THE GROWTH OF THE GLACIER CRYSTAL

By GERALD SELIGMAN

ABSTRACT. This paper concludes the earlier researches of the author and his colleagues on the development of glacier ice from the snow crystal. It traces the crystal growth down to the end of the glacier and records the distribution of large crystals in glacier tongues. Various agencies are suggested which might help in the proposed investigation of the mechanisms of growth of the crystals of glacier ice.

ZUSAMMENFASSUNG. Die vorliegende Abhandlung bringt die früheren Arbeiten des Verfassers und seiner Mitarbeiter über die Entwicklung des Gletschereises aus dem Schneekristall zum Abschluss. Es wird über den Verlauf des Kristallwachstums bis zum Gletscherende und die Verteilung grosser Kristalle in Gletscherzungen berichtet. Verschiedene Methoden werden vorgeschlagen, die zu einer in Zukunft beabsichtigten Untersuchung des Wachstums-Mechanismus der Gletschereiskristalle geeignet sein dürften.

The Alps: 1947

OBJECT OF THE RESEARCH

In 1932 the author began to amplify the work, commenced by Ahlmann, Paulcke and others, of the evolution of the snowflake into a crystal of firn snow.[1, 23] In 1938 the Jungfraujoch Research Party led by the author continued this work up to the transition of firn snow into glacier ice.[2] At this stage the crystals had diameters of about 0·5 to 2·0 mm. This already indicates considerable growth, for the new snow granules, once they have lost their dendritic structure, seldom exceed 0·1–0·3 mm. in diameter.

In the tongues of glaciers the crystals are of centimetre rather than millimetre size. The object of the present research was to observe these concluding stages. The ultimate aim is to throw light on the mechanism of growth. In the case of snow this is tolerably clear but little is known of the final stages of glacier ice. Much work has still to be done in the field and in the laboratory. A necessary preliminary is to ascertain to what size crystals can grow in glaciers, where in the glacier the largest are to be found and what are the conditions which might affect growth. This paper deals with these points and presents certain facts which will be useful in approaching the ultimate theme.

Some of the results confirm or amplify beliefs previously held but generally founded upon too little evidence for final acceptance. This research attempts to form a fresh approach to the subject by the use of more exact methods.

The final solution of the problem, with the aid of a thorough crystallographic examination of a single glacier tongue, would not only narrow a gap in our not too complete understanding of glacier physics, but might also bear upon other subjects. If, for instance, it were possible to determine the speed of crystal growth the age of stagnant ice formations might be calculable, which would be invaluable to climatologists and glacial geologists.

Again, to quote Professor J. D. Bernal:

> "A glacier presents an example of . . . crystalline material almost exactly at its melting point. . . . The growth and mutual relations of the crystals have therefore a crystal-physical interest particularly in relation to the recrystallization of hexagonal metals such as magnesium. Another aspect [is that] a glacier may be considered as a model . . . with fairly rapid rates of transformation, of . . . sedimentary rock undergoing dynamic metamorphism. The relation of crystallization to thrust and fault planes, and the size of the crystals, may throw light on the recrystallization which occurs in these rocks."

Investigations in these directions might be easier with ice than with the opaque crystals of minerals and metals.

Previous Work

A good deal of general descriptive work of the ice crystal exists. Among the oldest works of importance are those of Hugi,[3] the pioneer in this field, Hagenbach-Bischoff [4] and Forel,[5] but perhaps the most useful is that of Emden.[6] Of more recent age the researches of Tammann [7] are of interest. But practically every one of the large number of theses that has appeared has, of necessity, dealt either with laboratory experiments or with observations on the glacier but not with a combination of both. The Jungfraujoch Research Party of 1937–38, thanks to modern facilities of transport and apparatus, were able to link field observations with laboratory tests. They were thus able to correlate a microscopic study of the crystals with conditions in the glacier. They were assisted in their work by the crystallographic studies of Bader, Haefeli and their colleagues.[8] Of quite recent work that of de Quervain [9] is likely to prove of value.

Several observers have, in passing, noted the sizes of glacier crystals, Buchanan,[22] Heim,[10] Chamberlin [11] and von Drygalski [12] among them. Forel [5] mentioned that the grains in glacier tongues reached 4 and 6 cm. in diameter and even essayed to calculate their speed of growth. But the only attempt to make even a rough record of crystal sizes in various definitely ascertained positions in a glacier appears to be that of Wright and Priestley [13] in the Suess Glacier, Antarctica.

Recording the Crystal Sizes

The original intention was to photograph the crystals either *in situ* or in thin sections in polarized light. Both these methods were rejected for good reasons and after consultation with colleagues at the Forschungsinstitut, Weissfluhjoch (Weissfluhjoch Research Station) the making of pencil rubbings on paper was adopted, a method used by Forel and by Deeley many years before. Weathered crystal boundaries are depressed and show up clearly in a rubbing (see Fig. 13, p. 267).

One of the main advantages of this method is that the crystals are reproduced in their actual sizes, which removes all complications of measurement. It also enables the operator to appraise the results on the spot and to plan his further investigations without having to wait for the development of a photographic film—a disadvantage that would be reduced if a dark room were close at hand.

It cannot be claimed that any two-dimensional record is completely accurate. This is not a very serious error as crystals in active (flowing) ice generally measure roughly the same on their three axes. A greater source of error lies in the fact that a section cut through an assemblage of crystals will not pass through the largest diameters of all crystals. Results therefore tend to be low. It was felt, however, that to attempt to correct this discrepancy in these crystallites would be too complicated a matter for the present purpose. It may at least be assumed that, over the very considerable number of samples taken, the error is fairly constant. If further research demands more exact results, the method of obtaining three-dimensional (spatial) crystal sizes from two-dimensional (planar) data evolved by S. W. Johnson of the Westinghouse Metallurgical Research Laboratories, Pittsburgh,[14] would be useful.

