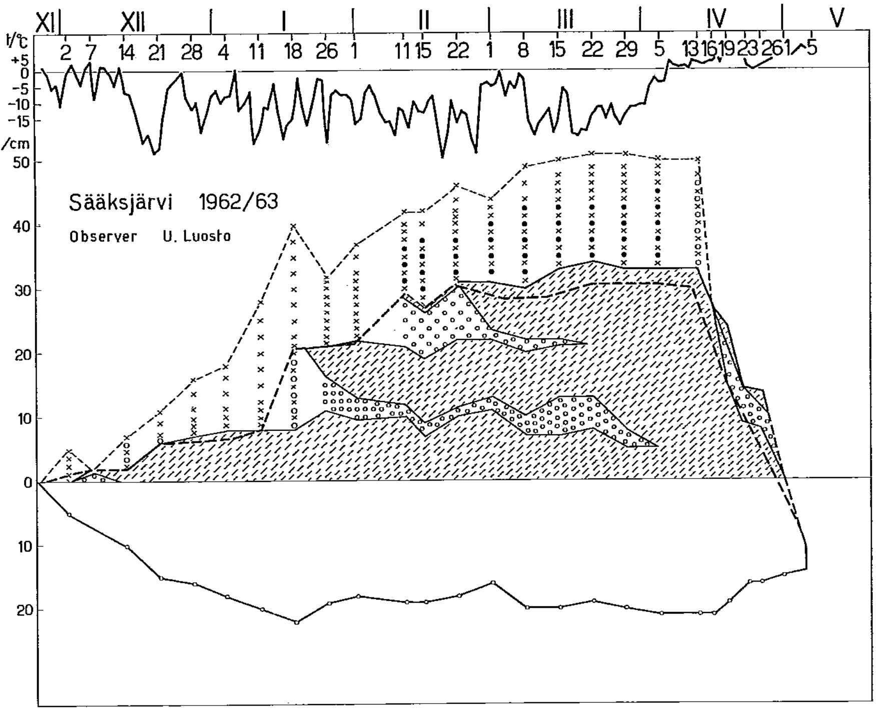


Fig. 2. The thickness of the ice and snow cover as a function of time at Sääksjärvi in the winter of 1962/63. Negative ordinates represent ice formed by freezing from the surface downward, positive ordinates (hatched areas) frozen slush formed on the other ice by freezing of snow slush. The dashed line represents the water surface. In the upper part of the figure the air temperature at Sääksjärvi is given.

February. This water was again covered by an ice crust. Not until March did the very severe cold close first the top water layer and then the lower layer, finally causing a slight growth on the under surface of the ice.

The amount of frozen slush in Sääksjärvi was at its maximum thickness of 33 cm on April 5, when the normal lake ice was 21 cm thick. The total thickness of the ice, 54 cm, measured at that time must be regarded as a little less than the average, considering that the winter of 1962/63 was both long and cold [11].

At the end of April the temperature increased and the ice began to melt rapidly. Some frosty nights caused a short-lived ice rind on the surface of the melt water, but no formation of frozen slush occurred as late as this. It has to be pointed out that the ice mostly melted in its upper layer, which caused a rise of the floating ice.

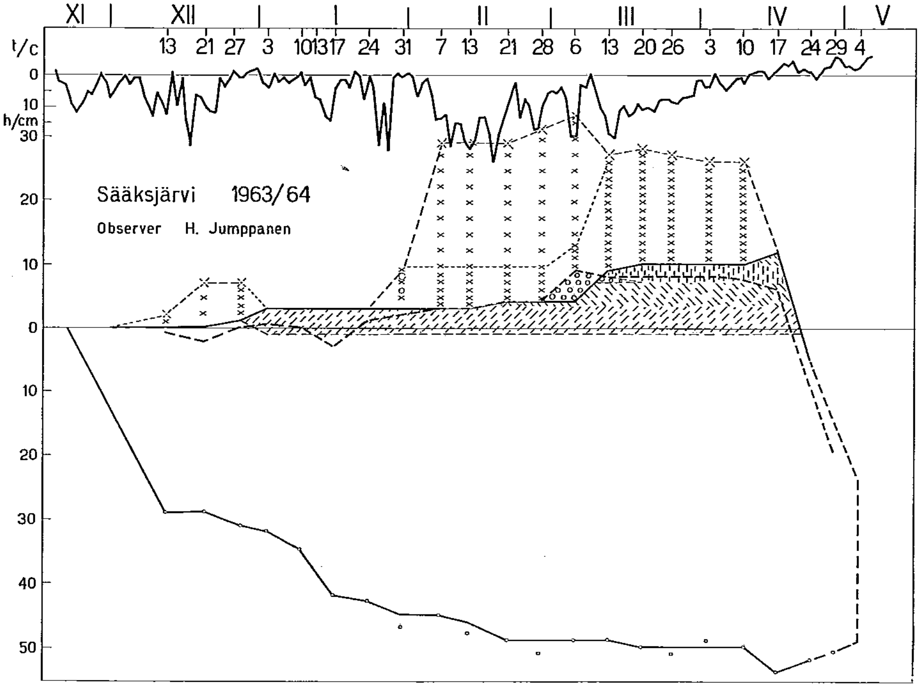


Fig. 3. The thickness of the ice and snow cover as a function of the time at Sääksjärvi in the winter of 1963/64. The hatched areas frozen slush.

