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ICE-CORED MORAINES IN THE KEBNEKAJSE AREA

Abstract

As a result of a study of air photographs from the Kebnekajse district in northern Sweden it was obvious that the size and shape of moraine ridges did not correspond with the size of the adjacent glaciers. Very large moraines often occurred beside small glaciers and vice versa. The shapes of the moraine ridges also suggested that they consisted of ice cores covered by relatively thin layers of morainic material.

Seismic and electric resistivity measurements proved that ice cores were preserved in many moraines, and a map was compiled of such features in this area. The earth resistivity method was also used for locating frozen ground under thawed surface material.

By digging in a frozen lateral moraine ridge, it was possible to obtain core samples from the buried ice. A crystallographic analysis of this ice proved that it must have formed from *in situ* snow, not from glacier ice.

The Kebnekajse region is one of the highest mountain areas in Sweden, and within this district are a large number of glaciers (figs. 1 and 2).

In front of most of the glaciers there is a series of end moraines. In some cases these moraines are relatively small and low ridges, in other cases they consist of huge masses of morainic material. Attempts have been made to date the different ridges in some of the end moraine systems (Larsson & Logewall 1958; Storch 1960). It has been believed that the outermost moraine ridges formed in the middle of the eighteenth century, at the time when nearly all Scandinavian glaciers had their greatest extension in historic time (Bergström 1954, p. 364; Faegri 1945, p. 293), and that the inner moraine ridges have formed during shorter periods of stillstand and/or slow advance during the last 200 years. Larsson and Logewall (1958) have shown that moraines probably were built up during the years 1790—1800 and 1890—1910. Their datings of the moraines are based upon studies of the vegetation on the various ridges, especially the lichen--covered stones. *Rhizocarpon geographicum* and *Rhizocarpon oreites* have proved to be the most useful species for relative dating of the moraines in this area.

It is also possible that some of the inner end moraines have been built up at a much earlier time, and that the glacier has later advanced over the ridges without destroying them. From an old photograph (pl. 1, taken sometime between 1907 and 1910) — it is obvious that the front of Isfallsglaciären was pushing up onto, and over the top of, the so-called 1910-moraine. The size of this ridge is so great that it is most unlikely