Procedure for Taking Rubbings

Exposed Surfaces. The most suitable surfaces for rubbings were found on the walls of crevasses or on the glacier margin itself. Horizontal surfaces were not so suitable.* The spot selected had

* The method adopted by Ahlmann and Droessler (see p. 269) is satisfactory for horizontal surfaces.

to be smooth, as free from air bubbles as possible and sufficiently weathered to render the depressed crystal boundaries visible to the eye. Wiping them gently with a pad of blotting paper often made them stand out better. It is important to make sure that all boundaries show up because the smaller crystals have less conspicuous boundaries than the large.

The area to be rubbed having been selected and if necessary dried, a piece of soft, unglazed and slightly absorbent printing paper was then placed over it and "rubbed" with a soft pencil. The whole process occupied only a few minutes. Crystals of 1 mm. diameter or less are liable to be missed by this method. For showing them up, *Darkalene*, a proprietary floor stain consisting of a dye in a cresol vehicle, proved very satisfactory. For this method the stain was applied to the surface and, filling the crystal boundaries, left an imprint when a sheet of paper was applied and smoothed over the surface with the palm of the hand.*

Unexposed Surfaces. If no good or typical ready-made surfaces were found the ice had to be ironed with a meta iron and rubbed for several minutes with a pad of blotting paper until the boundaries appeared. This process seldom took more than a quarter of an hour. Cutting out a thin block of ice a few crystals thick and ironing it brought the crystal boundaries out better but was more laborious.†

The Crystal Count

After prolonged tests the following method was found to give the most satisfactory results.

A series of standard circles of increasing size was drawn on tracing cloth. This was placed over the rubbing and the number of two-dimensional crystal surfaces corresponding to their equivalent circles was counted. The sum of the areas of each size of equivalent circle represented in the rubbing was then expressed as a percentage of the whole area of the sample. A histogram (see Figs. 5–7, p. 260) is the most convenient method of showing the areal proportions per cent. of crystals of each size present. The root mean square diameter of the standard circles gives the average crystal diameter of the whole sample. In this paper whenever a mean diameter of an assemblage of crystals is given it refers to the root mean square diameter.

The standard diameters were arranged logarithmically so as to give a constant ratio between each size and the next. They were 0·25, 0·4, 0·6, 1·0, 1·6, 2·5, 4·0, 6·3 and 10·0 cm. These figures are rounded off to not more than two significant places, the deviation being within the error of experiment, since each crystal can only be approximately matched with its equivalent circle. The results given in this paper are also shown to two places of decimals. No accuracy can be claimed for the second place but it is sometimes useful in suggesting a trend.

Glaciers Visited

The glacier tongues examined will be found in Table I (p. 257). In only one glacier, that of Findelen, were observations made above the firn line. Here the crystal diameter *at or near the surface* was of the order of 1–2 mm. and increased from there to the snout.‡ These sizes are of the same order as those found at about the same altitude by M. F. Perutz and the author working *downwards* from the source of the Great Aletsch Glacier in 1938.[15] Thus the present research can be linked up to the earlier stages of crystal growth noted at that time.

* Ahlmann and Droessler independently arrived at a similar but, for many purposes better, method.
† Ahlmann and Droessler used a blow lamp which seemed to give better results than the meta iron.
‡ The same state of affairs was found to occur in 1948 on Böverbreen in Jotunheimen.

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Distribution of Crystal Sizes in Glacier Tongues

General. The crystals at the margins of Alpine glaciers are larger than at the centres. Fig. 1 (p. 258) showing the crystal distribution in the tongue of the Eiger Glacier demonstrates this clearly, and also that the change in size is gradual so long as the ice is in active motion. On the other hand the final transition to stationary marginal ice showed an abrupt boundary with a considerable increase in crystal size as in the Findelen Glacier (Fig. 2, p. 267).

TABLE I

Mean Crystal Sizes near the Snouts of Active Ice Streams

(1)	(2) *Key to Figs. 3 and 4*	(3) *Approximate Inclined Travel (km.)*	(4) *Mean Angle of Slope* (sin α)	(5) sin α	(6) *Crystal Count*	(7) *Mean Crystal Diameter, cm.*	(8) *Approximate Dimensions of Largest Crystal*		(9) *Approximate Dimensions of Smallest Crystal Area, cm.²*
							Length, cm.	*Area, cm.²*	
Great Aletsch from Mönchjoch	AM	23	4° 53′	0·09	78	2·28	8·5	23·0	0·05
Great Aletsch from Lötschenlücke	AL	20½	4° 15′	0·07	172	2·32	14·5	76·0	0·13
Gorner (Boden) from Signalkuppe	G	13¾	9° 12′	0·16	44	2·05	5·0	13·6	0·13
Lower Grindelwald from Finsteraarjoch	LG	9	13° 4′	0·23	15	1·75	6·0	12·0	0·13
Findelen from Schwarzberg Weisstor	F	8¾	8° 28′	0·15	52	2·34	7·5	21·0	0·28
Morteratsch from Crasta Güzza	M	8¼	13° 21′	0·23	24	1·85	4·0	15·0	0·13
Stein	S	5⅔	13° 44′	0·24	29	2·22	4·0	10·0	0·13
Upper Grindelwald from Lauteraarsattel	UG	5	20° 18′	0·35	37	1·79	5·5	16·0	0·05
Rosenlaui from near Rosenhorn	E	4¾	18° 41′	0·32	105	1·75	5·0	10·5	0·13
Stein (Middle) *	SM	3½	19° 12′	0·33	52	1·95	8·0	32·0	0·05
Eiger	E	3⅓	25° 50′	0·44	34	1·43	3·3	6·0	0·28
Stein Limmi	SL	2⅔	13° 27′	0·23	208	1·82	4·0	12·0	0·05

Table I shows: (Col. 1) the glacier snouts investigated, (Col. 2) key initials to the graphs in Figs. 3 and 4 (p. 259), (Col. 3) the length of inclined travel, (Col. 4) the mean angle of the slope from bergschrund to snout as located in 1947, (Col. 5) the sine of that angle, (Col. 6) the crystal count and (Col. 7) the root mean square diameter of the crystal sizes at points as close to the snouts as were accessible.* In some cases the crystal counts will appear to be very small, but the samples were carefully chosen to represent a fair average over a much larger area—not an ideal method, but the only one possible in the short time available for examination of a large number of glaciers in a perforce restricted period of time in which, in all, 16,000 crystals were measured and summarized.