6. *The winter of 1963/64*

In the winter of 1963/64 Sääksjärvi froze at the end of November and on December 13 the ice was already 29 cm thick (Fig. 3). The ice was all but bare of snow. The rather small amount of snow which fell during the remainder of December melted to water and later on formed a thin opaque layer on the clear ice.

At the end of January a couple of cold periods made the ice grow in thickness at a rapid rate and thus a thickness of 42 cm was attained in January. This was sufficient to float the snow load of 30 cm which fell at the beginning of February. The snow did not grow until the beginning of March, when the snow cover became 33 cm thick. The water froze and a thin layer of frozen slush formed.

The greatest thickness of frozen slush measured during the winter of 1963/64 was 10 cm on April 17. The thickness of the normal lake ice was 53 cm. The total ice thickness of 63 cm is about normal for such a cold winter.

7. *Line measurements*

During both winters 1962/63 and 1963/64, line measurements were performed by mounting a series of stakes straight out from the shore. As so little frozen slush formed in 1963/64 only the results of 1962/63 will be discussed here.

The first stake of the measuring line was placed 16 metres from the shore and the other three at intervals of 50 metres (Fig. 4). At the point chosen the lake is about 600 metres wide and relatively tall forest covers the shore.

At the time of putting out the stakes on December 2, 1962, the ice was 5 cm thick close to the shore and 4 cm farther out. In the middle of December newly fallen snow drifted so that it was somewhat thicker in the vicinity of the shore than in the middle of the lake, with the result that there was more frozen slush near the shore (December 21 and January 4).

On January 18, as mentioned before, the ice was found to be wholly submerged. In the next observations on January 26 an ice crust had formed close to the shore (by states 1 and 2), but at the other measuring points the water had only penetrated the lower layers of the snow, without forming a separating layer. In the next observations the water was covered by an ice crust, but further out it remained thin.