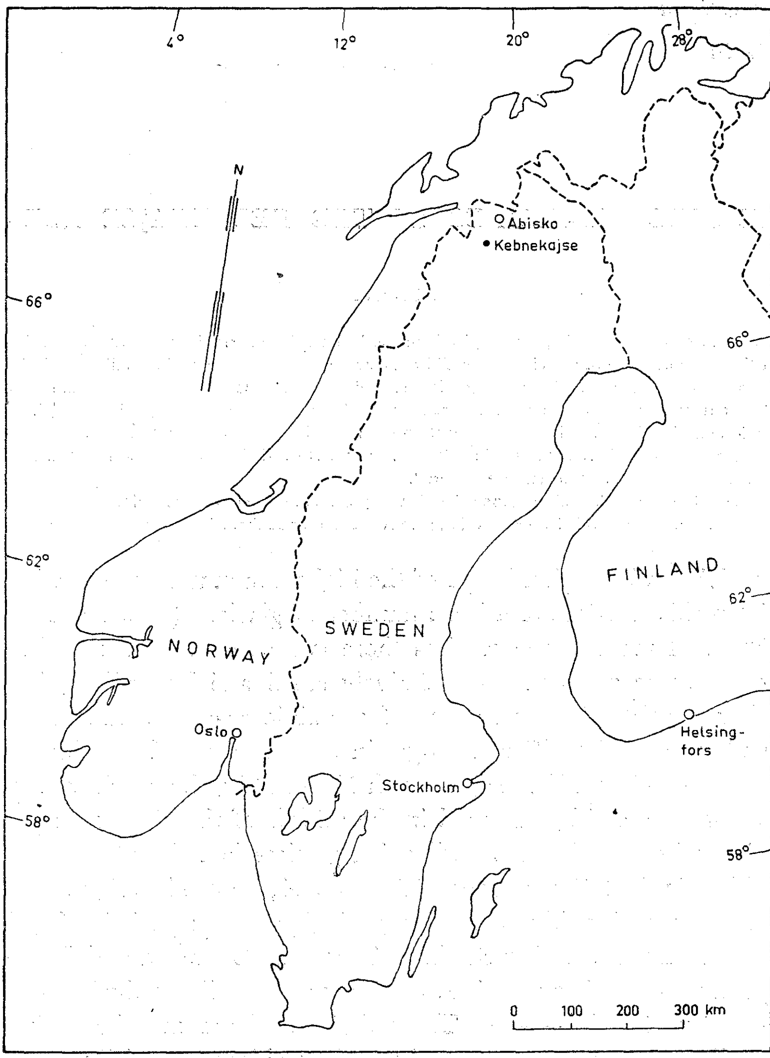

Fig. 1. Location map of the Kebnekajse area in northern Sweden

that it has been built up during the relatively short period (1890 to 1910), when the ice front is supposed to have occupied this position. Thus, a large part of the so-called 1910-ridge was probably deposited earlier, but the time of this earlier deposition has not been determined as yet.

When studying air photographs from the area it was obvious that the lateral moraines and the end moraine ridges in front of existing glaciers showed great differences in size and shape. In some cases large glaciers had built up only small end moraines, in other cases small glaciers had produced enough material to build up enormous moraine features at their fronts. As this situation seemed peculiar, a more detailed study of the moraines in the area was made during the years 1958 to 1960.

Using seismic refraction equipment (for further information, see Krynine & Judd 1957, p. 261—263, or Dobrin 1952, p. 218—235), a series of profiles were made across various moraine ridges, and from these measurements it was evident that many of the moraines had a 10—15 metres thick ice core under a relatively thin cover of morainic material (Östrem 1959, p. 229). To supplement these seismic profiles, electric resistivity measurements (for further information, see Krynine & Judd 1957, p. 264—266, or Dobrin 1952, p. 293—305) were carried out on several moraine ridges in the summers of 1959 and 1960. In most of the cases where an ice core was expected the resistivity instrument showed the moraine layer to be 2—3 metres thick; under this layer the resistivity was so great that it was impossible to measure the ice thickness (see fig. 4). The map (fig. 2) has been drawn on the basis of air photograph interpretation and the above mentioned control measurements by seismic and resistivity methods. A similar map of ice-cored moraines in the Jotunheimen district of Norway has been made by the author, and is printed in *Norsk Geografisk Tidskrift* (Östrem 1960).

The field work has shown that the earth resistivity method can be used for measurements of the thickness of the morainic layer covering an ice core, as the resistivity is so much greater in the ice than in the moraine. But even between frozen and unfrozen moraine the difference in resistivity is great, and therefore it should be possible to determine the depth of frozen earth layers under thawed surface layers. In the vicinity of Isfallsglaciären some measurements of this kind were carried out in August, 1959, and the frozen layers were found under 1,5—4 metres of unfrozen ground at different localities. However, resistivity of frozen ground may, under special conditions, be of the same or nearly the same magnitude as that of ice, and it may be difficult to determine whether the high-resistivity layer consists of ice or of frozen moraine. Nevertheless, in most cases the difference in resistivity is so great that a good differentiation between these layers can be made. Thus the method may also be used to discover the presence of permafrost.

In order to get more information about the ice core in one of the moraine ridges (see pl. 2) a hole was dug down to the ice. With the help of an Atlas-Copco rock drill (the type „Cobra", operated by a small built-in gasoline motor) a pit was excavated on the southern lateral moraine at Isfallsglaciären.