If the mean crystal sizes of all the glaciers are plotted against the lengths of their travel (Fig. 3, p. 259) they show considerable uniformity of arrangement, lying as they do fairly close to a mean line. This line is not a computed line of closest fit but has been estimated and drawn by eye. It shows a general increase of crystal size with length of travel. The Findelen and Stein figures are rather dissonant, the measurements having perforce been made at points not in the centre of the

* To assist comparison with Professor Ahlmann's figures the sizes of the largest crystals in each count have been added (Col. 8), and the areas of the equivalent circles of the smallest as recorded by rubbing (Col. 9).

main stream, so that the ice was probably somewhat "slack." Fig. 4 (p. 259) shows the same crystal sizes plotted against the sine of the angle of slope (sin α) in order to show a relationship between crystal size and velocity, this latter being *inter alia* dependent upon the sine of the angle of slope. In this case, too, it is not intended to show any definite correlation but only to mark the clear trend towards a smaller crystal on the steeper glaciers. That such a relationship exists seems certain.

It will be noted that the order of steepness and of length in which the glaciers have arranged themselves is not quite the same.

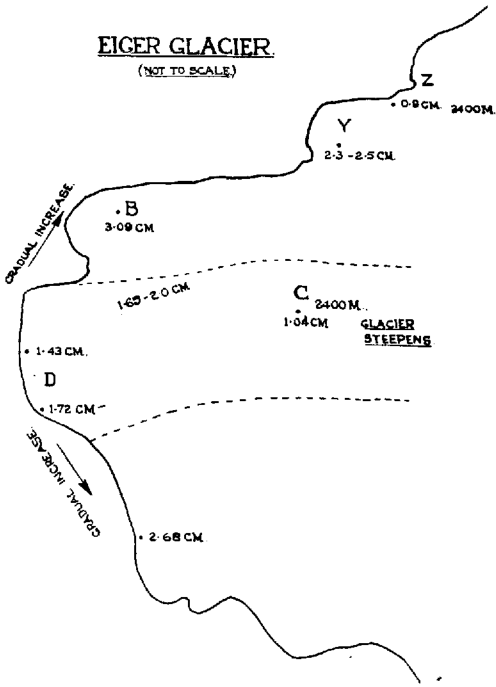

Fig. 1. Sketch map of the end of the Eiger Glacier showing mean crystal sizes

Distribution of Crystal Sizes in the Samples

Consideration of the accompanying histograms gives some indication of the habit of growth of the crystals.

Fig. 5 (p. 260) shows the final stages of growth in the Findelen Glacier: (a) and (b) give the distribution at 700 m. and 450 m. respectively from the snout, (c) shows that at the snout itself. The mean crystal sizes are circled. The transformation of the smaller to the larger crystals accompanied by the elimination of the smaller and the appearance of larger sizes is typical. Whereas in the first stage crystals corresponding to equivalent circles of 1·0 and 1·6 cm. cover 96·3 per cent. of the sample, they have been reduced to 30·5 per cent. in the second and to 19·0 per cent. in the third stage. The appearance there of 6·3 cm. crystals representing 14 per cent. of the whole area is striking. As pointed out above these results do not include any minute crystals but very few, if any, can have been present.

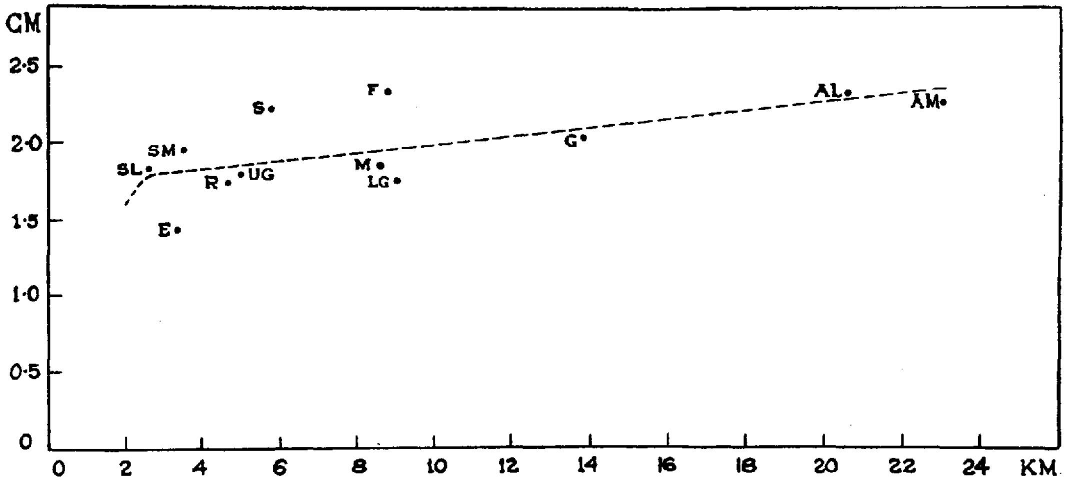

Fig. 3. Crystal sizes in centimetres plotted against length of travel of glaciers. (For key to glaciers see Table I, p. 257)