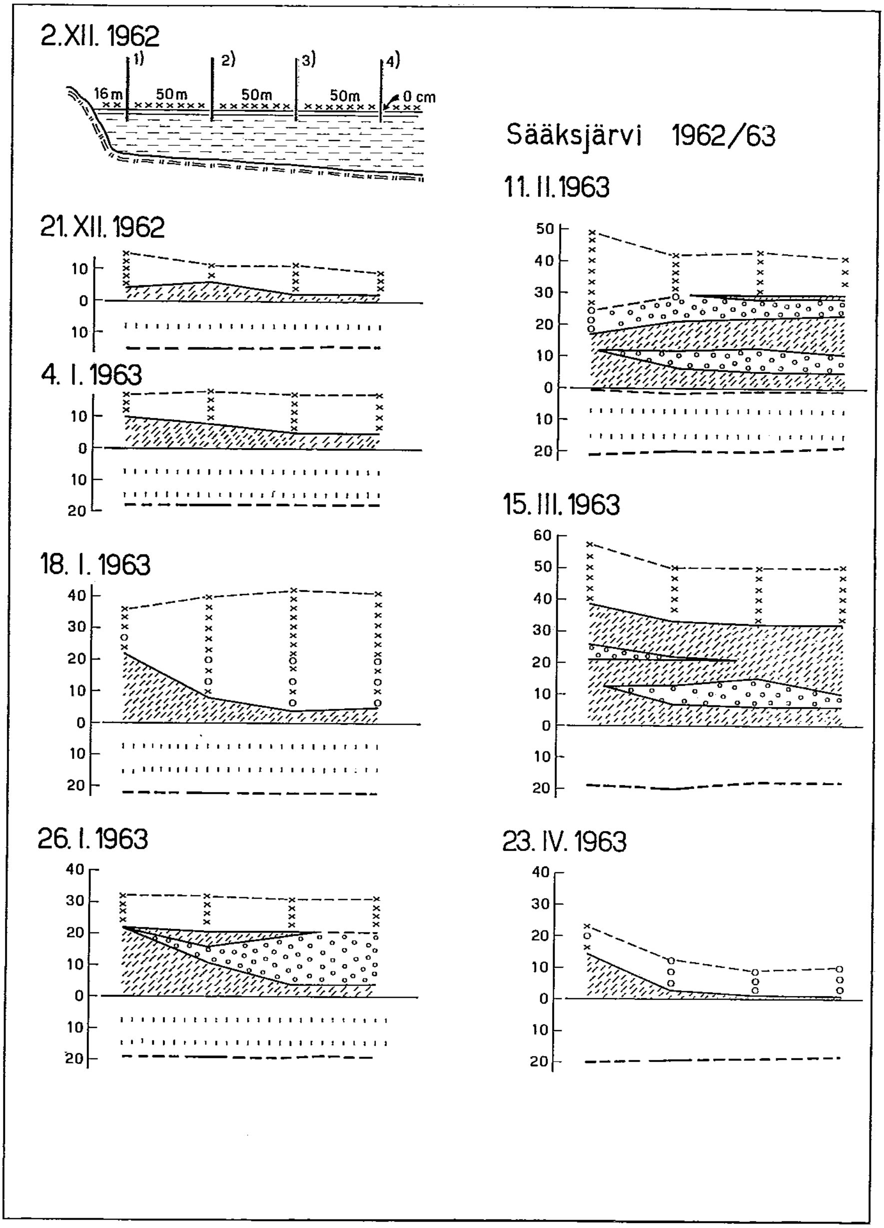


Fig. 4. The thickness of the ice and the snow cover in the line measurements at Sääksjärvi in the winter of 1962/63.

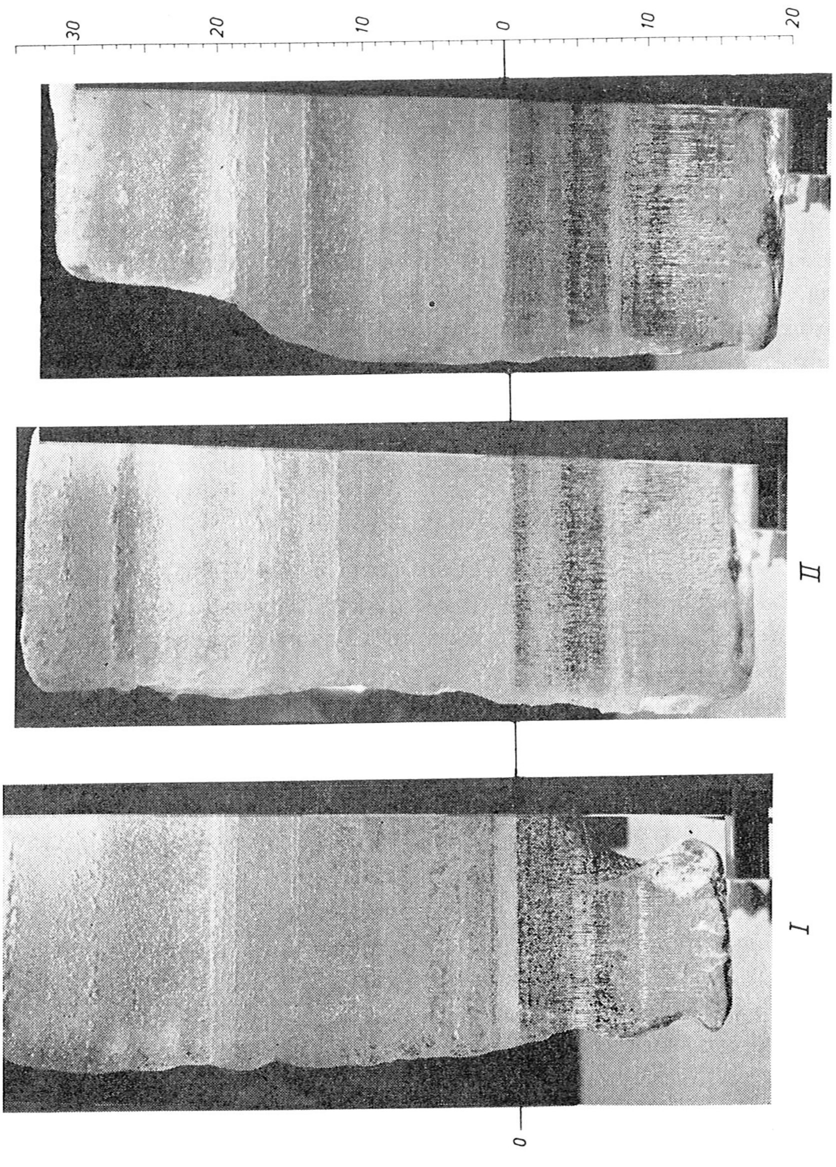


Fig. 5. The ice samples taken at Sääksjärvi on April 13, 1963 close to the stakes 1, 2 and 3. The normal lake ice below, the frozen slush above the zero of the vertical scale.