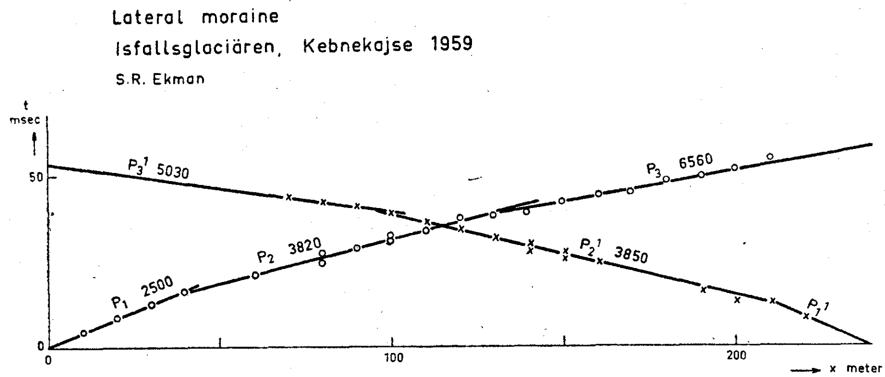

Fig. 3. Travel-time diagram made from the seismic records on an ice-cored moraine ridge

In this case the seismic waves have a velocity of a little more than 3 800 metres per second in the ice core. On top of the ice there is a layer of frozen moraine (the investigation was made in March, 1959), and under the ice there is bedrock. The ice core was found to be a little more than 10 metres thick. The seismic work has been carried out by S. R. Ekman, Stockholm

The only way to obtain a real pit in this moraine was to dig it during the winter when the moraine is frozen solid. Attempts have been made to dig into the moraine in the summer, but the material is so water-saturated, that it immediately forms a porridge which makes all further digging impossible.

The boring machine also made it possible to make holes in large boulders encountered while digging the pit, and by means of dynamite they were broken into smaller pieces and thrown up to the surface. Furthermore the machine could be used as a crowbar when the frozen ground was too compact to permit the use of a shovel.

After three days of hard work the ice core was reached under about 2,5 metres of morainic material, and a 2,2 metres long ice core was obtained with a core sampler. Unfortunately, a slight mishap precented further coring. The ice has later been analyzed between crossed polaroids in a three-axis universal stage. Thin sections of the ice core have been made in the horizontal and the vertical planes, and the ice crystals have been photographed. This work has been carried out by Dr. E. Palosuo at the Institute for Marine Research in Helsinki.

The glacier ice in the lower parts of Isfallsglaciären consists of large crystals (Ahlmann & Droessler 1949, p. 269—274), with axes about 3—11 cm long, and we expected that the ice underlying this glacier's lateral moraine would be similar to the main glacier ice, perhaps with even larger crystals. From other regions it has been reported that dead ice masses consist of estremely large crystals (for example see Liestöl 1952,

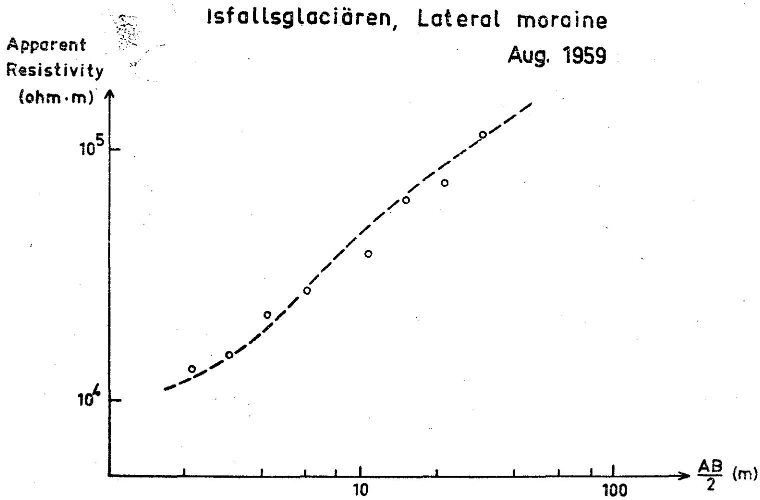

Fig. 4. Earth resistivity curve

The shape of curve indicates that ice must be present under 2,6 metres of moraine. The thickness of the ice cannot be determined from this curve. AB is the distance between the current electrodes. Most of the resistivity work has been carried out by S. Fredén, Statens Väginstitut, Stockholm

p. 63, for a description of dead ice from Norway). The crystallographic analysis of the ice core showed, however, that the crystals were very small (pl. 3, C) — only a few millimetres in diameter at the maximum.