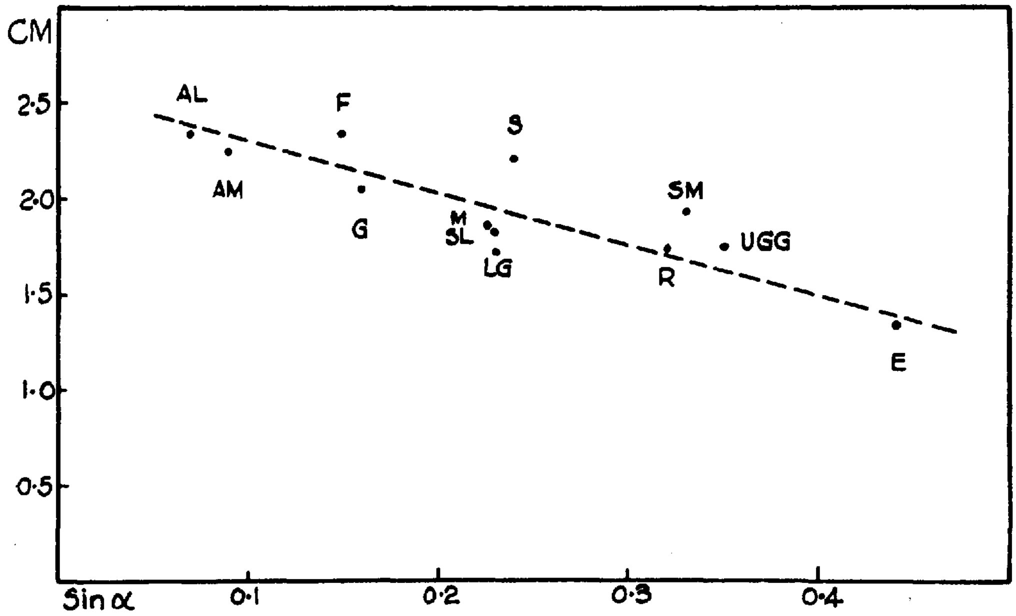

Fig. 4. Crystal sizes in centimetres plotted against the sine of the mean angle of slope (sin α) *of glaciers*

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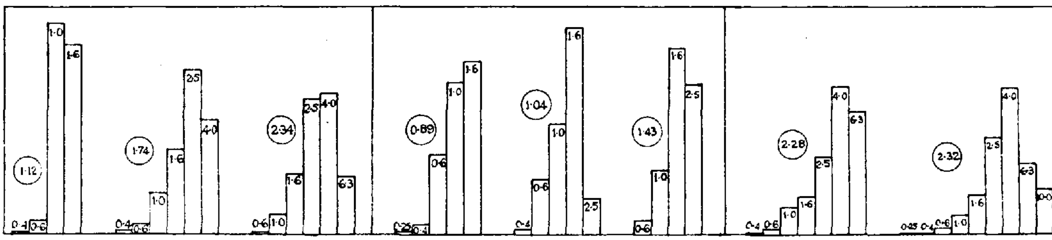
Fig. 6 (below) of ice from the Eiger Glacier shows that during growth the 1·0 cm. crystals have been reduced from 36 per cent. to 27 per cent. and then to 16 per cent. in the three stages; 0·25 and 0·4 cm. crystals have disappeared in the final stage; 2·5 cm. crystals, absent in the earliest stage, represent 8·7 per cent. in the second and have risen to 36 per cent. in the final stage.

By way of contrast the histograms of the two main streams very close to the snout of the Great Aletsch Glacier are interesting (Fig. 7, below). The true right-hand stream of the glacier (b) probably comes from the Lötschenlücke, a travel of about 20·5 km. and the left-hand stream (a) from the Mönchjoch, about 23·0 km. distant. In both cases 4·0 cm. crystals predominate, 6·3 cm. sizes are plentiful and in the Lötschenlücke stream 10·0 cm. diameter crystals make their appearance. Only two or three of these large crystals were found in the active ice of this glacier in a count of some 350 crystals. No crystals of this size were to be seen in the active ice of any other glacier.



(a) (b) (c) (a) (b) (c) (a) (b)

Fig. 5. Findelen Glacier
(a) *700 m. from snout*
(b) *450 m. from snout*
(c) *at snout*

Fig. 6. Eiger Glacier
(a) *about 1 km. from snout*
(b) *500 m. from snout*
(c) *at snout*

Fig. 7. Great Aletsch Glacier
(a) *Upper Mönchjoch stream*
(b) *Lötschenlücke stream*

Crystal distribution (percentage area occupied by each size of crystal in the samples measured) at various points in the three glaciers. Sizes of crystals at top of rectangles, mean crystal size of each sample in circles

Dead Ice

Ahlmann [17] defines dead ice as ice which is no longer fed from above. The mass may have a volume of a few cubic yards or it may cover large tracts of country. In the main it is stationary, although no doubt a receding glacier could leave deposits of ice on a slope steep enough to cause it to flow. Moreover a tall mound of dead ice would gradually sink like pitch; differential movement of crystal to crystal cannot therefore be excluded, but it must be very small compared with that in a flowing ice stream. In some cases, however, dead ice was investigated lying in pockets where movement was impossible.

Some of the dead ice met with lay at the margins of the glaciers, the narrowing stream leaving deposits high and dry. Occasionally, however, some of the ice in the glacier margins seemed unable to overcome the friction of the bank so that the moving ice stream swept past it with a well-defined break. This is well seen in Fig. 2 (p. 267) at the border of the Findelen Glacier. The ice here had all the characteristics of dead ice, being black, air-free and with very large crystals. It is doubtful whether ice of this particular habit and with this marked break has been recorded in the margin of a valley glacier. Below the Stein Glacier extensive beds of dead ice had been left behind. These assist in forming a dam to two considerable lakes.

Crystals in Dead Ice

The crystals in dead ice are very much larger than those in active ice. The largest measured was $18 \times 8 \times 5$ cm. Crystals like those in Fig. 8 (p. 267) are by no means uncommon. It is noteworthy that dead ice crystals are often elongated, having lost the roughly cubical or spherical shape. Figs. 9 and 10 (below) are tracings of rubbings of typical dead ice crystal assemblages in the Rosenlaui and Stein Glaciers respectively. There is a difference between these two in that in the former there are no small crystals and the size is more uniform.

In the Eiger Glacier, and indeed in other glaciers, there was some evidence that the dead ice in the margin near the snout was composed of larger crystals than the dead ice higher up.

Dead ice has only been examined at the surface where the conditions may differ from those deep down. Research in a shaft cut into dead ice is long overdue.