On February 11 another water layer had formed on the ice, this time due to the melting of the snow during mild weather. This time, too, the melt-water was covered by an ice crust but now beginning on the middle of the lake, where the snow cover was thinner. Under the ice crust there were accordingly two water layers which were still visible on March 15. On April 13 these water layers were nowhere to be seen.

In the ice samples taken on this date (Fig. 5), the stratification of the ice was clearly developed. The interface between the normal lake ice and frozen slush was readily identified and taken as the zero level of the measurements. Both the normal lake ice and the frozen slush contained air bubbles; the size and form will be discussed later. The present account will be confined to those layers with air bubbles which can be seen in all samples, although not always at the same depth.

During the spring melting the ice remained slightly thicker close to the shore than further out because of the larger amount of frozen slush. In the last observations the ice in the vicinity of the shore was still slightly thicker than the ice on the middle lake. On May 4 a crack parallel to the shore line opened between stakes 3 and 4.

8. *The density of ice and the air bubbles*

The observations included determinations of the density of the ice. Small ice samples were weighed in air and in ligroin of a density of 0.7430 g cm^{-3} at —5.2°C. The results of an ice sample taken on April 13, 1963, are shown in Figs. 6—7.

The density of normal lake ice without air bubbles (the lowest part) was found to be 0.919 g cm^{-3}, which is close to the density of single crystals 0.917 g cm^{-3} [1]. Normal lake ice with a moderate amount of air bubbles had a gross density of 0.910 g cm^{-3} and normal lake ice with many bubbles 0.906 g cm^{-3}. For a check, the total volume of the air bubbles was evaluated from the photographs of an ice sample with a moderate amount of air bubbles. For 10 cm^3 of ice the air volume arrived at was 0.6 cm^3 or in normal lake ice there is about 1% of air bubbles. The measured density of this ice was 9.906 g cm^{-3}. This gives a net density of single crystals to 0.916 g cm^{-3}.

It will be remarked that the air bubbles in the sample of April 13, 1963, were long (Fig. 5—7), a phenomenon very often observed in normal lake ice and in sea ice as well. But they did not appear in the very frist samples of the winter. They tend to be found after mild days. An example of ice without bubbles will be seen at the lower end of sample 3.

The density of the frozen slush in sample 3 taken on April 13, 1963, varied from 0.86 to 0.89. These values were measured at a temperature of —5°C, and no brine was to be found. The density of unfrozen slush on the ice is not measured here, but the values reported by HUZIOKA [2] are lower.

9. *The crystal structure of the ice*

To determine the crystal structure of the ice the samples were cut to suitable sizes (Figs. 6—7). Thin sections were then prepared according to the method of LANGWAY [5]. A thin vertical section was made through all parts and numerous thin horizontal sections were prepared from it. All these sections were photographed and the crystal size determined by measuring the sectional are of 100 to 200 crystals. The results are marked alongside the photographs.

