Icefabric Studies on Hamna Ice Fall and Honhörbrygga Glacier, Antarctica

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南極，ハムナ氷瀑およびホノールブルッガ氷河における構造氷河学の研究

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要　旨

リュッツォホルム湾沿岸には，大陸氷床に源を持つ多くの氷河や氷瀑が存在する．そのなかの，ハムナ氷瀑とホノールブルッガ氷河を研究の対象とした．この報告は，構造氷河学，つまり，微視的な氷結晶の方位をしらべるだけでなく，巨視的な氷河構造をも含めた予察的な研究である．しかし，ホノールブルッガ氷河の巨視的構造については，その巨大さと表面構造の複雑さ，危険さのために調査はできなかった．

氷河の構造は，多くの面構造によって特徴付けられている．それらを次のように分けた．廊下(corridor)，クレバス (crevass)，透明縞 (clear band)，片理 (foliation)，断層 (fault)，節理 (joint)，劈開 (cleavage)．この分類はあくまで現象的なものであり，すべて氷河流動に伴う一連の変形の産物である．

氷結晶の方位は，全てこれらの面，とくに透明縞，片理，劈開などの運動面に規定されて発達している．そのパターンは，底面を滑り面とする極大値をひとつ持つもの (single maximum) をはじめとして，偏圧あるいは剪断応力の増加にしたがって，4-極大値を持つダイアモンド型パターン，さらに，5-極大値を持つものに発達する．これらの現象は，RIGSBY (1958) や KAMB (1959) の多極大値にかんする仮説では説明できない．筆者は偏圧の強さに対応して氷結晶の滑り面が変化するために単極大値から多極大値に発展すると考えた．

また，氷結晶の波動消光によって認められる結晶軸のわずかな移動とそれに伴う細粒化作用 (polygonization) を観察した．これは，氷結晶の定方位をもたらす初期段階の機構を示すものであろう．

1. Introduction

The Hamna Ice Fall and the Honhörbrygga Glacier are located on the east coast of Lützow-Holm Bay, East Antarctica, into which flow many glaciers originating from the Antarctic ice sheet. The continental ice sheet flows down and forks into glacier streams and ice falls due to the coastal bedrock outcrops (Fig. 1). These tributary glaciers and ice falls enter the sea and break to form icebergs. The party could easily approach the above-named glacier and the ice fall in the autumn and the spring when the sea water was solidly frozen. Then, a camp was established near their snout and field work was carried out at the end of May and the beginning of September, 1960.

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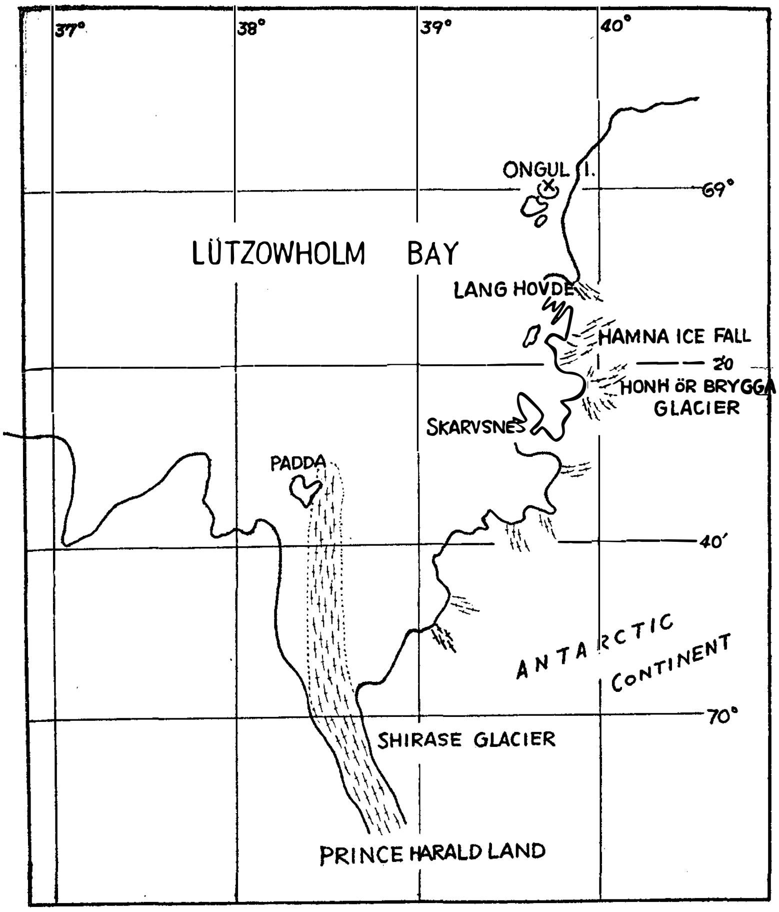

Fig. 1. Index map. X: Syowa Station.

The present investigation was undertaken as a preliminary study on the glacier tectonics not only from the microfabric but also from the macrofabric point of view. Therefore, tectonic mapping of the glacier was carried out first, followed by microfabric study of the glacier ice. However, it was very difficult to survery for mapping of the Honhörbrygga Glacier which is characterized by composite flows and falls so that the survey work was hampered by crevasses and seracs. Thus, the complex surface pattern of the glacier could not be mapped, and only a large iceberg calved out at the glacier's terminus was sampled vertically in a crevass which is about 36 m from sea level to the top.

The studies reported here are preliminary but they demonstrate the structural pattern of the ice fall and microfabrics, including not only the surface ice but also the deep-seated bottom ice of this particular ice fall and the Honhörbrygga Glacier. They reveal also the variation of fabrics at various depths to the glacier as related to glacier movement. The movement indicated by macrofabrics may be represented by shear strain, as manifested in planer structures such as foliation planes, clear bands, cleavages, etc., which are observed in glaciers and ice falls; fracture cleavages are found especially in bay ice in front of the ice fall. It is ascertained that the fabric patterns of four maxima of axes of ice crystals as reported in the original study by

RIGSBY (1951, 1955) are controlled by shearing planes such as foliation planes, and by clear bands which exhibit tectonics differentiated from that of the main direction of the glacier flow. Furthermore, in the present case, new multiple maximum fabrics are found, and the orientation pattern and the deformation behaviour in sea ice crystals are briefly treated.

2. Procedure in the fabric study

Oriented ice samples collected from the Hamna Ice Fall and the Honhörbrygga Glacier in autumn were stored in the glaciological laboratory of Syowa Base which was kept at minus 15 degrees Centigrade on the average. Fabric studies were carried out in the laboratory as well as other glaciological investigations throughout the wintering period.

A four-axes universal stage was used; it was the SIPRE model reported by C. C. LANGWAY (1958) and modified by T. TABATA of the Institute of Low Temperature Science of Hokkaido University. This stage, mounted between two 15 cm polaroid disks, accommodates an 11-centimeter square thin section of ice. The frame of the stage is machined out of phosphor-bronze and the wooden support for the stage also serves as a carrying box, making a compact and portable field unit (Fig. 2).

Fig. 2. Universal stage with thin section between two polaroids 15cm in diameter.

Thin sections: The preparation of thin sections of ice was not very difficult because the studies were carried out in the cold laboratory of the base. Oriented ice specimens were cut into slabs about 1.5 cm thick by means of a hand saw. One surface of the ice slab was made flat by planes, and the flat surface was pressed down firmly on the slide glass which had been moderately warmed in hot water. After a little while, the water film that had formed at the glass-ice contact, due to the heat of the glass plate, re-froze solidly and the bonding of glass to ice became strong enough for the process of section-making. Then, the ice slab was planed down to the desired thickness, 0.3–0.5 mm parallel to the glass plate. Its thickness was easily decided optically by the interference colour of the first order. The plane-down method recommended by the Institute of Low Temperature Science was the simplest but valid and fully satisfactory technique for the preparation of thin sections of ice. Two Japanese carpenter's planes were used at the base, one being for rough planing and another for smoothing and finishing (Fig. 3).

The average number of grains per section was 100 or so, but a few sections con-

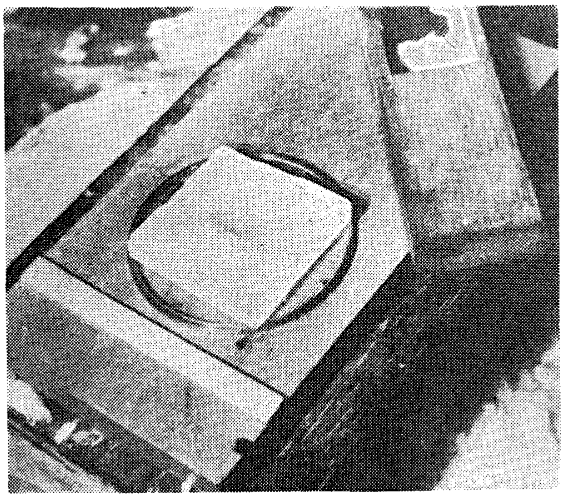

Fig. 3. Cutted ice sample mounted on a glass plate for reducing by plane.

tained about 70. LANGWAY (1958) stated that at least 200 axes should be plotted for a reliable statistical analysis, but in the present case, the number of grains per section seemed sufficient for fabric analysis because of their strong concentricity.

The measured c-axes inclinations, which were corrected for index of refraction by the correction table based on Snell's law (LANGWAY 1958), were plotted on the Schmidt equal area net for statistical analysis. The procedures for statistical analysis are well known petrofabrics (KNOPF and INGERSON 1938, FAIRBAIRN 1949, LANGWAY 1958).

Orientation of fabric diagram is represented by structural axes *a*, *b*, *c*: *a* means the flow direction of the Hamna Ice Fall and the Honhörbrygga Glacier, *ab*: the surface plane and *c*: vertical to (*ab*) plane in the present case. All the (*bc*) diagrams are vertical to the glacier flow and appear as if viewed downward from above the stream.

3. Hamna Ice Fall

The Hamna Ice Fall is located in the southern part of the Lang Hovde district of the Prince Harald Coast and flows down between Lang Hovde and Hamnenabben (69°15′S, 39°50′E). The ice fall exemplifies a small flow separated from the main Hamna Glacier which is one of many outlet glaciers originating from the continental ice sheet and descending to the sea. It is nearly 500 m long and 500 m wide and flows down in the north-northwest direction, its lower half being confined between steep bedrock walls, 100 m in height. On the western side of the fall, a narrow ablation valley is found with terminal moraine consisting of detritus ranging in size from very fine clay to blocks of 3 m or more in diameter. Fortunately, this ablation valley enables investigation of the entire profile of the fall from bottom to surface. The bay ice of Hamna Bay, at the terminus of the ice fall, develops bending, folding and crushing towards the snout. Cleavages in the bay ice are widely developed beyond the terminal area. Sea ice blocks of 1.5 m thickness are cast up on the bay ice at the front of the ice fall, due to the pressure of the fall (Fig. 4).

The downward movement of the flow was recorded at location 1 on the ice fall in May and December, 1960. The flow rate here averaged 5 m or so per month.