Certain parts of the core sample consist of another sort of ice. These parts appear as lighter or darker oblique bands, whose inclination is approximately 30 to 50 degrees from the horizontal. The bands are easily visible under transmitted white light (pl. 3, A). In some cases the bands are clearer or more translucent than the rest of the ice; in other cases the bands contain small rock particles, resulting in a dark band or horizon in the core.

Most of the thin sections show small crystals, but when a horizontal section is cut through one of the bands, the crystals are seen to be much larger in the band than in the rest of the ice (pl 3, B). However, these larger crystals are not as large as the crystals in the glacier tongue itself.

From these crystallographic studies, it is evident that the ice buried in the moraine ridge is not glacier ice; it must have been formed directly from snow *in situ.*

A great quatity of snow must have been buried under a layer of morainic material of sufficient thickness to prevent melting during the summers.

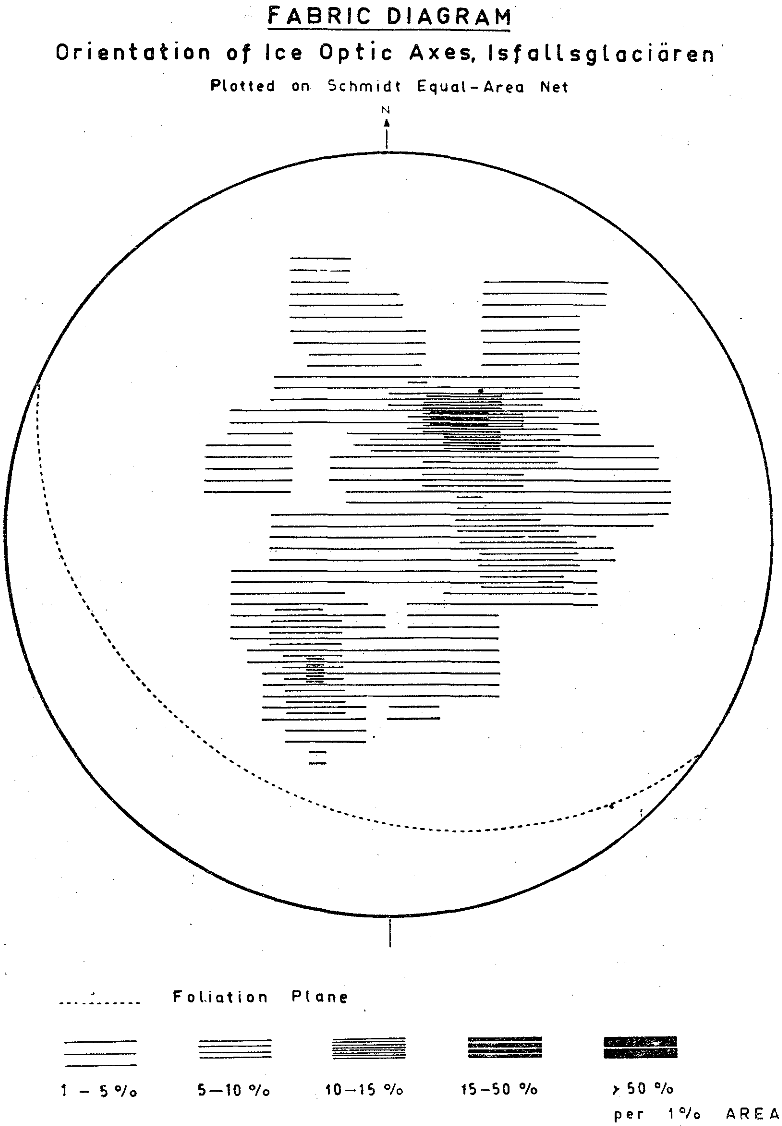

Fig. 5. The orientation of optic axes in an horizontal section from the ice core, 10 cm below the surface

The diagram has been made from orientation determinations of 100 individual crystals

The buried snow has then been converted into ice which now forms the ice core. The banded pattern of the ice makes it appear likely that the original snow has accmulated over a period of years; the dark layers, which also have crystals of larger size, indicate summer surfaces. „Dust" layers consisting of rock particles on the surface are a very common feature of snow-fields in this area today. The more translucent layers in the ice, with their larger crystals, may have originated as crusts formed during alternating periods of melting and refreezing.