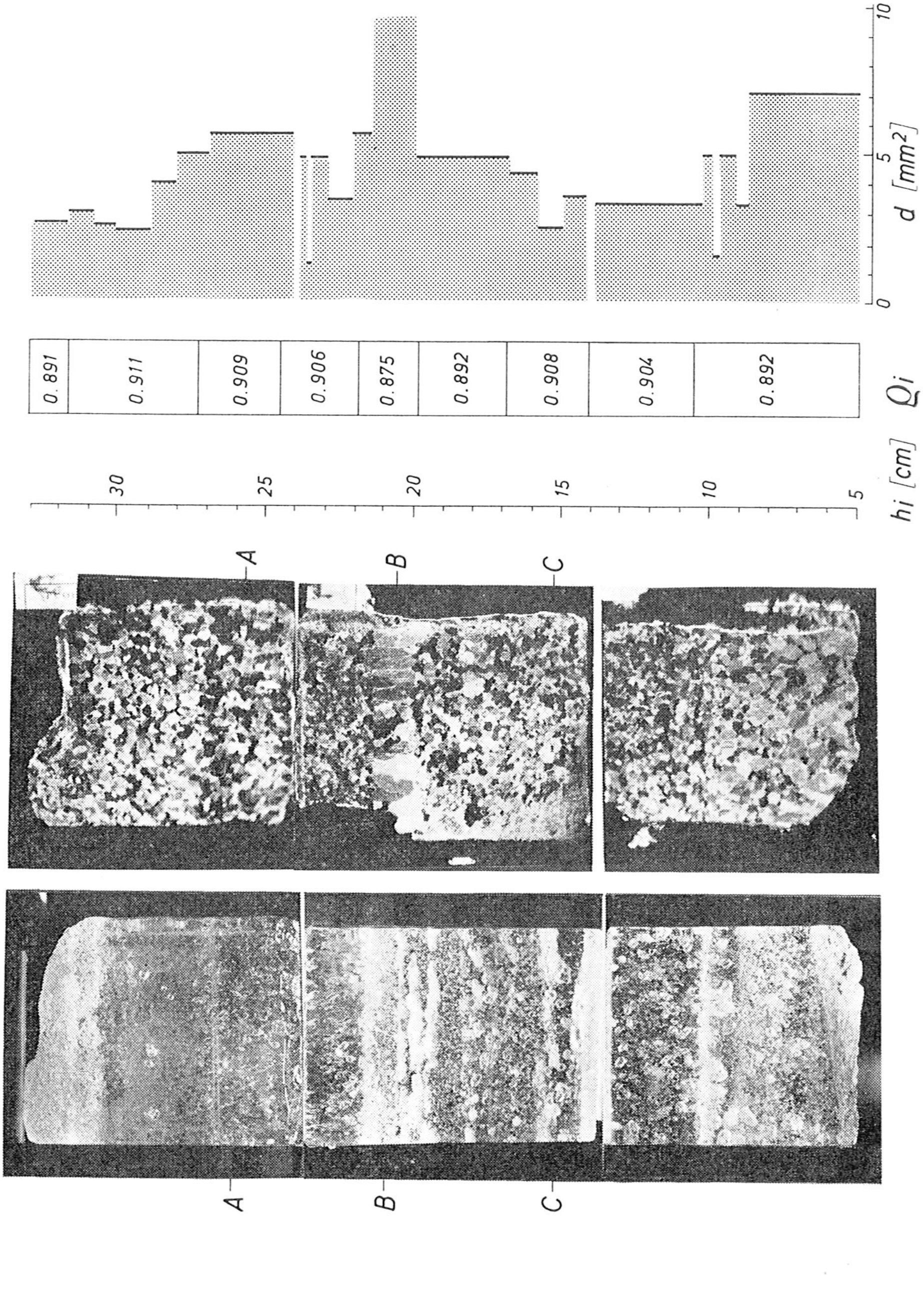
Fabric diagrams were drawn only for horizontal sections. Here only the results of the sampling on April 13, 1963, are shown, as on that date the frozen slush had attained its maximal thickness and all the water layers had frozen.

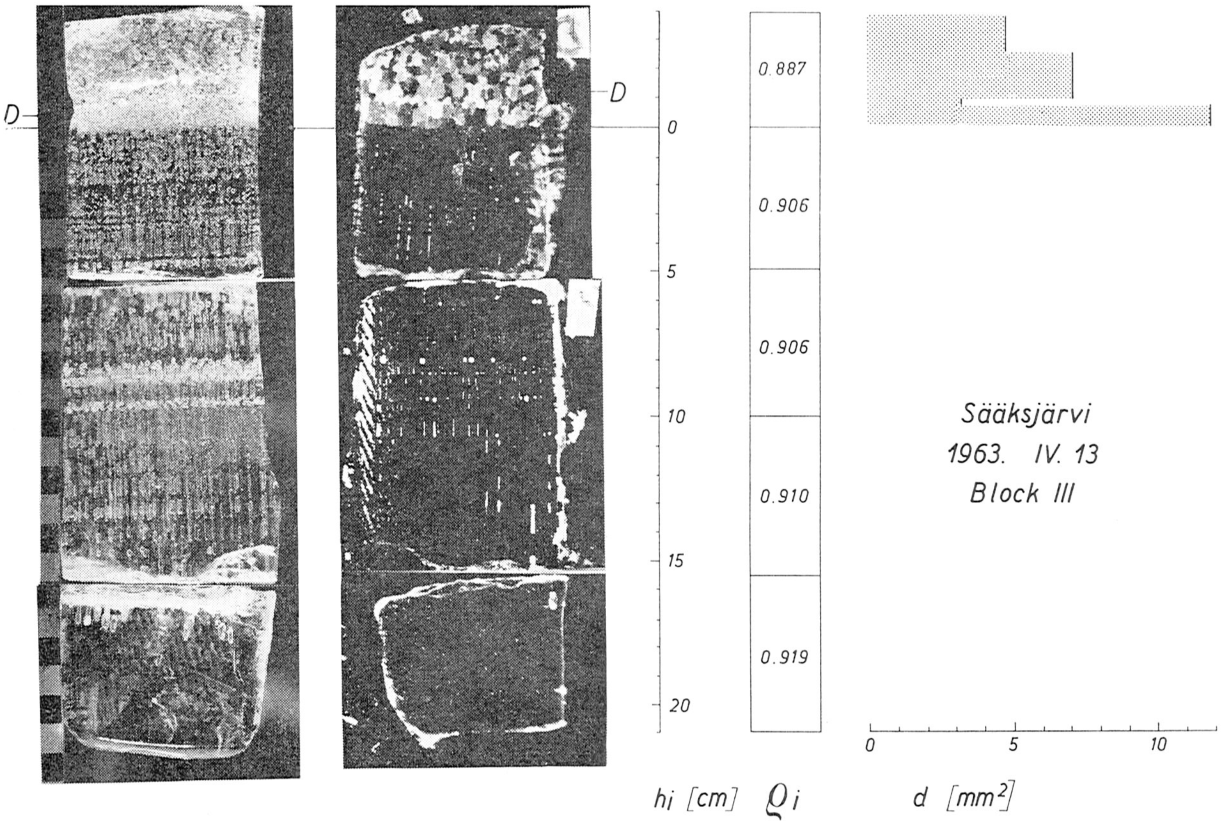
A study of the vertical section reveals the following features. At the upper surface of the ice a thin opaque layer is seen, in Fig. 6 from 32.5 to 30 cm. Between 30 and 27 cm the ice is fairly clear. This ice has probably been formed directly from snow. The crystal sizes vary in the main between 2.5 and 2.9 mm^2, with smaller crystals at the boundaries. Between 27 and 21 cm some large, elongated air bubbles occur and the crystal size is 4.0 to 5.6 mm^2. This ice must have been formed out of the water-logged snow (Fig. 2) of February. From this ice a horizontal fabric diagram was drawn (Fig. 8, A—A). The crystal orientation was predominantly vertical, 21% of the crystals measured lying exactly vertical. On the other hand, many crystals were horizontal, too.