1) Macroscopic fabrics

Structural elements of a glacier are generally characterized by planer structures such as foliation, clear bands, crevasses, etc. These planer structures are also developed

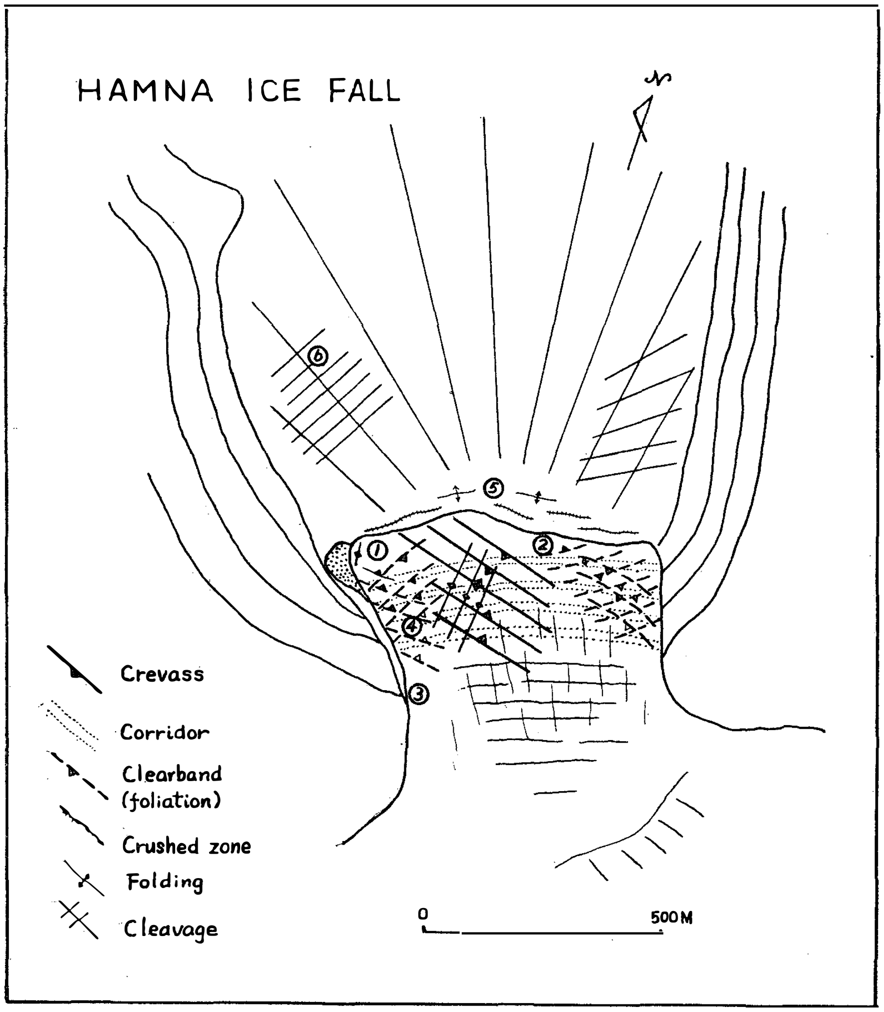

Fig. 4. Structural pattern of Hamna Ice Fall.

in the Hamna Ice Fall. In the present case, the following seven structural elements are observed: corridor, foliation, clear band, crevass, fault, joint and cleavage (Fig. 4).

Corridor: Corridors are a characteristic structure of this ice fall in the lower half where it is traversed by four or five corridors, about 5 m wide, at right angles to the flow direction. The corridors separate the ranks of seracs; in summer puddles occur on their bottom. In the upper stream of the fall, crevasses (tension fractures) traversing the ice fall come to open out to form corridors due to the steep inclination of the bedrock in the upper part.

Foliation: Pronounced foliation is obseved in banded ice of 4 m thickness near the bottom of the ice fall. The foliation is defined by alternating layers of bubbly part and bubble-free clear part which are 1–2 cm wide. The banded ice is greyish in colour at a glance because it contains fine sand particles smaller than 2 mm, and occasionally boulders of 50 cm or more diameter. The strike and dip of the banded ice are concordant with the surface of the bedrock in the upper stream of the fall, but in the lower part they are disturbed owing to later slip planes in the glacier such as clear band and fault. Folding and minor thrusting of the banded ice are visible at the

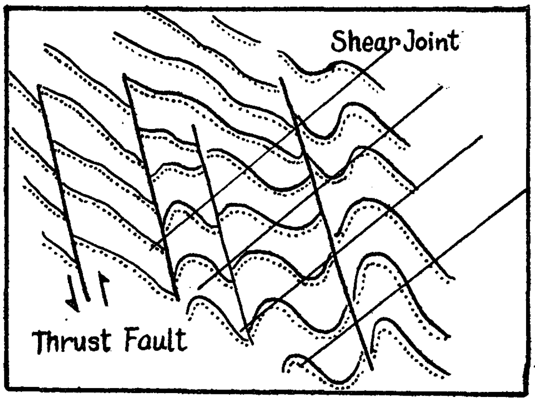

Fig. 5. Folding and thrust fault of banded ice with shear joints at later stage.

terminus (Fig. 5). The foliation in the upper stream changes from banded ice to clear band and it dips gradually to a steep inclination relative to the surface.

Clear band: A conspicuous structural element in glacier tectonics is the so-called clear band (or blue band) which is defined as a bubble free or almost bubble free band formed by transparent clear ice in predominantly bubbly glacier ice. In the Hamna Ice Fall, clear bands, a few centimeters wide, are well developed; their formation may be divided into at least two stages (C_1, C_2), according to the structural sequence. The clear band of the first stage (C_1) is the older one; it is found all over the ice fall with strikes in the west-northwest to east-southeast direction on the western side, contrary to the eastern side where the strikes show east-northeast to west-southwest direction. It is observed clearly that the dip of these planes characterized by C_1 bands becomes steeper as the ice flows down and bends over in the lower part (Fig. 6). This phenomenon may indicate no simple shear strain relation but a bodily rotation of each serac. To ascertain the bodily rotation of a serac, a U-gauge, a kind of electric resistance strain gauge, was used succesfully. Description of the reconnaissance work on the glacier ice using a strain gauge is to be published by the author and SATŌ.

The movement of seracs is undoubtedly associated with the deformation by shear stress which is indicated by the origination of the second stage clear band C_2 in the lower part of the Hamna Ice Fall.

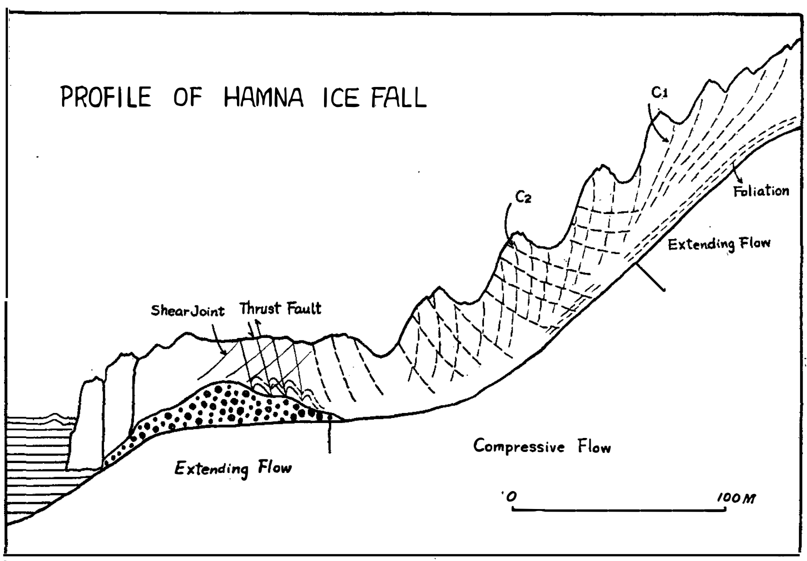

Fig. 6. Schematic profile of Hamna Ice Fall.

However, it may be observed that the banded ice turns gradually into the clear band in the upper stream ; a difference of tectonic style is evident between the movement of seracs and the basal flow of the Hamna Ice Fall, because the basal banded ice moves constantly on the base of the ice fall even when it is traversed by C_2 planes, and then every serac rotates on the basal flow in the upper part.

The second stage clear band C_2, originating in the lower half of the Hamna Ice Fall, dips to the south, showing a low angle about 35 degrees at first, but gradually changing to a high angle in the lower part. This suggests a differential flow in which C_1 is dislocated having been cut by C_2 planes (Photo. 8). The occurrence of C_2 planes sets an example of a compressive flow contrary to the area where C_1 occurs in the upper part indicating an extending flow in the Hamna Ice Fall (NYE 1952).

The pattern of the clear band C_1 in Fig. 4 reveals a structure concave to the flow direction, but a convex structure on C_2 plane according to the stress distribution as stated above. It is considered also that the pattern of C_2 may reflect the internal structure of a kind of ogive.

Joint and fault (Fig. 5) : The lowest part of the ice fall flows up to a moraine pile, so that the stress condition of the flow changes alternatively to the extending stage. New planes originate as faults and shear joints. A fault with a N–S direction traverses the banded ice of the basal flow which shows minor folding. It thrusts up with a small scale dislocation towards the west which seems to be deviated from the main direction of the flow. The thrust faulting seems to represent a local movement of the ice fall on the moraine differentiated from the direction of the tectonic transport. Shear joints without dislocation distributed on both sides of the lowest part of this ice fall, may prove the latest structural element with an inclination to north in the extending state.

Faults as well as shear joints are diagnosed as clear band of the original state which is newly formed and has not yet recrystallized.

Cleavage in bay ice: Bay ice of Hamna Bay, 1.5 m in thickness, spreads out in front of the ice fall. It is clearly observed that the area in front of the fall indicates morphologically the existence of a fiord about 1000 m in length. The stress effect of the fall is revealed in the whole area as fracture cleavage. Vertical cleavages at a few centimeter intervals develope radially outward from the center of the snout. Rather weak cleavages in the northeast direction traverse the radial cleavages on both sides of the fiord ice.

The bay ice as well as the ice of the fall is usually deformed elastically, so that the stress is easily released by the shock of persons walking with crampons or striking with an ice axe, resulting in cracks.

Fig. 6 shows the entire view of planer structures in schematic profile in which clear bands are especially proved equivalent to shear planes such as crevasses (NYE 1952) ; besides, they have no opening but are recrystallized with increase in size of ice crystals. C_1 planes originate in the extending state in the upper part and are traversed by newly formed C_2 planes in the middle-lower part of the area of compressive state. The rotation of seracs is proved by the bending of C_1 planes and by accurate measurements using a U-gauge. Banded ice commonly flows down on the basement as a basal flow even when it is traversed by some other planer structures. At the terminus, the character of the fall changes again to the extending flow, so that minor folding and thrusting faults occur and jointing originates.

2) Icefabrics

The solid ice, on which the fabric study has been carried out, shows two different types of texture; glacier ice and bay ice, as described below.

Glacier ice: It takes the form of medium crystalline-crystals 0.5 to 3 cm in diameter, occasionally coarse crystals 5 cm or more in diameter as seen in cross section. Individual crystals have very interlocking and irregular boundary shapes. Within the ice and mostly within the individual crystals rather than along the grain boundaries, occur numerous spheroidal bubbles, 1 to 2 mm in diameter, containing air and water vapor. The bubbles are arranged with more or less preferred orientation. The banded ice of the basal flow exhibits alternation of bubble-rich and bubble-poor layers in foliations but not necessarily at other localities. At location 1, the preferred orientation of bubbles is vertical, having no relation to a clear band. The crystalline texture is completely uninfluenced by foliation, clear band or grain size.

Bay ice: It occurs as medium crystalline-crystals 0.5 to 6 cm in diameter; nearly bubble free, forming a clear, transparent aggregate; interlocking grain texture. Individual crystals have very elongated and irregular shapes. The elongation is generally normal to c-axes, which is characteristic to sea ice; the crystal growth occurred in the a-axes direction. Grain boundaries of individual crystals tend to become obscure because of the concentration to one maximum of c-axes, as well as of the strong strain shadow (undulatory extinction) which is parallel to c-axes of the ice crystals. Individual grains are fractured into many particles of elongated lath shape resultant from intense strain; then the displacement of axes within the individual undulose ice grains extends gradually to the neighbouring crystals. Therefore, it is not very easy to ascertain either the boundary of the individual grains or the ruptured particles. Among the larger crystals with intense strain shadow,

Table 1. Fabric data from Hamna Ice Fall and bay ice.

Location	Type of ice	Number of c-axes	Type of fabric	Undulatory extinction	Controlling plane
1	medium bubbly	90	4-max.	weak	C_2
2	medium bubbly	71	4-max.	weak partial	C_2
3	fine bubbly layer	110	5-max.	weak	foliation
4	fine with medium grain bubbly	103	5-max.	weak	C_1
5	medium elongated	70	1-max.	strong	radial cleavage
6	medium elongated	70	1-max.	strong	radial cleavage

a few small fresh grains without strain shadow were observed; these grains may be newly formed crystals having a different orientation from others (Figs. 11 and 12).

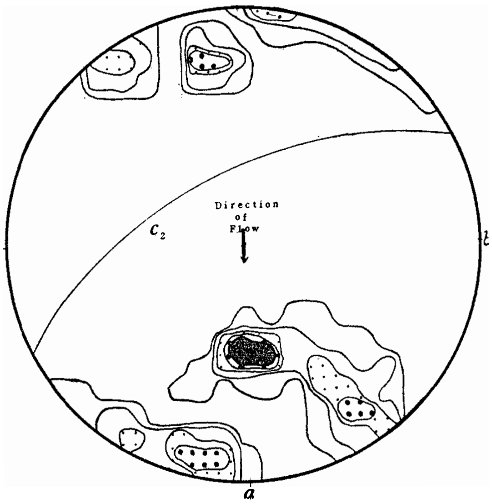

Fig. 7. 90 ice c-axes at location 1 of Hamna Ice Fall; contours 1-3-5-7-10 <per cent, max. 13 per cent.