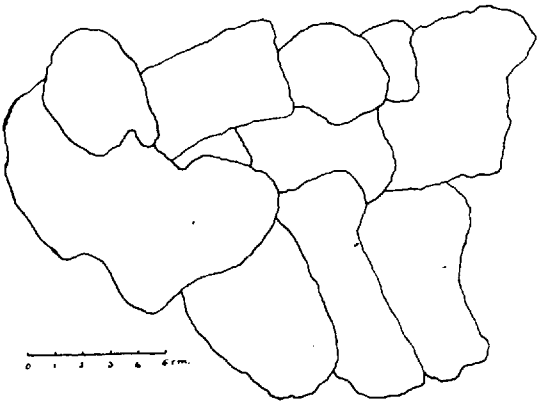


Fig. 9. Dead ice crystals in Rosenlaui Glacier

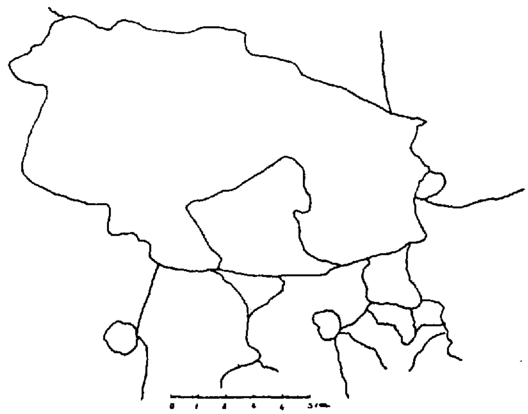


Fig. 10. Dead ice crystals in Stein Glacier

Crystals of Subnormal Size

One exception was found to the increase in crystal size from source to snout.

In a tunnel in the Upper Grindelwald Glacier there was a sudden diminution of the crystals.

Fig. 11 (p. 267) shows a general view of the glacier and Fig. 12 (p. 262) a sketch plan of the tongue. The mean inclination of the ice fall is about 33°. An artificial tunnel enters the glacier near its snout and is about 30 m. in length. Its end lies a few score metres below the glacier surface. Above the ice fall there is a comparatively flat stretch of ice about a kilometre long and of a mean width of 400 m. Seven rubbings (nearly 400 crystals) were made at widely separated points on this rectangle. Their locations are shown by dots on the plan. The smallest mean size of any assemblage was 1·07 cm., the largest 1·67 cm.

Fig. 12 also shows the sizes in the tunnel, which of course was much further down the glacier where crystals larger than those above the fall were to be expected. But at the tunnel mouth they averaged 1·24 cm. decreasing to a minimum of 0·47 cm. near the tunnel end (26 m. from the mouth) where an enlarged chamber had been hollowed out. The upper rubbing in Fig. 13 (p. 267) shows the size. Search through old writings showed that Deeley [16] had found very small crystals in a tunnel in the same glacier and also in tunnels in the Lower Grindelwald and Morteratsch Glaciers. Deeley's crystals appeared elongated which he attributed to shearing movements.* Later in 1947 the author found subnormal crystals in a tunnel in the Lower Grindelwald Glacier. In 1948 Mr. G. Hattersley Smith found small crystals again in both the Upper and Lower Grindelwald Glacier tunnels, but in both cases the crystals near the mouth were more nearly of normal size; he was unavoidably prevented from making a more detailed examination as had been projected.

* **Professor Ahlmann in the paper which follows has also noted small, elongated crystals under comparable conditions.**

Discussion

The present research was conducted at or near the glacier surface. Nowhere were depths lower than 6 m. explored except in the tunnels as described above. Little is known of the crystal conditions deep in glaciers. Excavations a few metres down from the surface showed no perceptible variation in crystal size or habit. (In the firn area the excavations of 1938 [2] showed a slow increase in grain size down to 19½ m. and from there to about 30 m. depth no marked change.) The conclusions reached in this research must therefore be understood to apply to those parts of the glacier readily accessible. According to the generally accepted Finsterwalder flow theory the large crystals at or near the surface of the snout were once deep down in the glacier. They may have grown to large size either as they approached the surface or else in the glacier depths.

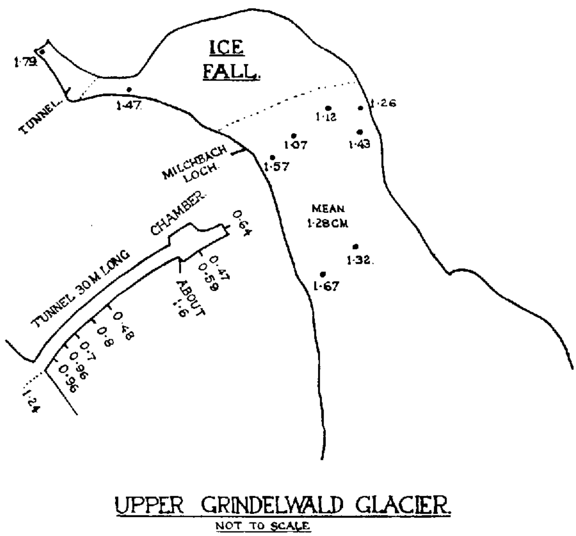


Fig. 12. Sketch map of the Upper Grindelwald Glacier showing crystal sizes on the flatter region. The ice fall is between the dotted lines; the tunnel is also shown with its crystal sizes

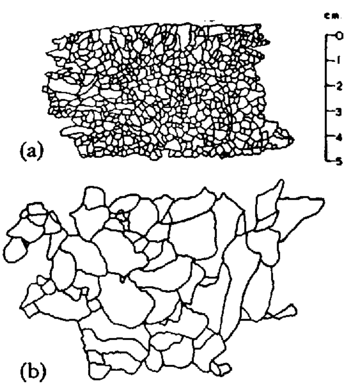


Fig. 14. (a) *Normal crystal size in the ice apron near the Sphinx (Jungfraujoch), Mean diameter 0·29 cm.*
(b) *Crystal sizes in the same ice apron close to an electric lamp. Mean diameter 1·1 cm.*

As pointed out above no attempt was made to investigate the mechanism of growth in this preliminary research. It will be helpful however for future work to sum up the information obtained and examine such of the results as could influence growth.

1. *The Effect of Time*

We have seen that in the living glacier the crystals increase from source to snout and from centre to margins. We have seen too that the longer the glacier the larger the crystals at its end and that the steeper its inclination (and so in general the faster the speed) the smaller the crystals. Crystals in ice which is dead are larger than those in the flowing glacier, which is of course of more recent origin.