The next layer, from 21 to 19.5 cm, is singular, in that it was derived from water only and froze as an isolated body between the adjacent layers. This layer is rather opaque and contains many air bubbles; the largest bubbles are platelike and in the bottom section of this layer. As the water froze from the top downwards in this case, the freezing water must have expelled the air as it froze, at least the greater part of it.

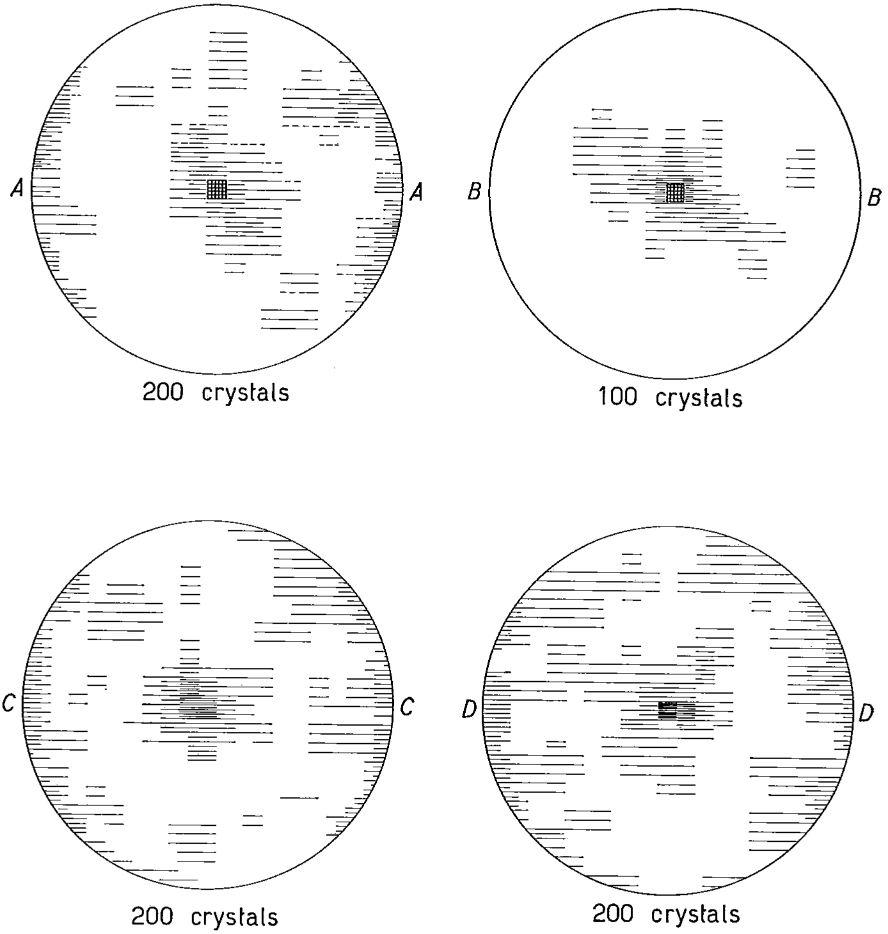
In this layer the ice crystals are large and diagonally orientated. In the horizontal section, however, the crystals do not seem abnormally large. The fabric diagram (Fig. 8, B—B) shows the crystal axes to be vertical. The axes of 25 crystals out of the 100 determined were exactly vertical and all the others close to vertical.