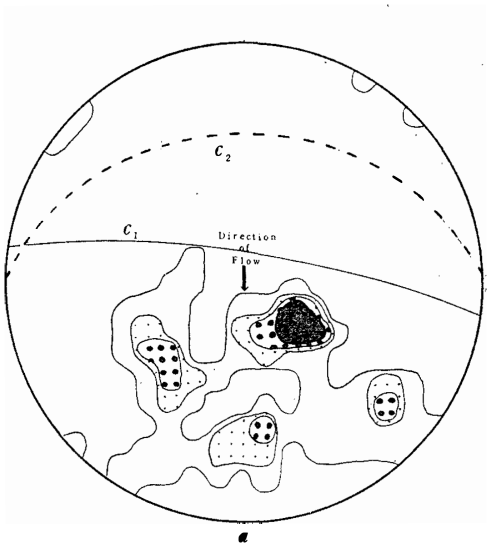

Fig. 8. 71 ice c-axes at location 2 of Hamna Ice Fall; contours 1-6-10-14 < per cent, max. 30 per cent.

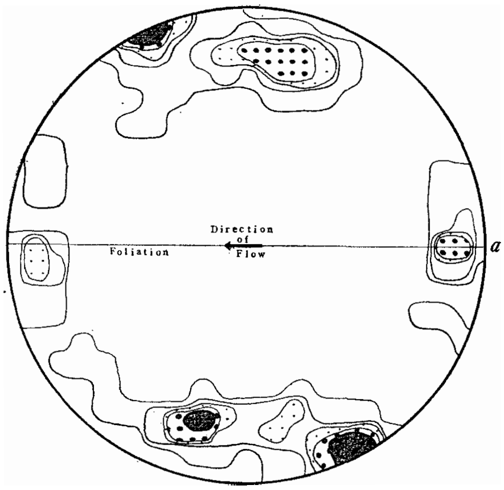

Fig. 9. 110 ice c-axes at location 3 of Hamna Ice Fall; contours 1-3-5-7-10 <per cent, max. 13 per cent.

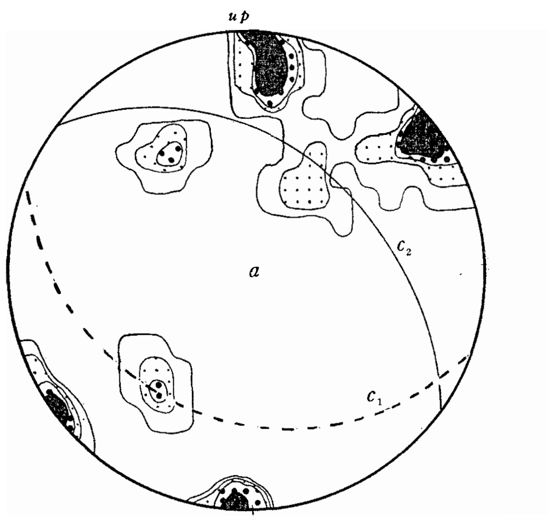

Fig. 10. 103 ice c-axes at location 4 of Hamna Ice Fall; contours 1-4-7-10< per cent, max. 20 per cent.

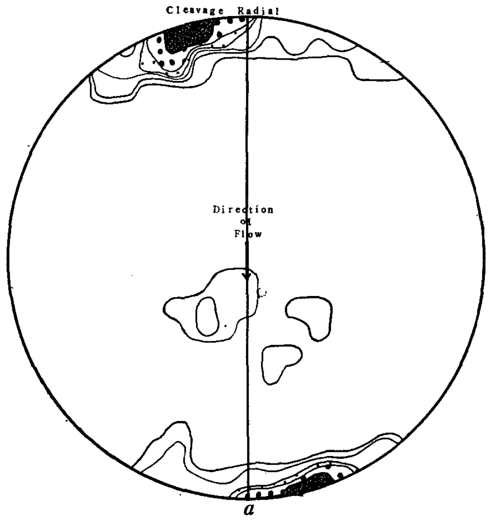

Fig. 11. 70 bay ice c-axes at location 5 in front of Hamna Ice Fall; contours 1–5 –10–15–20<per cent, max. 26 per cent.

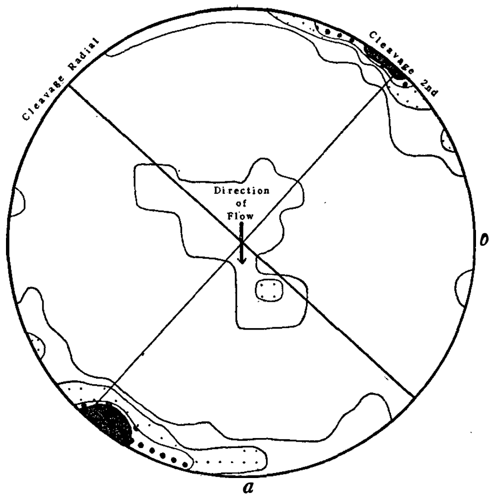

Fig. 12. 70 bay ice c-axes at location 6 in front of Hamna Ice Fall; contours 1–6 –10–14 per cent, max. 16 per cent.

3) Fabric pattern

Shown in Figs. 7～12 are fabric diagrams obtained from samples taken at four locations on the Hamna Ice Fall and two locations on bay ice ; the diagrams were secured by plotting the optic axes on the lower hemisphere of a Schmidt equiareal projection.

Glacier ice: The orientation of the axes of the ice crystals shows the strong four maxima pattern as a rule. The four maxima pattern was reported originally by RIGSBY (1951). He and other investigators have treated the problem; especially it has been studied theoretically by KAMB (1959). Multiple maximum fabrics (four maxima with one or two submaxima) are found in the upper part of the ice fall. It is evident that these diamond-shaped patterns are intimately associated with clear bands which are diagnosed as shear planes. In the lower part of the ice fall, it is postulated that the center of each diamond-shaped pattern is the pole of a clear band C_2 (Figs. 7 and 8), while in the upper part, it is the pole of a clear band C_1 and of a foliation plane (Figs. 9 and 10). It seems clear that the orientation of ice crystals is controlled by foliation plane at the first stage, and that controlling planes are followed by C_1 and C_2 clear bands owing to the tectonic sequence of the ice fall. Submaxima on the foliation plane (Fig. 9) and the clear band C_1 (Fig. 10) are characteristic patterns which suggest the axes to be parallel or subparallel to the controlling planes.

Ideal four maxima fabrics are found consistently in ice that has been subjected to long-continued strain in simple shear, and the development of several maxima is to be ascribed to locally varying rotation (with respect to the foliation plane) superimposed on the ice by a shearing motion (KAMB 1959).

In the present case, however, multiple maxima patterns are found at the base of the Hamna Ice Fall (Fig. 9) and at location 4 which is about 20 m deep in the ice of the middle part of the fall. It appears that these fabrics are subjected to more intense long-continued strain under strong shearing stress than other typical four maxima fabrics occurring at the surface of the lower part of the fall (locations 1 and 2). In the multiple maxima pattern, the strain effect may be due to simple shearing because any other local control of varying orientation is improbable within the basal flow of the banded ice. Strain shadow with a slight displacement of axes is observed more or less in every section.

Bay ice: The orientation of axes of bay ice crystals reveals an intense single maximum pattern parallel to the surface plane. Fig. 11 shows the fabric from the bay ice that is folded with a 1.5 m wave length just in front of the snout. The single maximum is subparallel to the radial cleavage which is conspicuously developed as stated above (location 5). However, it is observed that c-axes of ice crystals tend to point toward the pole of the radial cleavage which signifies the basal plane of the ice crystal gliding in Fig. 12; also an incomplete girdle is recognized that may indicate a tendency to concentration of the axes. This fabric pattern is from the level ice about 700 m distant from the snout of the ice fall (location 6). The basal plane of an ice crystal seems to behave as a glide plane under a weak stress condition so that the single maximum fabric will be produced. Then, the stress at location 5 (Fig. 11), is considered to be rather stronger than at location 6 (Fig. 12).

The plotted axes of a few small and fresh crystals without strain shadow occupy the central part of the diagrams (Figs. 11 and 12), which means that the c-axes of the ice crystals are vertical to the surface unlike the case of normal sea ice. annealing recrystallization appears to result in the production of a few small crystals without strain shadow accompanied by re-orientation, although the cause of re-orientation is still unknown.

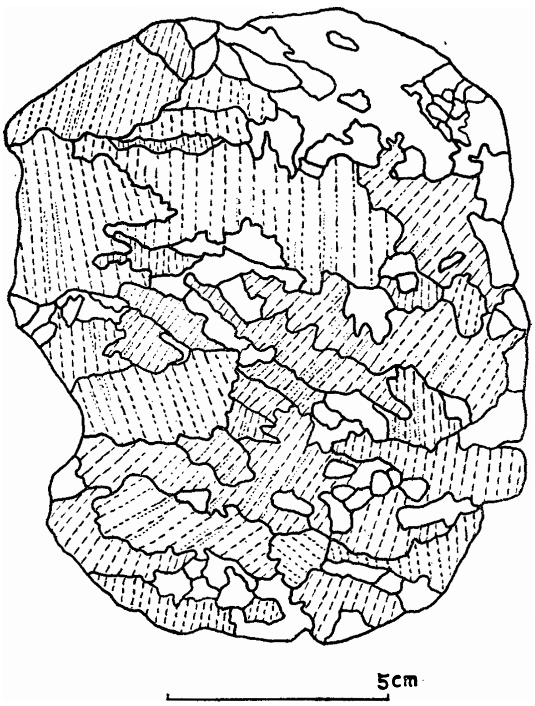

Fig. 13. Fabric of bay ice at location 6 showing undulatory extinction parallel to c-axes.

The intense undulatory extinction of crystals is a striking character of the bay ice of the area, and it inevitably leads to plastic deformation owing to the stress of the ice fall. The trend of the strain shadow usually parallels the orientation of the c-axes of crystals; also, the elongation of crystals is normal to c-axes as a whole. One crystal comprises many small separate lath-shaped particles which are the product of intense strain shadow due to the displacement of axes. The smallest particle shows a 0.2 mm long lath within a crystal of 5 cm length. This phenomenon may represent a kind of polygonization, showing deformation mechanism and re-orientation of axis of the ice crystals (Fig. 13).

4 Honhörbrygga Glacier

The Honhörbrygga Glacier (69°20′ S, 39°50′ E) is located about 10 km south of the Hamna Ice Fall, and flows down between two rock outcrops, Breidvognippa and Byvogosane. The glacier is accompanied by two others; one on the southern side flows down to the north-northwest, and the other on the northern side flows to the south. An ice fall south of the main flow, besides the main glacier stream in the northeasterly direction, flows down to form a complex ice fall near the lower part. The glacier, being an ice stream on a shallow valley of the continental slope, may flow for several tens of kilometers in the northeast direction according to the surface morphology of the ice sheet. However, the whole picture of this glacier is not known as yet.

A large tongue of the glacier extending from the present terminus is indicated on the geomorphological map and shown by the aerial photograph in the report of LARS CHRISTENSEN's Expedition 1936~37, but in 1960, the whole glacier tongue has disappeared except for a few iceberg remnants in the area where the tongue may have existed. Why the tongue has vanished? Its disappearance is probably due to the retreat of the continental ice sheet because of climatic change, or it may be due to accidental wave motion of the ice stream, or does it may be washed out by strong wave and current abruptly (Fig. 14).