It is clear therefore that crystal growth is to a greater or less extent dependent upon time. This is in accord with the general observation of Hagenbach-Bischoff [4] (*cf.* Hess [21]) that the smaller ice crystals gradually become incorporated in the larger. Clearly the longer the time the more complete would be this process. But it cannot be said that growth proceeds at a regular speed. Reference to the graph in Fig. 3 (p. 259) shows that this is not the case or the curve would pass close to

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zero. There is also some empirical evidence to show that there is a variation of speed of growth as a crystal passes down the glacier, but confirmation must await exact measurements of crystal sizes in *all parts of a single glacier*. As our knowledge stands at present it seems necessary to look for other possible influences on the mechanism of growth than the mere effect of time.

2. *The Influence of Glacier Movement*

Tammann [7] and others believed that movement or stress was a necessary condition of crystal growth. In a paper of which the present writer was part author [15] it was suggested that crystals, so orientated in the glacier that they could yield to shear stresses caused by its movement, would possess less free energy than others and would grow at their expense by the transfer of molecules across the crystal boundaries.

Another result of movement may be suggested as a working hypothesis. In this case, unlike the one mentioned above, the transfer of liquid water from one crystal to another may take place. In a glacier at pressure melting point there must be minute local changes of pressure caused by its flow. This would cause a continual interchange of minute units of the solid and liquid phases as pointed out by Holmes [24] and Lewis.[25] It seems reasonable to assume that in these conditions the smaller crystals would disappear by degrees, their material going to increase the larger ones.

It may even be that movement, entailing, as it must, changing stresses, may cause or contribute to variation of speed of growth suggested in the last section. In other words there may be a region in every glacier where growth proceeds rapidly. The region where conditions would be most favourable for movement to affect the crystals would be that place where the ice had not yet reached its maximum density. Such a region would be common to every glacier whatever its length. This would explain, for instance, why a glacier that had only flowed say 10 km. has crystals much larger than half the size of one that had flowed 20 km. (see Fig. 3, p. 259).

It is hoped that laboratory experiments under different controlled conditions, which are now under consideration, will throw light on these points.

It must not be forgotten however that crystals in dead ice incapable of movement grow to larger sizes than those in active ice, which proves that movement is not essential for crystal growth, although, given the right conditions it may well contribute towards it.

3. *The Effect of Temperature*

From such scanty details as are available the crystals in glaciers of high latitude appear to be smaller than those in the Alps. The largest recorded by Wright and Priestley [13] in the Suess Glacier, Antarctica, measured about 1 cm. in diameter. The largest seen by von Drygalski [12] in Greenland did not exceed 7 cm. in length. Preliminary results of an accurate crystal record made at the author's request by Mr. W. R. Battle in a glacier near the coast of East Greenland, show smaller crystals than in otherwise comparable alpine glaciers.*

This indicates that temperature is of importance in crystal growth.

A striking confirmation of this was found at the Jungfraujoch. There is a very large mass of ice forming part of the Sphinx ice apron, which lies immovable in a kind of pocket. A series of large halls and long corridors has been excavated in this. They are lit by electric lights close to the ice walls. The normal crystal size throughout the excavations was of the order of 0·29 cm. (see Fig. 14(*a*), p. 262). But near the lights measurements showed a mean size of 1·07 cm. (see Fig. 14(*b*), p. 262). The size tailed off as the distance from a light increased. There was no sign of melt water either close to the lights or by percolation from the surface 10 or 12 m. above.

The bulk of the ice apron being at about $-4°$ C. crystal growth tends to be slow. Near the

* The author has been promised crystal rubbings from many parts of the world and from many climates. Their correlation should prove of great value in the further stages of this research.

lamp, however, the ice is warmed up probably to 0° C. This rise in temperature no doubt accelerates crystal growth in ice as it does in all other substances. The process can be compared with annealing in stressed metals accompanied by crystal growth, for it is very probable that the ice in these labyrinths is in a stressed condition.

From the foregoing it appears certain that heat encourages crystal growth in ice, and that such growth can take place without visible melting.

In temperate glaciers this will, in the main, be a surface effect, for they are at the pressure melting point almost throughout their mass. But in polar glaciers deeply penetrating cold will check the speed of crystal growth in a large part of the ice mass.

4. *The Effect of Surface Melt Water*

In the case of true ice subjected to strong thawing in temperate regions the crystal boundaries tend to melt, and thaw water, percolating in thin films through the interstices, will freeze on to the crystals when the temperature falls. The small crystals can thus thaw away and the large crystals grow.

In the main, however, glacier ice is impermeable to water and this effect must be confined to the surface and be transitory, since at the few places where this "thaw-freeze" can occur summer thaw will remove the whole glacier surface so affected.

Crystals of Subnormal Size

Various explanations suggest themselves:

(i) As the phenomenon has only been observed in artificially excavated tunnels it may be caused by the excavation. In support of this suggestion men making a new tunnel in 1948 in the Upper Grindelwald Glacier told Mr. Hattersley Smith that they *thought* the crystals were larger when they first started excavations.

(ii) It was at one time thought possible that crystal growth deep down in the glacier might be slower than at the surface and that these small crystals were the undeveloped crystals of the basal ice opened up to inspection by the excavation of a tunnel. This now seems most unlikely. Moreover the following is to be noted. In the chamber of the tunnel some 24 m. from the mouth, there was a small stratum of ice with an average crystal size of about 1·6 cm., that is to say about normal for its position in the glacier. (See Fig. 13, p. 267.) One might well ask what this mass of larger crystals was doing here surrounded by small ones, and why they had grown so much larger than the others, since they themselves had also been deep in the glacier.

(iii) It has been suggested that these very small crystals were the remains of snow which had fallen on the glacier and had penetrated into it through crevasses. In that case, being much younger than the surrounding ice, the crystals would naturally be smaller.