Between 19.5 and 10 cm the ice, which formed at the end of January out of a slush of wet snow, contains some large bubbles. The crystals vary in size between 3.3 and 5.0 mm^2 and in some places thin layers of small crystals were found. A fabric diagram was prepared from a section located


d [mm²]
0
5
10
Qi
0.891
0.911
0.909
0.906
0.875
0.892
0.908
0.904
0.892
hi [cm]
30
25
20
15
10
5
A
B
C
A
B
C



Figs. 6—7. The ice sample taken on April 13, 1963 close to stake number 3 on Sääksjärvi. The sample was cut up and the parts trimmed down to a thickness about 2 cm (left). Thereupon thin sections were prepared, which were photographed between two polaroid plates (middle). The densities and crystal sizes are shown to the right.



200 crystals

100 crystals

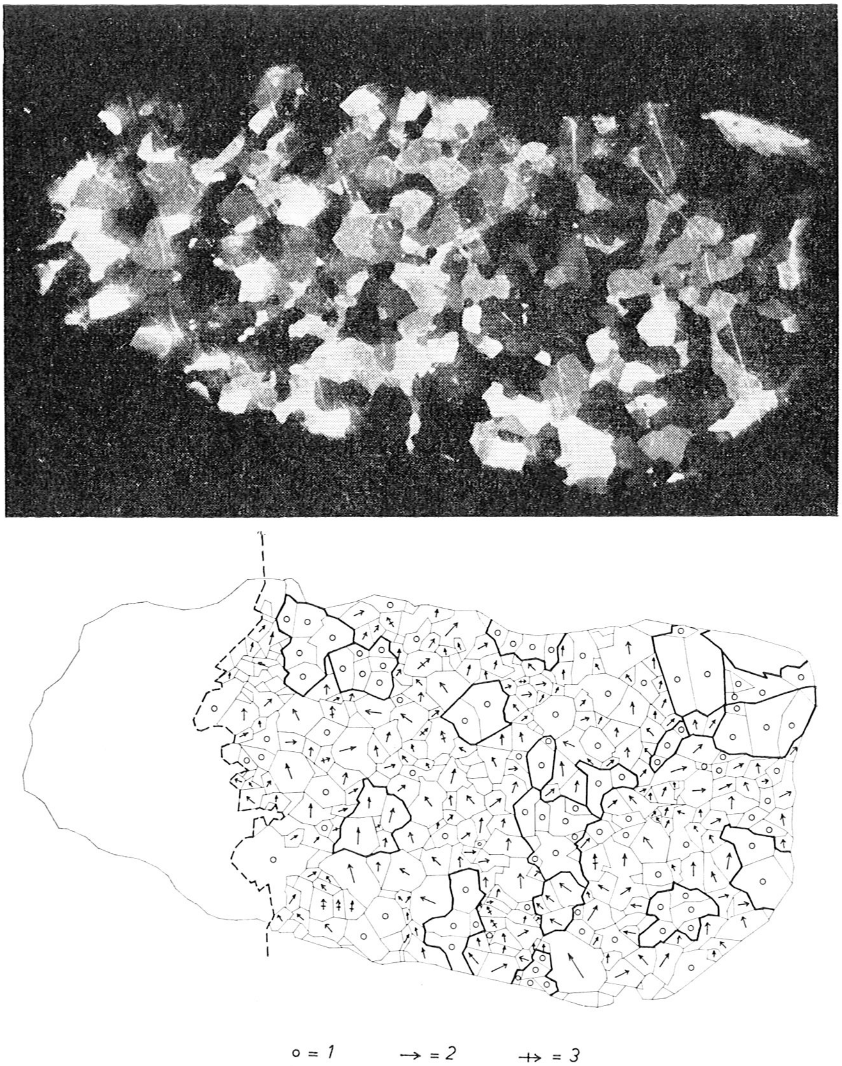
200 crystals

200 crystals

Fig. 8. Fabric diagram of the ice sample shown in Figs. 6—7. The horizontal sections were located: A—A 7 cm, B—B 12 cm, C—C 18 cm and D—D 31 cm from the top of the sample. The fabric diagrams have been drawn in the Schmidt equal area net, the frequency intervals are 1, 2, 4, 10 and 20 percentages.

17 cm below the surface (Fig. 8. C—C). A predominantly vertical orientation of the axes is seen, with almost half the crystals close to the centre and the greatest concentration of 7% per cm^2 in the Schmidt equal area net. Curiously enough, in frozen slush horizontal crystals are also present, but the intermediate skew positions are very rare [4, 6].

The lower part of the frozen slush, in the interval 10 to 2 cm, is rather opaque and contains many large air bubbles. This ice was formed around



Figs. 9—10. Horizontal section C—C photographed and drawn. In the drawn picture circels represent vertical optical axes, arrows horizontal axes and crossed arrows skew axes.