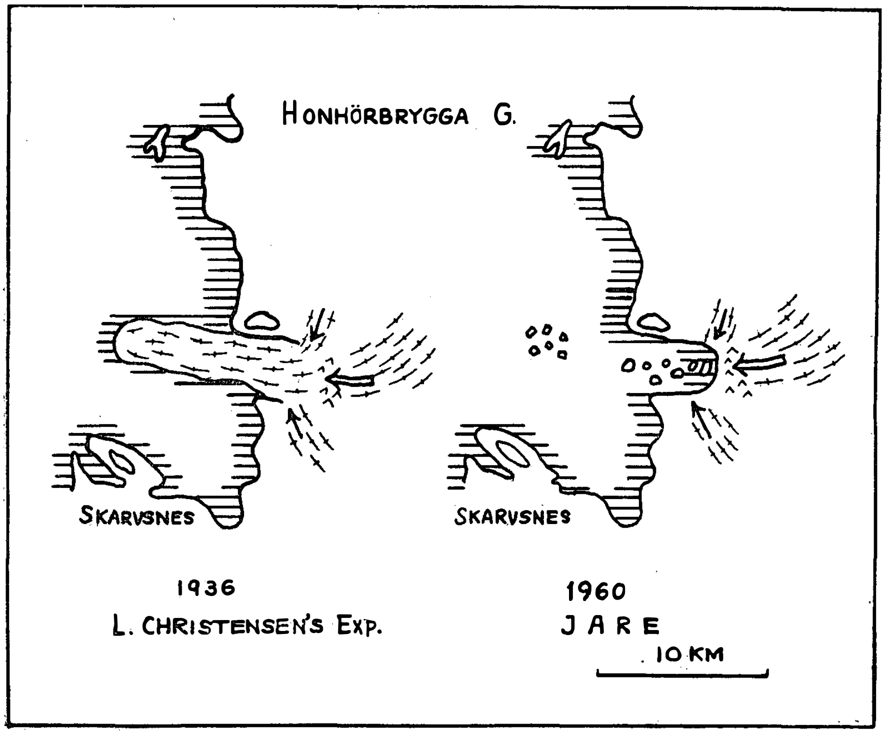

Fig. 14. Retreat of Honhörbrygga Glacier.

In the area in front of the glacier, a few large icebergs which are calved out from the glacier are scattered, and the interspace is clogged disorderly by small icebergs and ice bits with ice debris.

Bay ice that may not necessarily open to water every summer is bended, folded and crushed by the pressure of the glacier flow. The flowing pressure especially gives rise to pressure ridges in the area in front of the terminus of the glacier. Fracture cleavages develop in bay ice throughout the area (Fig. 15).

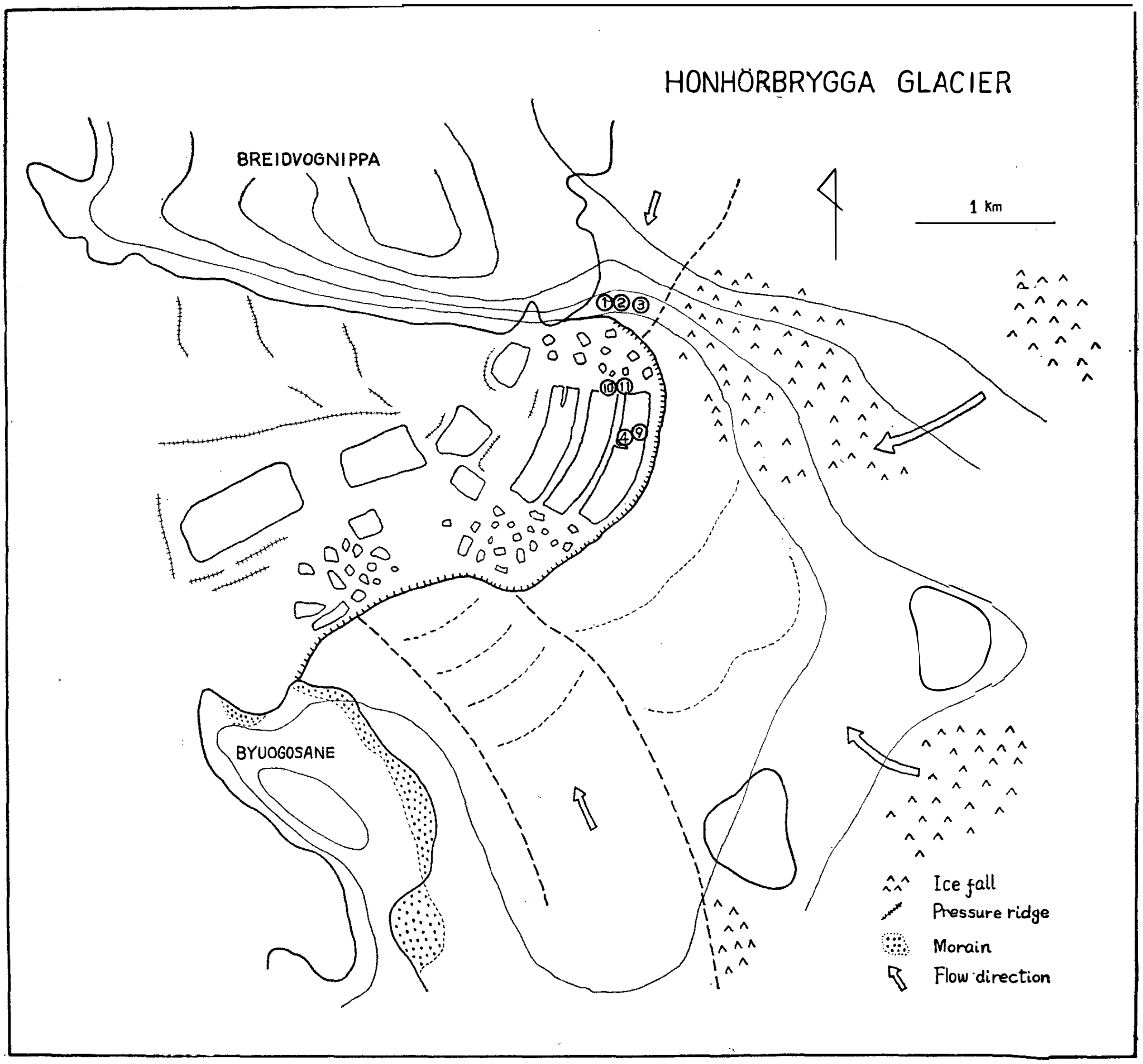

Fig. 15. Schematic map of Honhörbrygga Glacier.

Tectonic mapping was impossible because this composite glacier occupies an extensive area; precise surveys were also impossible on account of many seracs and crevasses. Hence, the party was obliged to be satisfied with merely collecting samples from one of three table-shaped icebergs calved out of the glacier, 1 km long and 36 m high, situated in front of the terminus. The sampling was carried out successfully in a crevass from sea level to the top of the iceberg at vertical intervals of about 5 m to 10 m.

1) Icefabrics

The texture of the glacier ice on which fabric study has been carried out is uniform grain size of medium type irrespective of depth. Clear band is composed of coarse ice and fine ice are rarely found.

Medium bubbly ice: Medium crystalline-crystals 0.5 to 3 cm in diameter, occasionally coarse crystals 5 cm or more in diameter are seen in thin section. Individual crystals have highly interlocking and irregular boundary shapes. Elongation of crystals parallel to clear band and banded structure (foliation) indicated by the alternation of bubble-rich and bubble-free layers, is observed at locations 1, 2 and 6. Bubbles, 0.5 to 3 mm, 5 mm in maximum diameter, have more or less preferred orientation according to grain arrangement as well as to elongated ovoidal form. A question whether the orientation is related to the movement of the glacier or not remains unanswered, as a structural analysis from the megascopic point of view has not yet been completed. The fabric patterns of the glacier ice are not controlled by the orientation of bubbles in the present case, although the patterns show intimate connection with clear bands and foliation. Undulatory extinction is observed in almost all sections; however, it is not always observed in every grain of a section but in a limited number of grains. It appears that plastic deformation without annealing recrystallization inevitably leads to undulatory extinction and the undulose grains may be reduced to clear grains in proportion to the advance of annealing recrystallization. This is an explanation for the case of the coexistence of undulose grains and clear grains in one section.

Coarse clear ice: This type of ice is characterized by coarse crystalline-crystals 3 to 6 cm in diameter; nearly bubble-free and forming clear, transparent aggregates; interlocking and irregular grain texture similar to that of the medium bubbly ice.

Coarse clear ice occurs in two structural situations in this glacier; a) thin (1 to 5 cm) layers intercalated with medium bubbly ice forming clear bands; b) lenticular pods contained within medium bubbly ice, elongated incline with the foliation which is subparallel to the flow direction of the glacier.

Fine bubbly ice: Two kinds of fine ice in texture and in occurrence are found at locations 10 and 12. Foliation indicated by alternation of bubble-rich and bubble-free layers, 5 cm width is developed at location 10. Fine ice there is generally crystalline, the crystals being 0.2 to 1 cm in diameter, rarely up to 2 cm in maximum dimension; individual grains have irregular and weak interlocking texture; the ice contains scattering small bubbles (0.2 mm). A bubble-rich layer is usually composed of fine ice partially showing undulatory extinction.

Fine ice at location 12 was collected from the surface of the continental ice sheet at about 40 km northeast of the terminus from the upper stream of the glacier. Crystals are 0.2 to 0.5 cm in diameter; individual grains are somewhat like subideomorphic hexagonal plate in shape without strain shadow. The ice contains many small bubbles (0.3 mm) which have a preferred orientation vertical to the surface.

Flow cleavage: Throughout this discussion "flow cleavage" refers to a kind of slip plane where recrystallization took place in bubble free, clear bands less than 5 mm thick, without formation of a distinct layer or variation in grain size, but the development is on a smaller scale than that of "clear band" (Fig. 16). A slippage related to the formation of flow cleavage is observed by the appearance of bubble orientation at location 8 (Fig. 17). The fabric patterns are controlled by these flow cleavages according to the following suggestions.

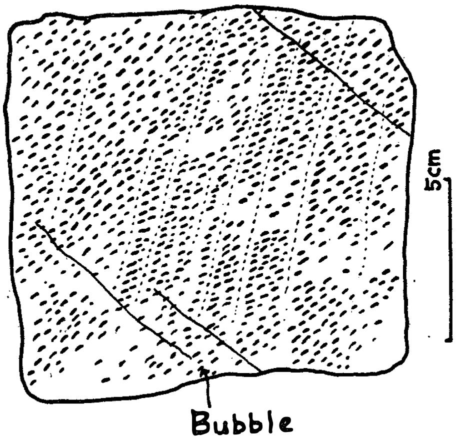

Fig. 16. Flow cleavages in the ice of Honhörbrygga Glacier.

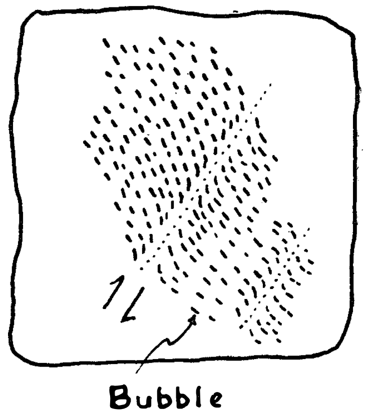

Fig. 17. Flow cleavages showing slippage.

2) Fabric pattern

Fabric diagrams were obtained from samples taken at thirteen locations on the Honhörbrygga Glacier, of which three diagrams are from the surface of the small glacier north of the main flow, nine diagrams vertically from a crevass of the large iceberg at the terminus, and the last one from the uppermost stream about 40 km northeast of the terminus. They are shown in Figs. 18~29.

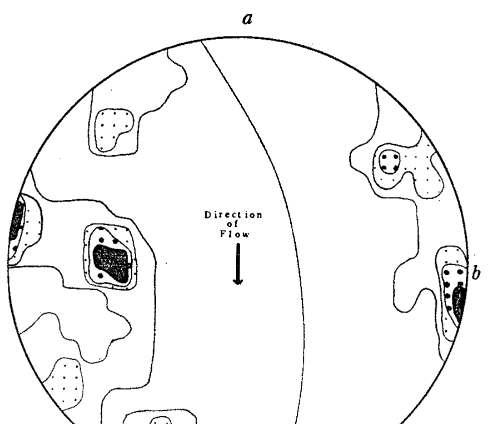

Fig. 18. 85 ice c-axes at location 1 of Honhörbrbygga Glacier; contours 1-4-7-10<per cent, max. 16 per cent.

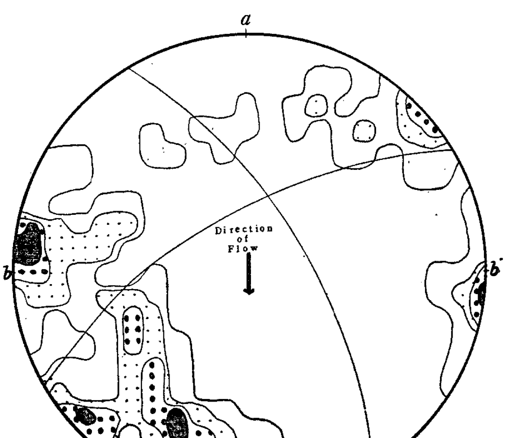

Fig. 19. 100 ice c-axes at location 2 of Honhörbrygga Glacier; contours 1-3-5-7<per cent, max. 9 per cent.