(iv) Tarr and von Engeln [18] noted the fracture of single ice crystals under pressures of about 18 kg./cm.^{2}, which is about equal to the static head in the ice fall of this glacier. Their experiments, however, were carried out at low temperatures. Deeley [16] suggested shearing as the cause and the author has many times found hundreds of crystals of a millimetre or less in diameter in shear planes in glacier ice.*

While actual fracture seems doubtful recrystallization caused by the stresses in the ice fall offers another explanation. There is ample evidence for this in the behaviour of worked metals in which new crystal nuclei develop.[19] Tammann,[7] discussing the behaviour of camphor, writes: ". . . *Bei stärkere Deformation bilden sich viele Rekristallisationszentren.*" Later in the same paper he implies similar behaviour in ice immediately after being rolled in the laboratory.

* Wood [26] has shown that "progressive deformation of an annealed metal breaks down the grains into smaller units *which have a minimum size characteristic of the metal.*"

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There is another analogy with worked metals. These small crystals under suitable conditions grow very fast. In the Upper Grindelwald Glacier the mean crystal size in the snout was 1·79 cm., betokening very rapid growth between the tunnel and there, the distance being a matter of only a few score metres. Nowhere else was anything approaching this speed of growth observed.

Against the concept of recrystallization the views of Bader nust be cited. Bader [20] subjected a block of ice to shear and although he found rapid crystal growth he noticed no development of new nuclei. His experiments, however, were conducted at $-5°$ C. as opposed to the zero glacier temperature and it is possible that other conditions in the laboratory may have had some preventive influence. Bader himself published his results with some reserve. Clearly the matter needs more detailed investigation than was possible either in 1947 or 1948.

Conclusions

The results of the research can be summarized as follows:

(1) The crystal size observed at or near the glacier surface of an Alpine glacier shows an increase from bergschrund to snout.

(2) In active ice the crystals of the tongue are smallest on the lines of fastest flow, that is to say normally in the centre of the stream. They increase gradually towards the margins.

(3) The longer the glacier the larger the crystals.

(4) The steeper the glacier the smaller the crystals.

(5) The relationships of crystal size to length of travel and to glacier speed indicate that while time must influence crystal growth in active ice there are probably other agencies as well.

(6) Glacier movement may cause crystal growth by local shear stresses and by local pressure variations.

(7) Crystals grow to very large sizes in dead ice even in the absence of stream flow.

(8) Low temperatures retard crystal growth, warmth stimulates it even when no melt water is present.

(9) The freezing of melt water does not play any important part in the growth of the crystals of true ice.

(10) Vast assemblages of abnormally small crystals are sometimes found in glacier tongues, the conditions being apparently exceptional and, as yet, not clearly understood.

(11) No crystal assemblages with a larger mean diameter than about 2·5 cm. were found in the active ice of any Alpine glacier.

Norway: 1948

A perforce rapid examination of glaciers in Jostedalen and Jotunheimen did not in all respects confirm the observations made in the Alps in 1947.

In all the glaciers investigated there was the same transition from small to large crystals from source to snout. But in glaciers of the Scandinavian type and in the ice cap outflows the gradual decrease from sides to centre, so conspicuous in the Alps, was missing. Nor were the crystals so uniform in size in a given area. Masses of large crystals alternated with masses of small. Even in an assemblage of small crystals one or two very large ones were often to be seen.*

This may be due to the many directions from which the ice flows before it finally collects in the very short outflows, the immense extent of the accumulation areas making for varying conditions. In a rapid survey of Tunsbergdalsbreen, an unusually long outflow glacier from the Jostedal ice cap, the crystals appeared more uniform, suggesting an equalizing up over the long glacier.

* Similar irregular conditions were found by Professor Ahlmann in Kebnekajse (see p. 269 *et seq.*).

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The only valley glacier tongue which could be more fully examined was that of Storjuvbreen, and here the crystal size approached more closely to the orderly arrangement seen in the Alps. Five hundred metres from the snout the crystals in the centre of the glacier measured 1·6 cm. mean diameter and increased up to about 3·4 cm. mean diameter towards the margins. But even in this glacier the crystals at the snout, averaging 2·2 cm. over large areas, were interspersed with big assemblages of crystals of enormous size, one measuring 22·5 × 9 cm. on its exposed face, which is larger than any crystal measured in the Alps in 1947. There was nothing in the position of this ice to show that it was dead. Further reports have been promised from Norwegian sources, from which it should ultimately become possible to throw light on these anomalies.

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MS. dated July 1948.

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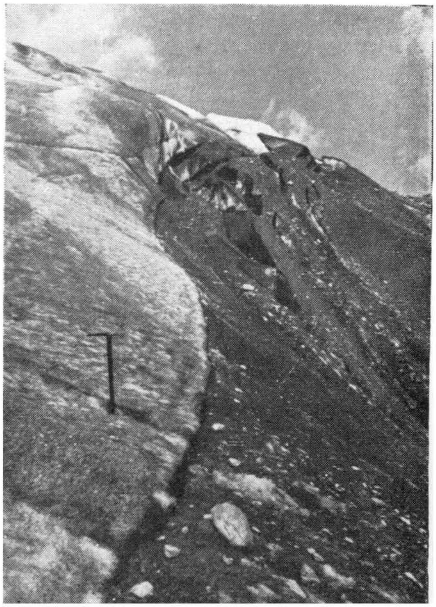

Fig. 2. Findelen Glacier. Left bank at about 2,500 m. showing junction between active ice (left) and marginal ice (right). (See text p. 257)

Fig. 8. Single crystals of dead ice from Stein Glacier. (See text p. 260)

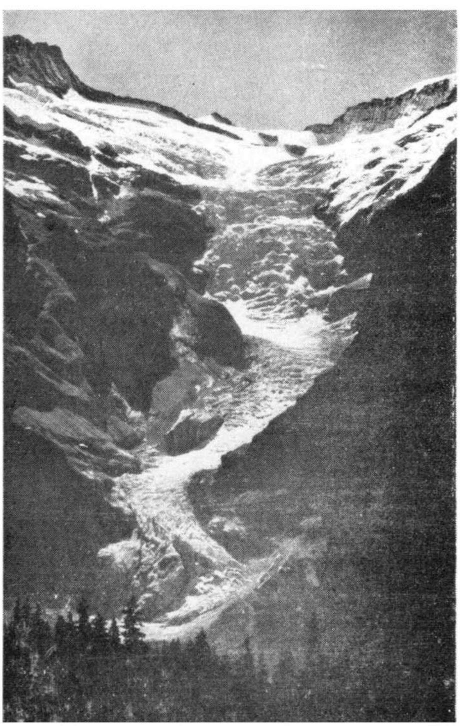

Fig. 11. Upper Grindelwald Glacier showing the last ice fall and the flatter region above. (See text p. 261 and Fig. 12, p. 262)