New Years Day out of compressed snow. The crystal size is 4.8 to 7.1 mm^2, again neglecting the small crystals at the interfaces between the layers. The crystals may have grown so large because water from above has penetrated between them and given rise to partial recrystallization.

Such effects could not be studied in greater detail with the present samples.

Directly on the normal lake-ice, the frozen slush between 2 and 0 cm was opaque and contained rather small air bubbles. The crystal size in this layer was 2.5 mm^2. The crystal orientation was predominantly vertical, 22% of the crystals examined being exactly vertical (Fig. 8, D—D). On the other hand, many crystals were horizontal, too. As this ice formed out of slush or water in December, the large crystal size was to be expected. But the ice sheet below had little if any influence on the crystal orientation. This thin slush layer also seems to have frozen from the top downwards, with an ice rind as the first freezing stage.

A photograph of a horizontal section of such ice between polaroids is shown in Fig. 9. Below the photograph a diagram shows the crystal boundaries and crystal orientation (Fig. 10). Circles represent axes in a vertical or almost vertical position, arrows horizontal or almost horizontal axes and crossed arrows axes lying between angles of 30 to 60 degree to the main planes.

It is interesting to observe how adjacent crystals often have their axes nearly parallel, thus forming groups of similarly orientated crystals. These groups have been connected by tracing their boundaries somewhat more heavily than the other crystal boundaries in the figures. One might suppose that the crystals of such groups, with axes within a few degrees of the mean direction, form at the same time in a common system, perhaps like the branches of a tree. Many of these groups are vertically oriented.

The normal lake ice consists of very large crystals with their axes orientated vertically.

Although a larger supply of samples would have been desirable, the present material seems to warrant the following conclusions:

— The crystal size in the frozen slush is small; the largest of them are to be found when sufficient water is contained in the freezing slush.

— The more water and the less snow the freezing slush contains the more the crystals in the frozen slush become vertical orientated. Horizontal axes seem at the same time to be more prevalent than skew axes.

— Air bubbles are less plentiful in frozen slush formed out of a mixture rich in snow, plentiful in ice formed out of an ice-covered watre layer.

Acknowledgements: The author wishes to thank the personel of the Geophysical Observatory at Nurmijärvi for assistance in the field and the personel of the Research Center of the Finnish Defence Forces for assistance in the laboratory. The National Research Council for Sciences (Valtion luonnontieteellinen toimikunta) supplied a grant for this study.

REFERENCES

1. Butkovich, T. R., 1953: Density of single crystals of ice from a temperature glaciers. *SIPRE, Research Paper*, **9**, 1—12.
2. Huzioka, Tosio; Tabata, Tadashi and Kinosita Seiiti, 1963: »Snow Jam» in Lake Oze. *Low Temperature Science, A*, 21, 96—114.
3. Kanavin, Edvigs V., 1964: Oversikt over Avlops- og Isforholdene i Holsvassdraget. Norges Vassdrags- og Elektrisitetsvesen, (Multigraphed report).
4. Knight, Charles A., 1962: Studies of Arctic lake ice. *Journ. of Glac.*, **4**, 33, 319—335.
5. Langway, Chester C., 1958: Ice fabrics and the universal stage. *SIPRE, Technical Report*, **62**, 1—17.
6. Lyons, J. B. and Stoiber, R. E., 1962: Orientation fabrics in lake ice. *Journ. of Glac.*, **4**, 33, 367—370.
7. Malmgrén, Finn, 1927: On the properties of sea ice. *Scien. results of the »Maud» Exp., I*, 5.
8. *Merentutkimuslaitoksen julkaisu* 213, 1964: Ice winter 1962/63 along the Finnish coast. 1—28.
9. Palosuo, Erkki, 1963: The Gulf of Bothnia in winter. II. Freezing and ice forms. *Merentutk. Julk.* 209, 1—64.
10. de Quervain, M. R., 1963: On the methamorphism of snow. *Ice and Snow.* Massachusetts Institute of Technology, 377—390.
11. Simojoki, Heikki, 1940: Über die Eisverhältnisse der Binnenseen Finnlands. *Mitteil. des Meteor. Inst. der Univers. Helsinki*, **43**, 1—198.
12. Untersteiner, N. and Badgley, Franklin, I., 1958: Preliminary results of thermal budget studies on Arctic pack ice during summer and autumn. *Arctic Sea Ice.* National Academy of Sciences — National Research Council, Washington, D.C., 598, 85—92.
13. Weeks, W. F. and W. L. Hamilton, 1962: Petrographic characteristics of young sea ice, Point Barrow, Alaska. *Amer. Mineralogist*, **47**, 945—961.
14. Zubov, N. N., 1944: *Arctic Ice.* (Translated by U.S. Navy Electronics Laboratory, 1963.) 1—491.