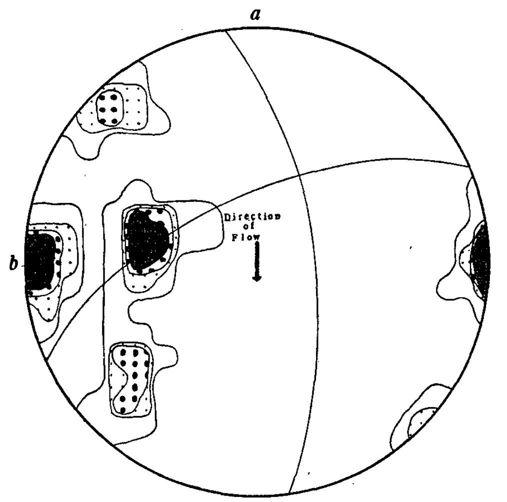

Fig. 20. 105 ice c-axes at location 3 of Honhörbrygga Glacier; contours 1-4-7-10<per cent, max. 19 per cent.

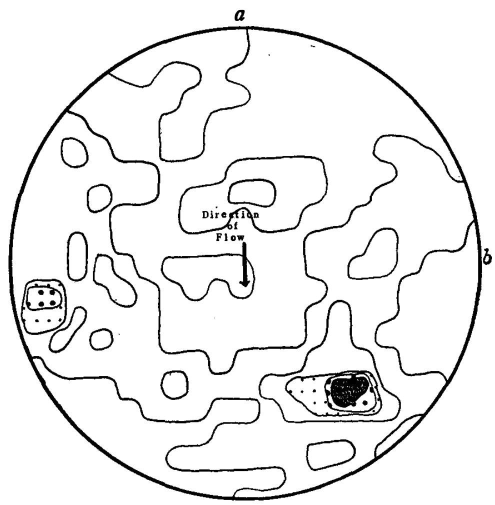

Fig. 21. 103 ice c-axes at location 4 of Honhörbrygga Glacier; contours 1-3-5-7-9<per cent, max. 11 per cent.

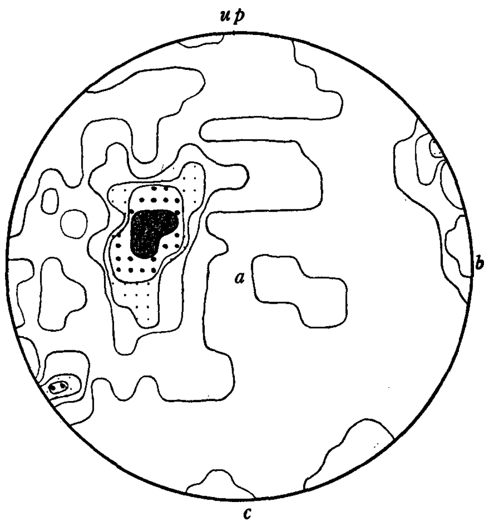

Fig. 22. 102 ice c-axes at location 5 of Honhörbrygga Glacier; contours 1-3-5-7-9<per cent, max. 12 per cent.

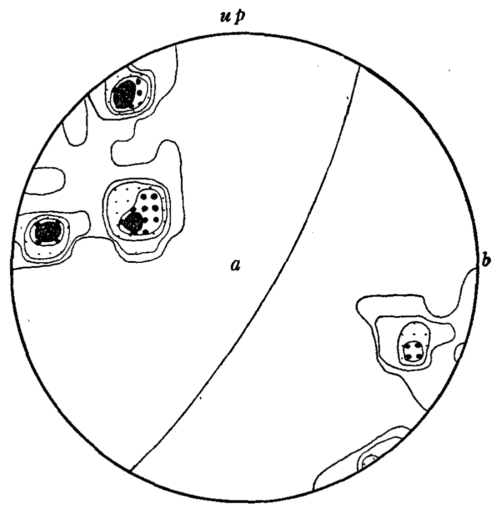

Fig. 23. 90 ice c-axes at location 6 of Honhörbrygga Glacier; contours 1-4-7-10-13<per cent, max. 17 per cent.

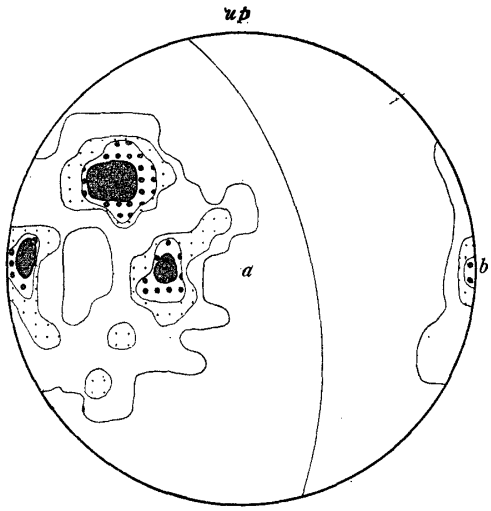

Fig. 24. 114 ice c-axes at location 7 of Honhörbrygga Glacier; contours 1-4-7-10 < per cent, max. 14 per cent.

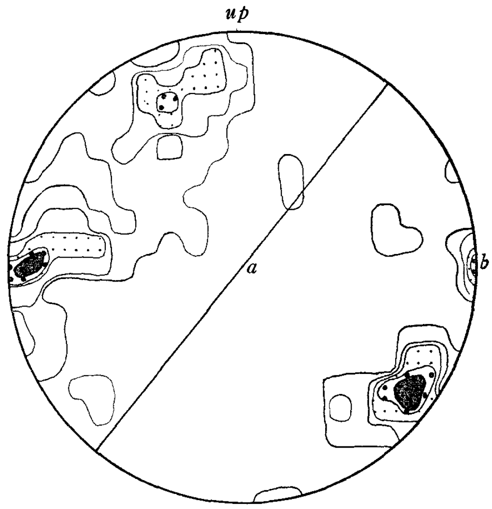

Fig. 25. 90 ice c-axes at location 8 of Honhörbrygga Glacier; contours 1-3-5-7-9 < per cent, max. 11 per cent.

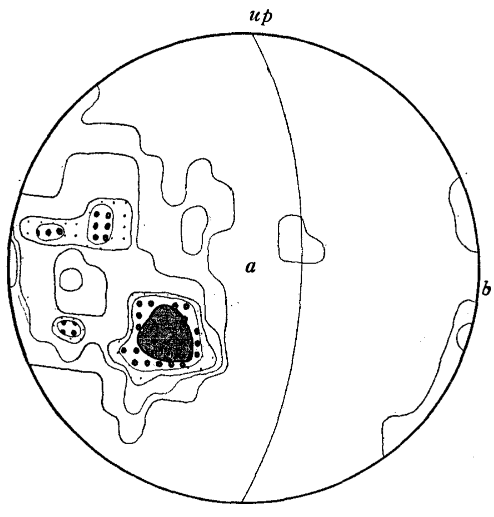

Fig. 26. 117 ice c-axes at location 9 of Honhörbrygga Glacier; contours 1-3-5-7-9-11 < per cent, max. 20 per cent.

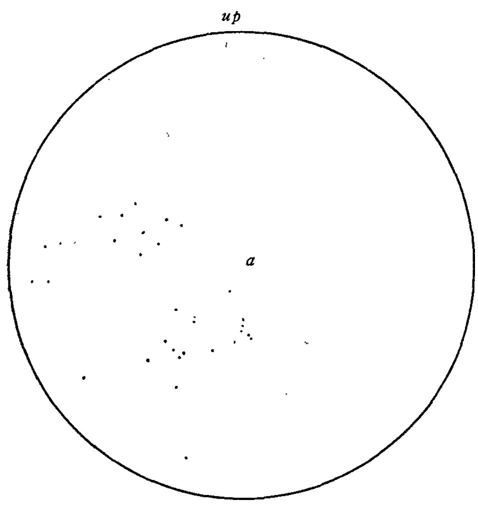

Fig. 27. 30 ice c-axes at location 10, coarse clear band.

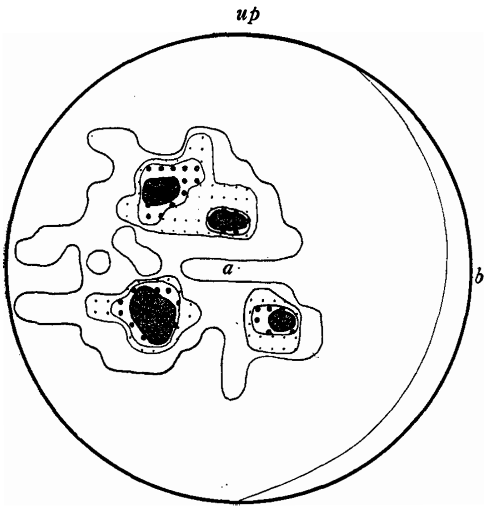

Fig. 28. 111 ice c-axes at location 11 of Honhörbrygga Glacier; contours 1-4-7-10-13< per cent, max. 17 per cent.

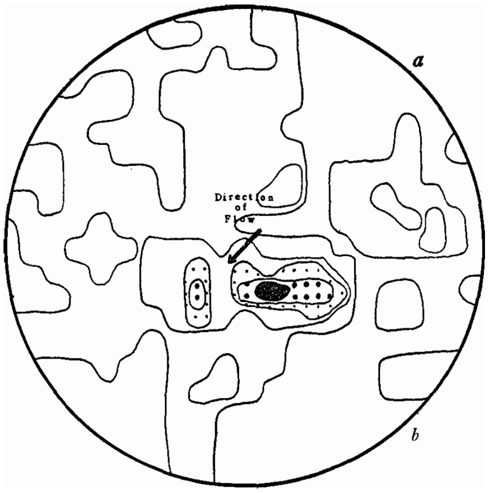

Fig. 29. 105 ice c-axes at location 12 of uppermost stream of Honhörbrygga Glacier; contours 1-3-5-7-9< per cent, max. 10 per cent.

In Figs. 18, 19 and 20, four maxima patterns are revealed to be controlled by a clear band which is the older one of a set of clear bands, according to the preliminary strutural survey of the surface pattern. The girdle-like pattern traversing the controlling plane in Fig. 19, shows some of the c-axes parallel to the controlling plane, the older clear band, as shown in Figs. 9 and 10. This may be a transitional pattern due to the rotation of c-axes to a new stable situation.

Table 2. Fabric data from Honhörbrygga Glacier.

Location	Height from sea level (m)	Type of ice	Bubble orientation	No. of ice	Type of fabric	Undulatory extinction	Controlling plane
1		med. elongated	none	85	4-max.	partial	clear band
2		med. elongated	none	100	4-max.	partial	clear band
3		med.	oriented	105	4-max.	partial	clear band
4	36	med.	oriented	103	broad 2-max.	partial	
4_a	31	med.	none	102	broad 2-max.	partial	
5	26	coarse	none	56	uncertain	partial	
6	18	med. elongated	oriented	90	4-max.	partial	foliation
7	6	med.	oriented	114	4-max.	partial	flow cleavage
8	3	med. rather coarse	oriented	90	3-max.	none	clear band
10	0	fine to med.	bubble band	117	4-max.	partial	foliation
10_a	0	coarse	bubble free	30	2-max.	partial weak	
11	0	med.	none	111	4-max.	partial	flow cleavage
12	40 km upper stream	fine	bubble rich oriented	105	broad 2-max.	none	deposition plane (?)

It is of interest that a vertical variation of fabric patterns is observable in Figs. 21～28. The heights of each location in the crevass where the sampling was carried out are shown in Table 2. Broad single maximum patterns with a submaximum are observed in the diagrams, Figs. 21 and 22, of the surface or nearby locations, although the controlling planes of these diagrams are indistinct.

A fabric diagram showing a single maximum with a submaximum is also obtained at location 12 which is the bare ice at the marginal slope just below the firn accumulated on the continental ice sheet. The diagram suggests that the fabric may be an initial deposition fabric, judging from the field occurrence as well as from the textural character as stated above. If so, the patterns in Figs. 21 and 22, may be deposition fabrics which are more or less disturbed.