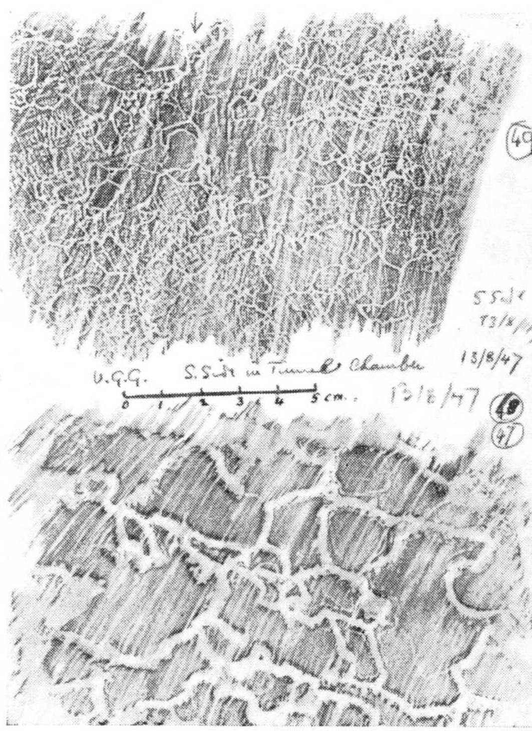

Fig. 13. Above: small crystals at the end of the tunnel in the Upper Grindelwald Glacier 30 m. from mouth. Below: a band of large crystals in the chamber of the tunnel. (See text pp. 261 and 264)

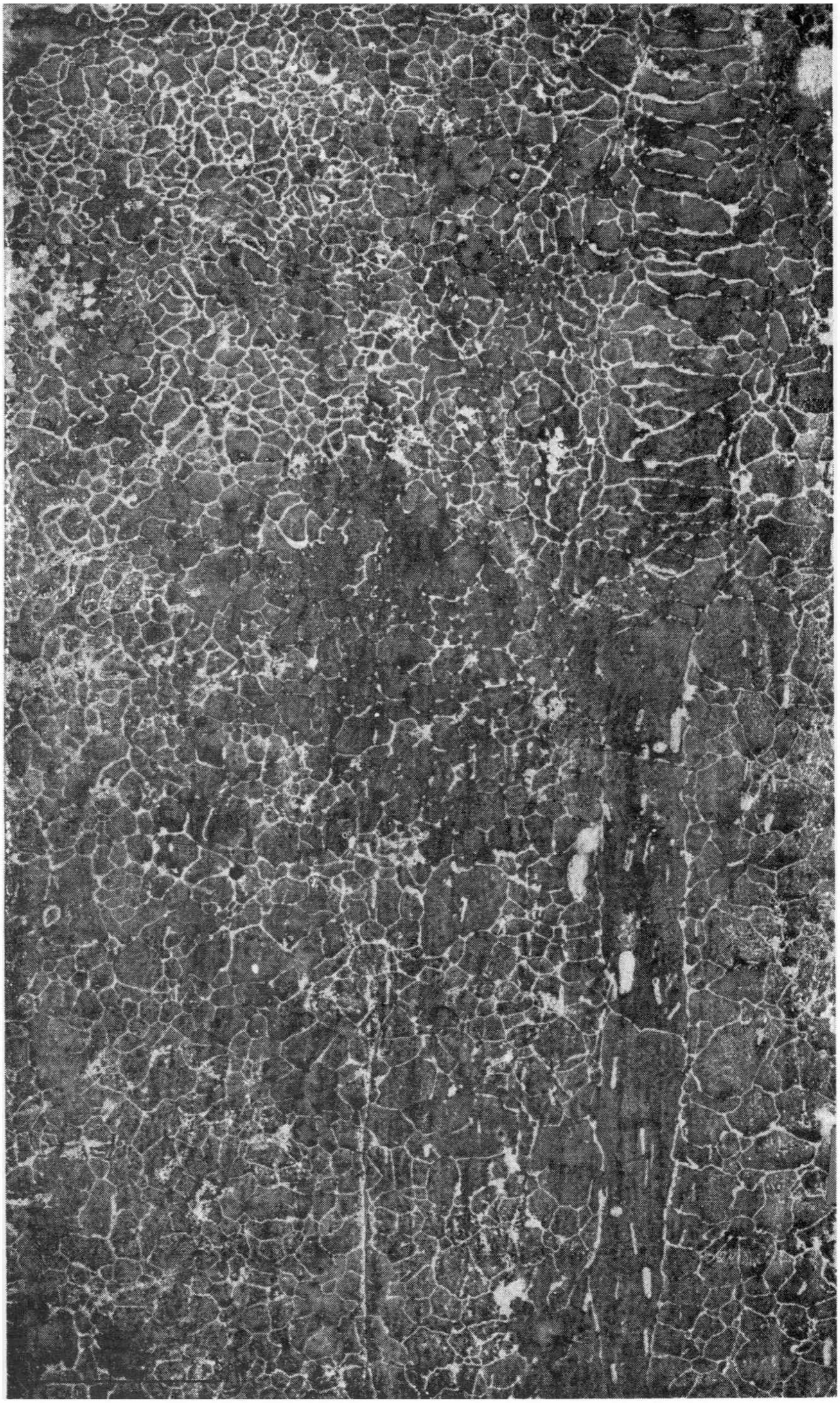

Fig. 6. Impression of crystals on Kebnepakteglaciären. A 5 cm. long line in the bottom left corner shows the scale. (*See pp.* 269 *and* 273)