The orientation diagram for the crystals in one of these bands shows a preferred orientation perpendicular to the band (fig. 5).

The photograph from 1910 (pl. 1) shows that a snowdrift lay on the south side of the glacier tongue at that time. In recent years a large snowdrift has often accumulated during the winter on the southern side of the lateral moraine, and this snow often remains throughout the summer. It is therefore probable that a snowdrift has occupied this position for a long time. During periods when the glacier was larger and more active than today, this snow may have been covered with morainic material which the glacier transported to its frontal parts.

It seems likely that many of the ice-cored moraines, especially the end moraines, have developed as a result of the transport of material up shear planes, as described by Goldthwait (1951, p. 567—577) from Baffin Island. Then the ice core consists of dead glacier ice. But in some cases, as shown from Isfallsglaciären, the ice in ice-cored moraines originated as snow accumulated in snowdrifts.

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GLACIERS AND LARGE MORAINE RIDGES IN THE KEBNEKAJSE REGION

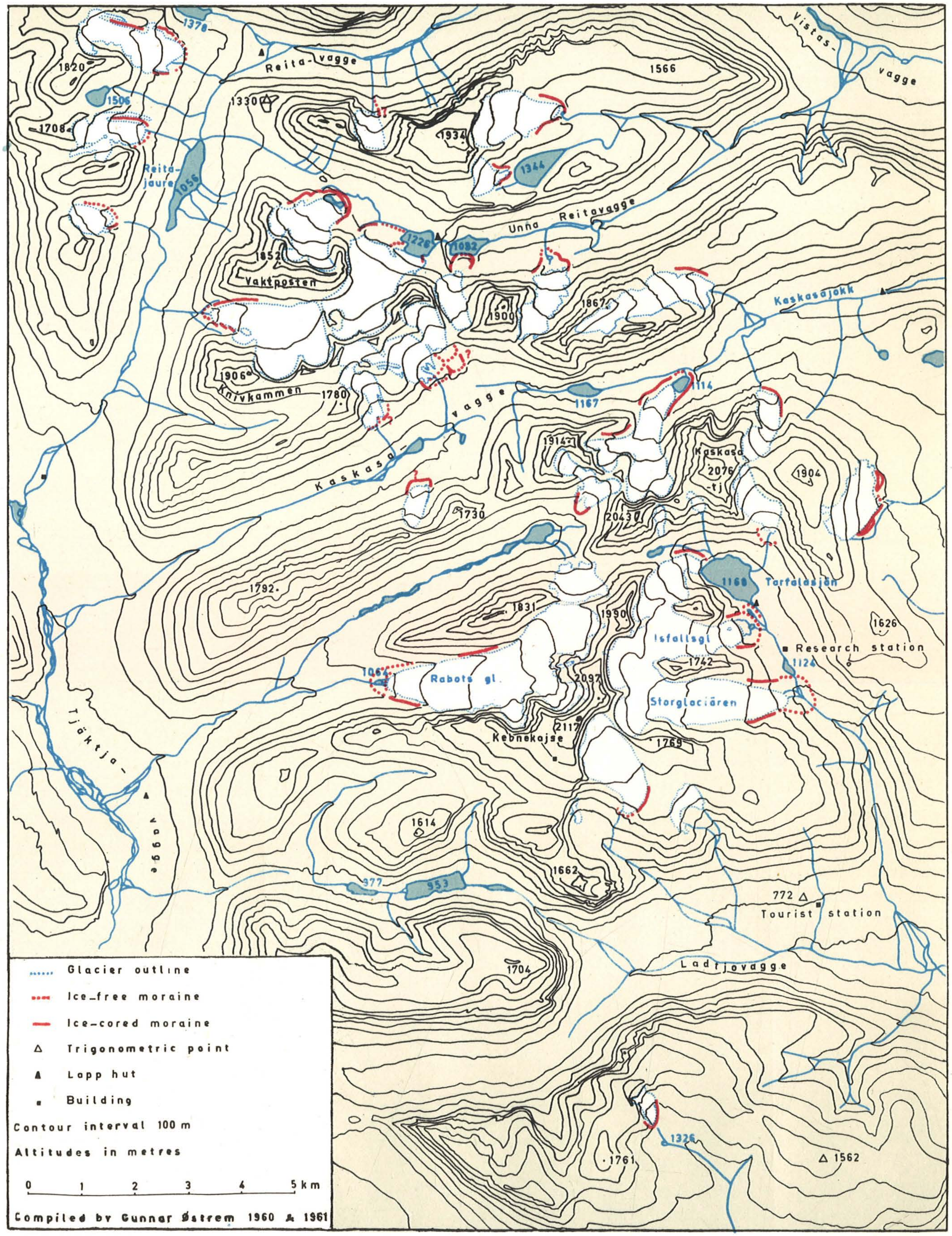


Fig. 2.

Photo by F. Enqvist, 1907 or 1910

Pl. 1. Photograph of the innermost part of Tarfala Valley, seen from the southeast. To the left the front of Isfallsglaciären is pushing over the so-called 1910 end moraine

At the ice margin, in the left part of the picture, a snow-drift can be seen. Snowdrifts in such positions may become covered by morainic material