The four maxima fabric becomes more distinct downward to the bottom of the iceberg crevass. A typical four maxima fabric is obtained in the lowest part at sea level which is 36 m below the surface of the iceberg. These four maxima patterns are controlled, without exception, by planer structures, such as clear band, foliation and flow cleavage. Some c-axes parallel to the controlling plane are also noticed in Figs. 25 and 26.

The fabric of the coarse clear ice is shown in Fig. 27 which is a scatter diagram as the measured ice grains were too few in number to be represented statistically. The figure reveals roughly two maxima pattern. Fig. 26 shows the four maxima diagram of the medium bubbly ice at the same location. Coarse clear ice may be produced later than the medium bubbly ice of the country ice so that stress effect on the fabric of coarse clear ice may be revealed to be less than that of medium bubbly ice. Therefore, the strain of the coarse clear ice may be weaker than that of medium bubbly ice. Two maxima fabric of the coarse clear ice may be produced under the same stress condition as that of the medium bubbly ice which is indicated by the same position of two maxima on each fabric diagram (Figs. 26 and 27), less short time elapsed in the case of coarse clear ice under external stress than in the case of original medium bubbly ice.

5 Fabric corresponds to stress condition

Single maximum fabric: There are three kinds of single maximum fabrics in the areas where the fabric study was carried out. Two kinds of fabrics are from bay ice, and the other one may be a deposition fabric. It is clearly known experimentally that the basal plane of an ice crystal plays a role of a glide plane under the condition of weaker stress. This is the case with the fabrics of the bay ice about 700m distant from the snout of the Hamna Ice Fall. Another case is the fabric just in front of the snout which reveals a single maximum parallel to the controlling plane (radial cleavage). Such fabric may have been formed due to a more large stress than the stress that in the case of the fabric of basal plane gliding, when judged from the

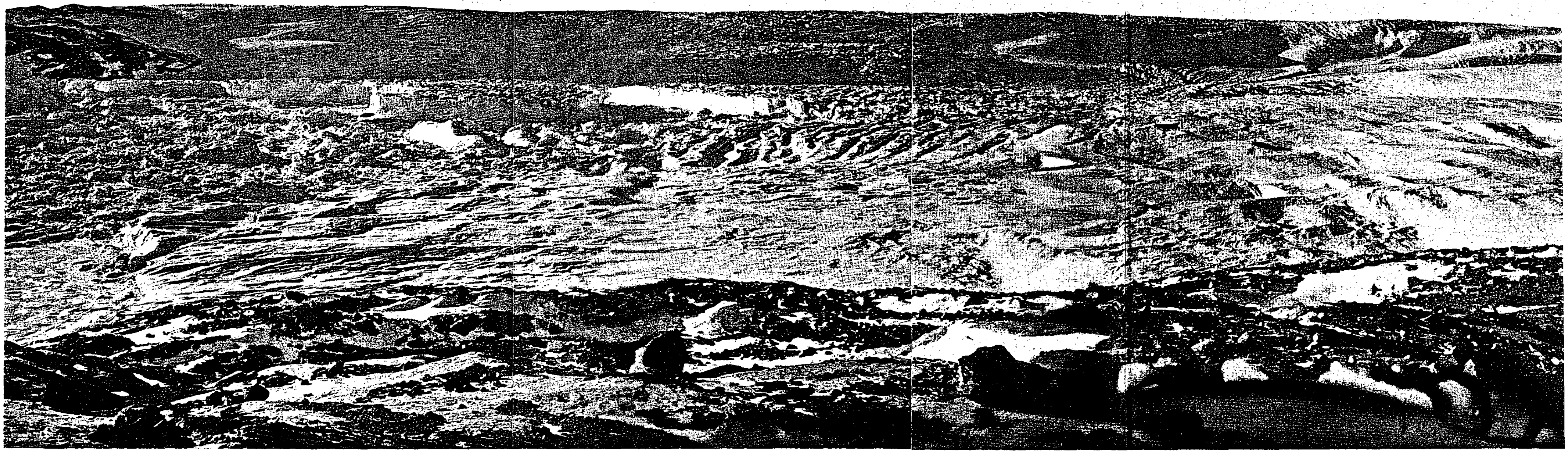

Plate 1. A panoramic view of Honhörbrygga Glacier from sou

of Honhörbrygga Glacier from south.

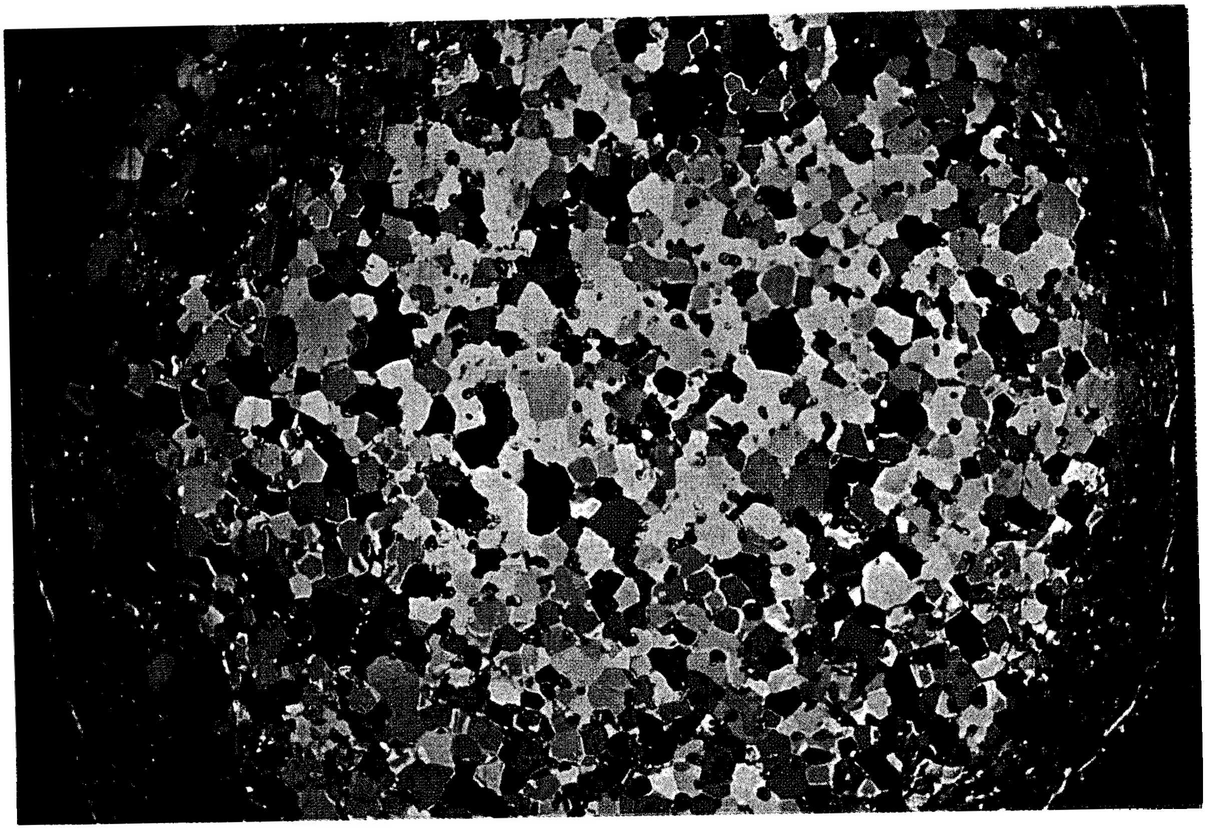

Photo. 1. Fine bubbly ice (surface ice of continental ice sheet) at location 12. ×0.9