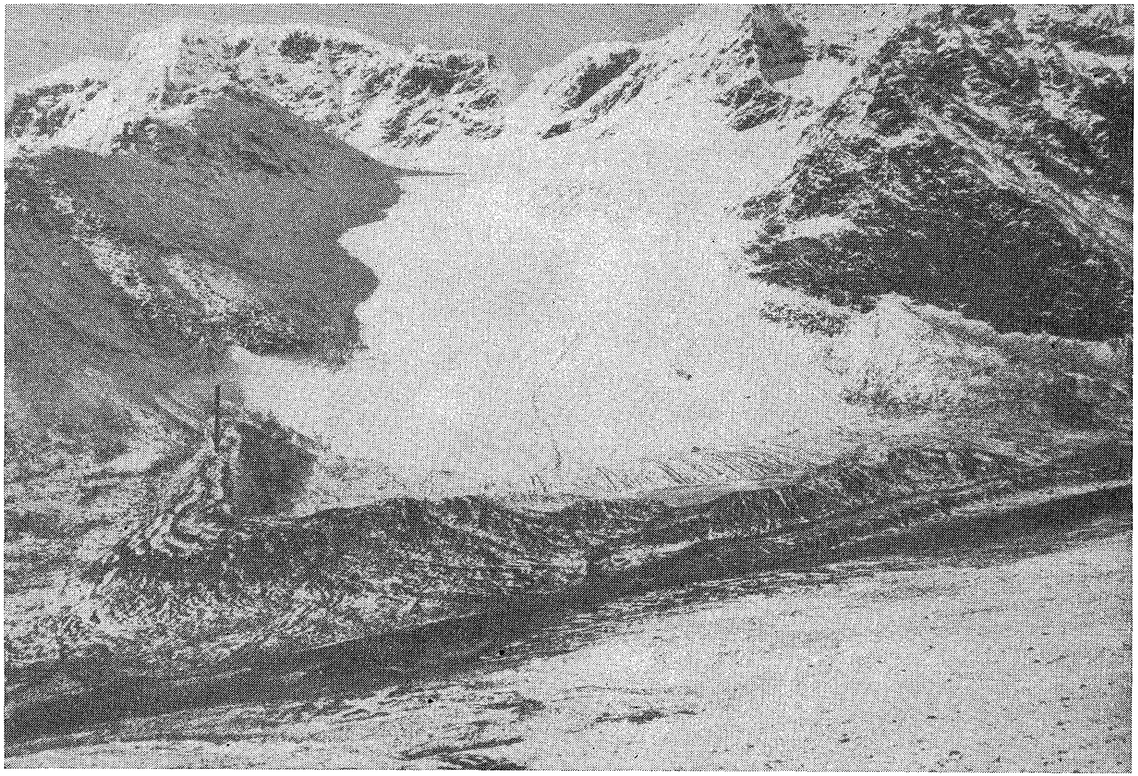
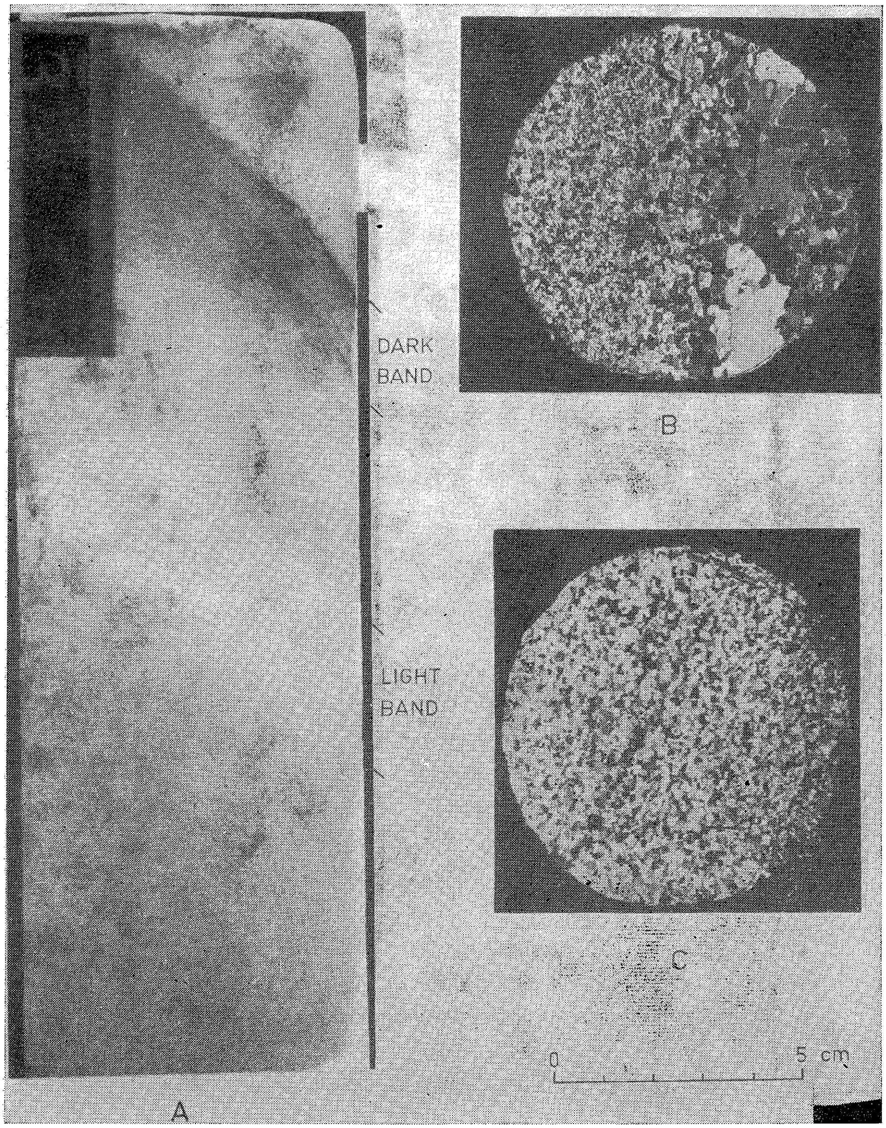


Photo by V. Karlén, September 1960

Pl. 2. Isfallsglaciären in the Tarfala Valley, seen from the east. In the left background are the peaks of Kebnekajse, Sweden's highest mountain. A pit was dug down to the ice core on the lateral moraine to the left (south) of the glacier (see arrow)



Pl. 3. A core sample from the buried ice in the lateral moraine at Isfallsglaciären

A — part of the core photographed under transmitted white light. Note the light and dark layers; B — a horizontal thin section of the core, cutting through a dark layer such as shown in A. The larger crystals come from the dark layer. Photographed between crossed polaroids; C — a horizontal thin section photographed between crossed polaroids. The small size of the crystals is typical of the main part of the core