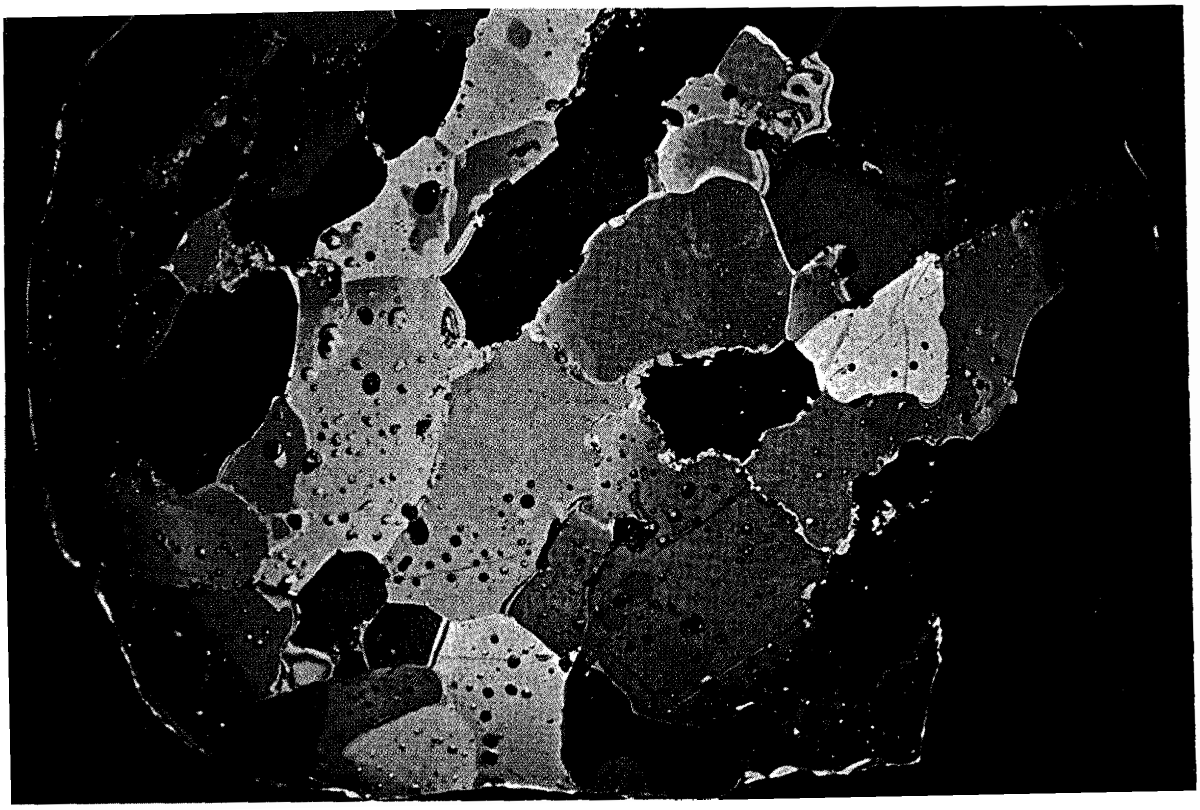

Photo. 2. Coarse bubbly ice at location 4. Honhörbrygga Glacier. ×0.9

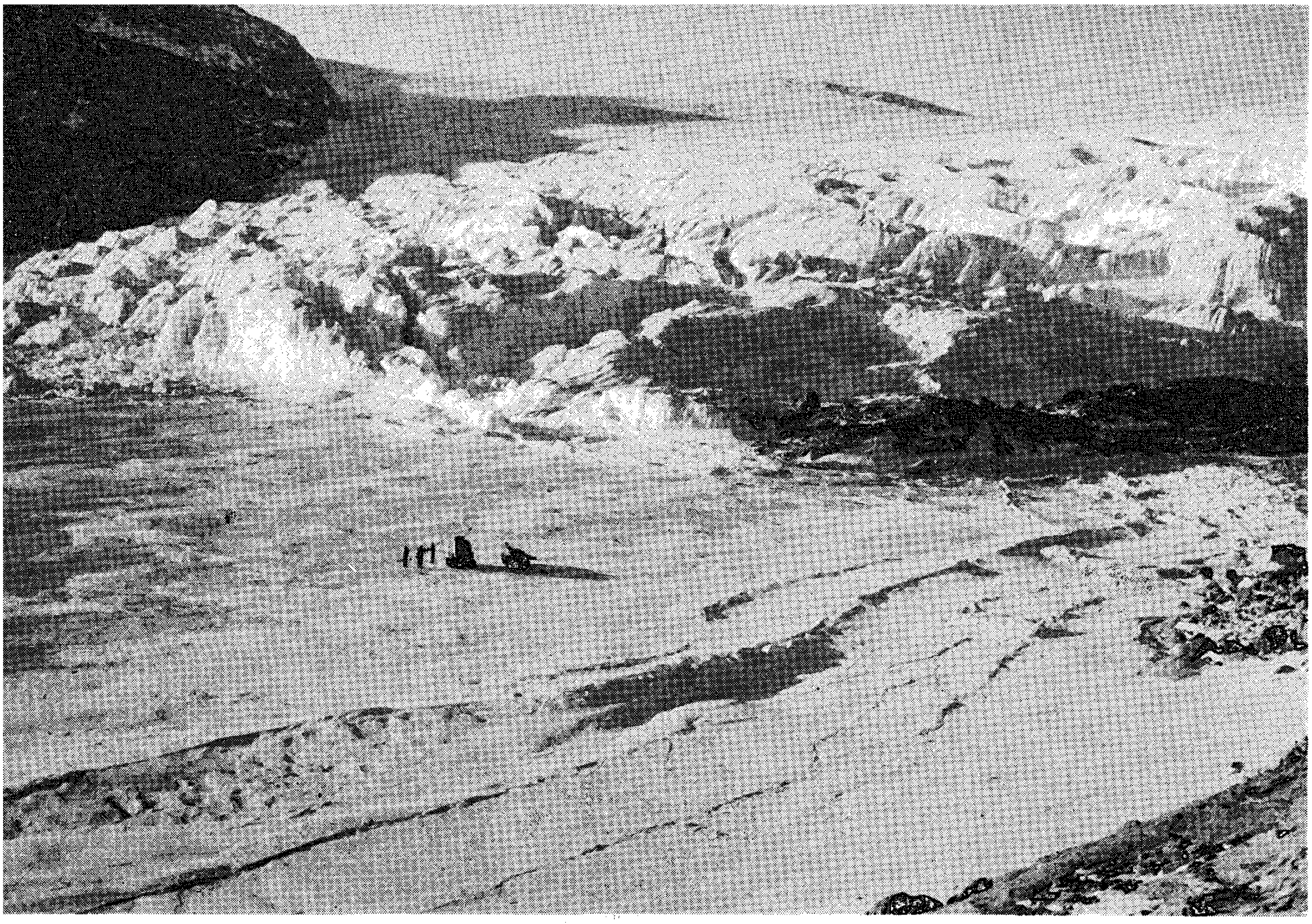

Photo. 3. Hamna Ice Fall viewed from west.

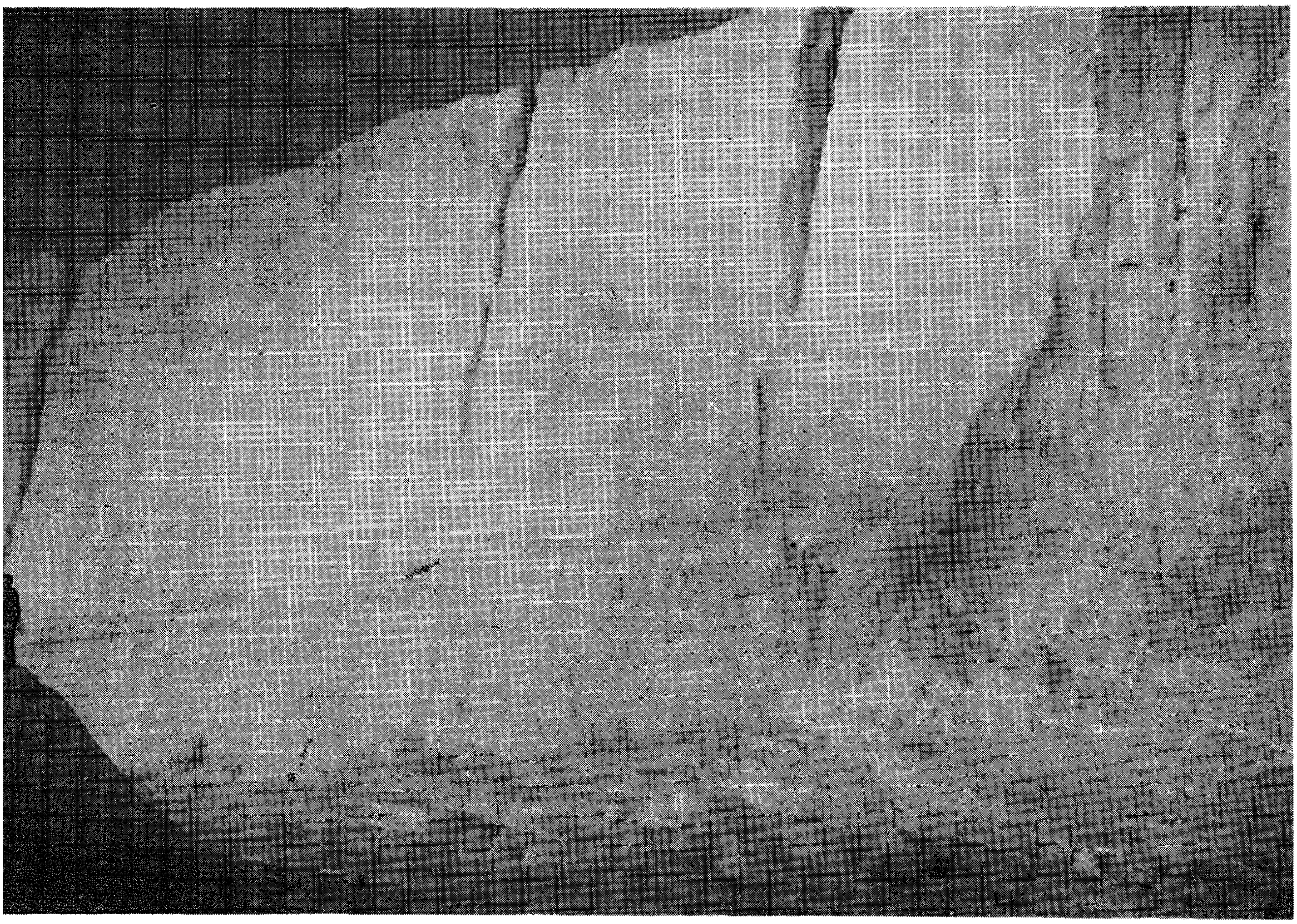

Photo. 4. An iceberg with crevasses in front of the terminus of Honhörbrygga Glacier. 40 m in height.

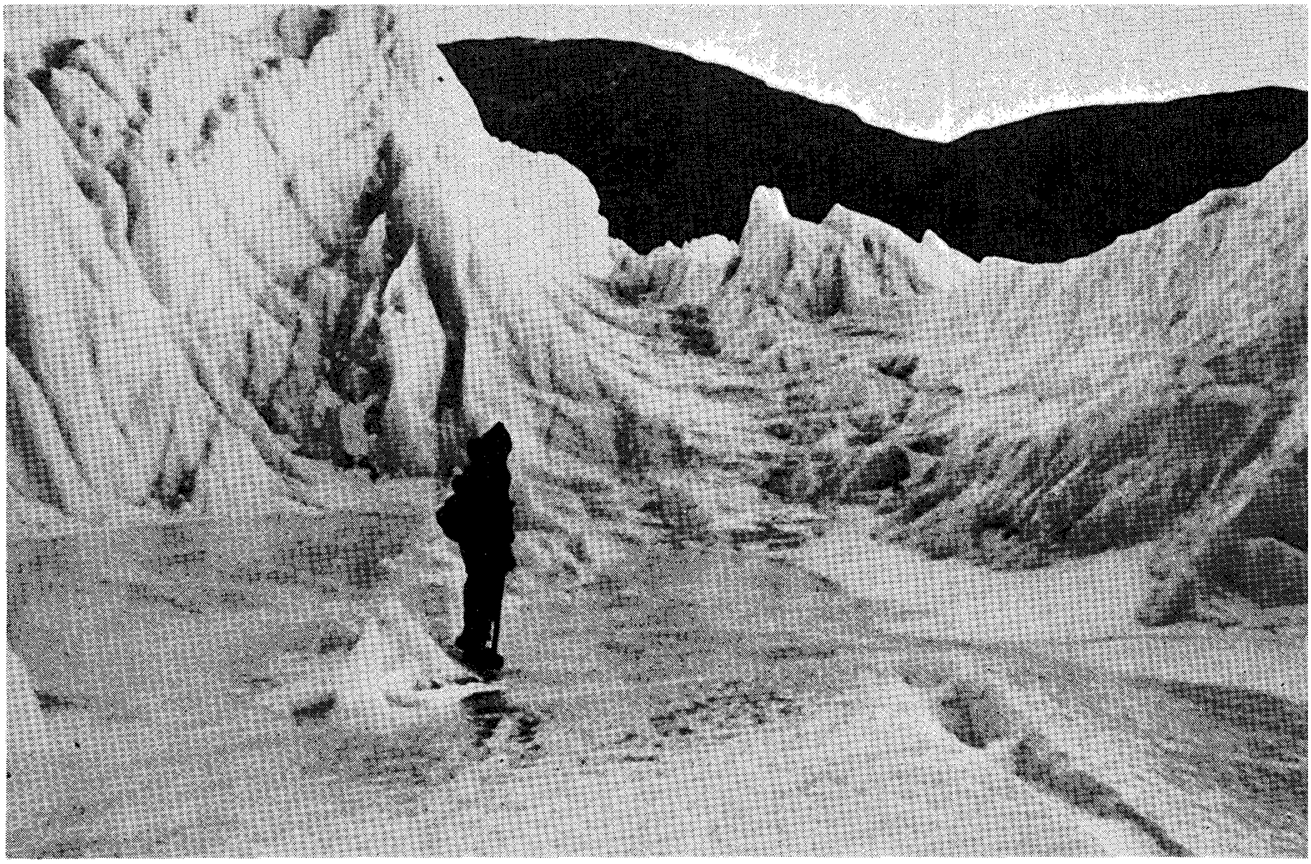

Photo. 5. Corridor in Hamna Ice Fall showing clear bands in background.

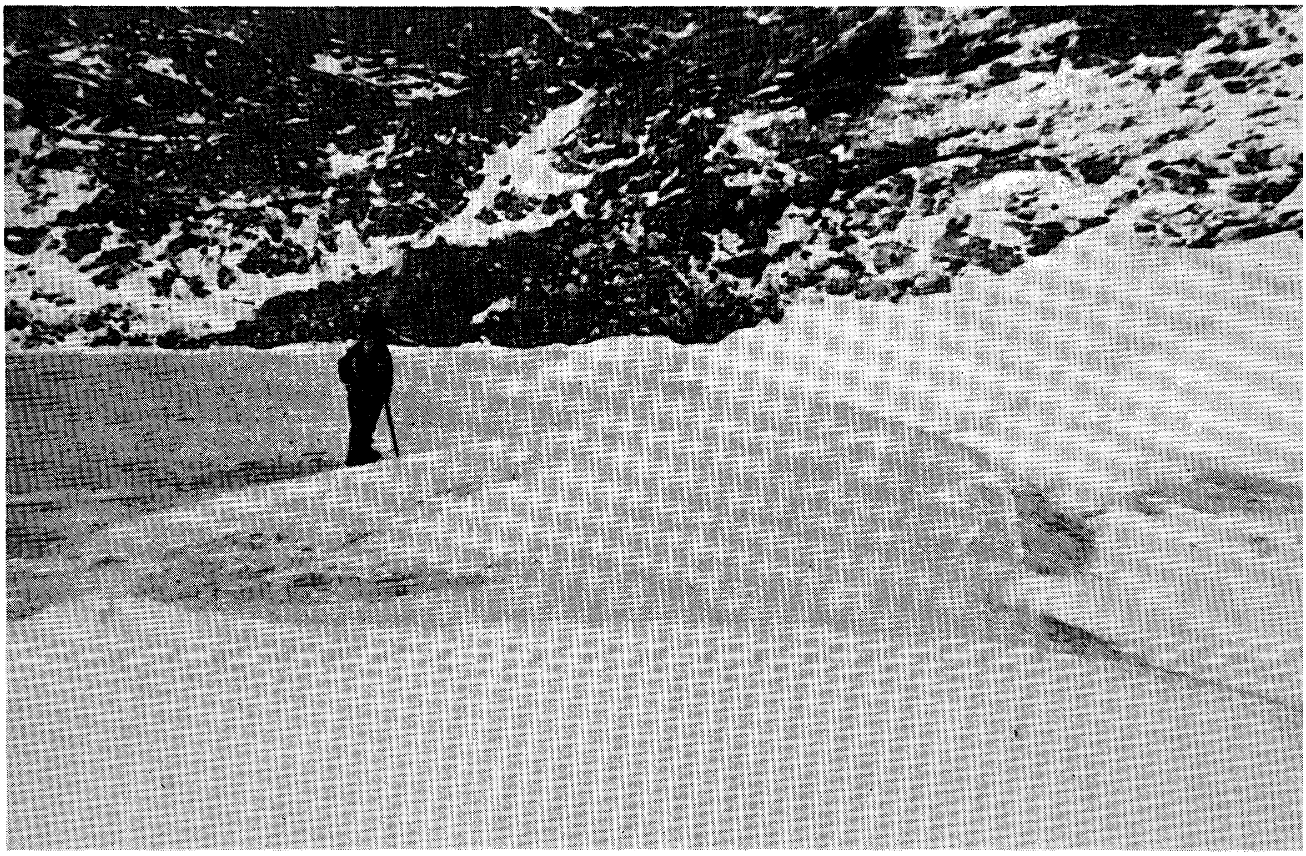

Photo. 6. Folding of bay ice in front of the snout of Hamna Ice Fall.

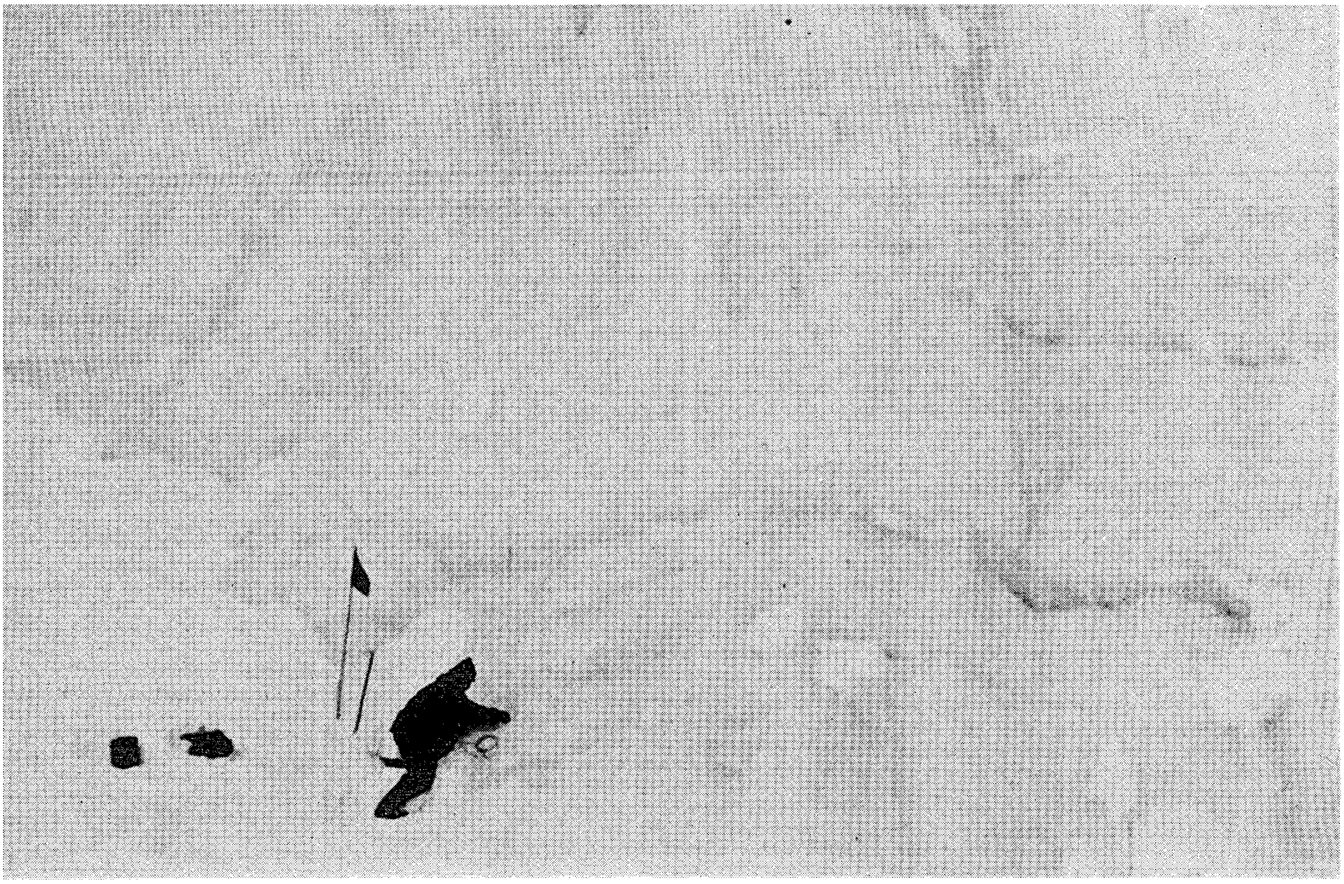

Photo. 7. Burying U-gauge in a serac which shows clear bands, Hamna Ice Fall.

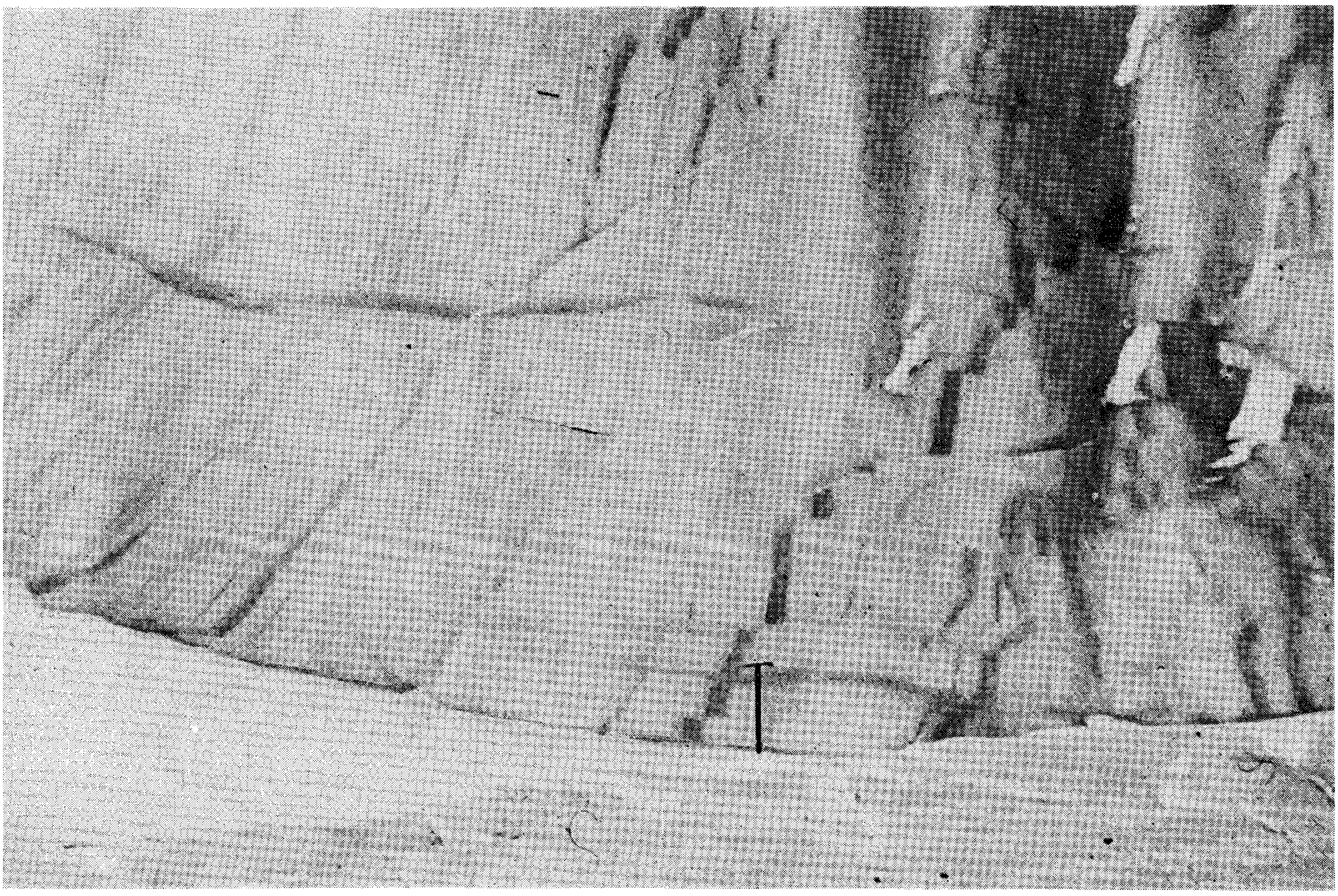

Photo. 8. Vertical clear band (C_1) dislocated by traversing horizontal clear band (C_2), Hamna Ice Fall.

Photo. 9. Medium bubbly ice. ×3/8

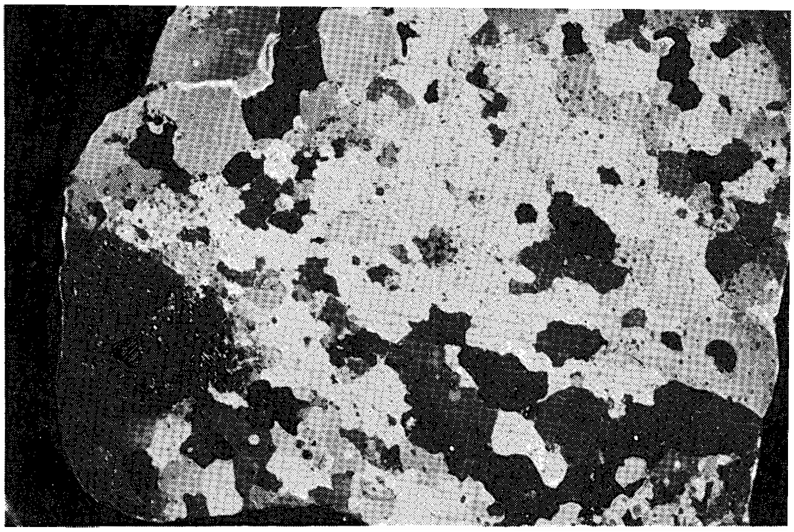

Photo. 10. Transparent coarse ice in clear band. ×3/8

Photo. 11. Bay ice showing intense undulatory extinction and a kind of polygonization. ×3/8

field occurrence; then, it gets mixed with a four maxima fabric to form a multiple maximum pattern. In the bay ice in front of the snout, where the original orientation of the c-axis of sea ice is seen, the parallelism to the surface may easily contribute to the formation of the pattern with the single maximum parallel to the controlling plane under a stronger stress.

At location 12 on the Honhörbrygga Glacier, a deposition fabric is found showing a broad single maximum with a submaximum vertical to the surface. The characteristics of the pattern survived in spite of the pattern's rotation and disturbance at the surface of the iceberg at the terminus of the Honhörbrygga Glacier.

Two maxima fabric: This type of fabric is observed in Fig. 27 though the pattern is not definite. It is clear in this case that the fabric may have been produced under weaker stress than the fabric with four maxima.

Four maxima fabric: Four maxima fabric patterns are found in the lower part of the Hamna Ice Fall and in the iceberg where the ice has been subjected to long-continued strain under strong stress. It is admitted that the fabric is found on the surface of ice fall or glacier, but the ice may have come up from the lower part.

Multiple maxima fabric: In the present case, the multiple maxima fabric is composed of four maxima fabric and single maximum fabric parallel or subparallel to the controlling plane, as shown in Figs. 9 and 10. This pattern is shown by RIGSBY (1951) in the Emmons Glacier without any explanations. It is proved now that this type of fabric may be produced under intense stress, rather than the four maxima fabric as formed in the Hamna Ice Fall, though the mixing with the single maximum fabric is not yet accounted for.

The easiest glide plane of an ice crystal is proved experimentally to be the basal plane forming a single maximum fabric under weak stress. It means that the crystal structure parallel to the basal plane shows the weakest bonding. Then, as the more intense stress condition develops, the glide plane of an ice crystal may change to the face having strong bonding corresponding to the stress: $\{11\bar{2}2\}$, $\{10\bar{1}2\}$, $\{11\bar{2}4\}$. This would account for the sequence of single maximum→two maxima→four maxima→multiple maxima fabrics. A small girdle appearing in four maxima fabric may be a transitional character of the pattern caused by the displacement of c-axes in settling.

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