SYMPOSIUM ON THE CRYSTALLIZATION OF METALS, ROCKS AND ICE

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Chairman: Professor K. Lonsdale, F.R.S.

The following papers were read:

Dr. C. H. Desch, F.R.S.: The Crystallization of Metals.

Dr. A. G. MacGregor: Ice Crystals in Glaciers compared with Quartz Crystals in Dynamically Metamorphosed Sandstones.

Dr. P. G. Owston: The Crystallization of Ice.

Dr. MacGregor's and Dr. P. G. Owston's papers are printed below. Dr. Desch's paper, owing to unavoidable delay, will be published in a later issue of this Journal.

ICE CRYSTALS IN GLACIERS COMPARED WITH QUARTZ CRYSTALS IN DYNAMICALLY META-MORPHOSED SANDSTONES*

By A. G. MacGregor

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ABSTRACT. Attention is drawn to resemblances between two contrasted styles of mosaic crystallization—tessellate and equigranular as compared with irregularly interlocking (sutured) and inequigranular—that characterize ice in alpine glaciers and quartz in dynamically metamorphosed sandstones of the Moinian area of the northern Scottish Highlands. It is suggested that in both environments the contrasted types of mosaic are due to crystallization under conditions of shearing stress that were respectively minimal and maximal. Similarities are also pointed out between the orientation of the principal crystallographic axes of crystals in ice subjected to shearing stress, and the "girdle" arrangement of the principal crystallographic axes of quartz in Moinian metamorphic sandstones.

ZUSAMMENFASSUNG. Es wird auf die Aehnlichkeit zwischen zwei typischen Arten der mosaikförmigen Kristallisation hingewiesen—würfelförmig und gleichkörnig gegenüber ungleichmässig verzahnt und ungleichkörnig—wodurch einerseits das Eis der alpinen Gletscher und andrerseits der Quarz in dynamisch metamorphen Sandsteinen der Moinian Formation des nördlichen schottischen Hochlandes charakterisiert werden. Es wird vermutet, dass in beiden Fällen der festgestellte Typus des Mosaiks bedingt sei durch eine unter dem Einfluss von minimalen bzw. maximalen Scherspannungen erfolgte Kristallisation. Ferner wird die Verwandtschaft zwischen der Orientierung der kristallographischen Hauptaxen des durch Scherspannungen beanspruchten Eises und der umgürtenden Anordnung der kristallographischen Axen des Quarzes in metamorphen Sandsteinen der Moine Formation hervorgehoben.

I. Alpine Research on Glacier Ice

A concluding summary of some of the earlier work † of the Jungfraujoch Research Party of 1937–38, led by G. Seligman and with M. F. Perutz as crystallographer, has recently become available (Seligman [16]). Other inferences regarding the mechanism of glacier movement had been published previously (Seligman, p. 307, 312 [14]).

As far as metamorphic petrology is concerned, Seligman's main conclusions of 1941 [14] (first item below) and of 1949 [16] (other items: Seligman, p. 262–65 [16]), based on the study of the *more*

* Communicated with the permission of the Director, Geological Survey & Museum.
† Certain results, also of petrological interest, but not mentioned in this summary, are considered in Section II.2.

superficial layers of the Aletsch Glacier and on observations made on other alpine glaciers, are as follows:

(1) Movement in glacier ice involves (*a*) slip of layers of ice one upon another (laminar motion), and (*b*) plastic deformation (gliding) in individual crystals, accompanied by crystal growth. In the firn or *névé* region, laminar motion and plastic deformation are absent; movement simply involves relative slip or rotation of crystal units or clusters.

(2) Ice crystals near the surface of an active glacier are smallest on the lines of fastest flow,[*] that is to say normally in the centre of the ice stream; towards the margins they increase gradually in size.

(3) The steeper the glacier, the smaller the crystals.

(4) Crystal size increases from bergschrund to snout.

(5) The longer the glacier, the larger are the crystals at its end.

(6) Crystal size is, to a greater or lesser extent, dependent on time.

(7) Glacier movement may cause crystal growth by the operation of local shearing stresses and by local pressure variations.

(8) Crystals in dead ice grow to larger sizes than in moving ice; hence movement is not essential to crystal growth.

The following exception to generalization (4) is of importance. In the deeper layers of glacier ice (investigated only in a tunnel in the snout of the Upper Grindelwald Glacier) Seligman found assemblages of abnormally small crystals. After discussing various possibilities, he has suggested tentatively that they may be due to recrystallization under abnormally great stresses caused by an ice fall not far "up-stream" (Seligman 1949, p. 264[16]; 1950, p. 379–80[17]). In this suggestion he was influenced by Deeley and Fletcher who, some fifty years ago, attributed to shearing (and in part to fracture) the formation of many small elongated ice crystals observed in tunnels in the Upper Grindelwald and other glaciers (Deeley and Fletcher, p. 155–57[5]). Seligman has also many times found very small ice crystals in shear-planes in glacier ice (Seligman, p. 264[16]).

II. Petrological Significance of the Results of Research on the Crystal Structure of Ice

Seligman (p. 254[16]) quotes J. D. Bernal as saying "A glacier may be considered as a model ... with a fairly rapid rate of transformation, of . . . sedimentary rock undergoing dynamic metamorphism. The relation of crystallisation to thrust and fault planes, and the size of the crystals. may throw light on the crystallisation that occurs in these rocks." This idea, which has also occurred to others (*e.g.* Niggli, p. ix, x[9]), appears to be particularly apposite when one compares the effect of shearing stress on ice and on quartz, for they are, respectively, the only mineral of glaciers and the most important constituent mineral of the great majority of dynamically metamorphosed sediments; and both are hexagonal. Petrologists will be grateful to Mr. Seligman for envisaging the study of glacier-ice crystals under a polarizing microscope, and to Dr. Perutz for carrying out this work, with its difficult technique (Perutz and Seligman, p. 340–41[11]; Seligman, p. 295, 298, Fig. 2 and Plate 19[14]; Bader, p. 49[3]).

1. *Ice and Quartz Mosaics in Regions of Minimum and Maximum Shearing Stress*

Within recent years the writer has been studying Scottish psammitic granulites (metamorphosed sandstones) of the Moine Series, which H. H. Read[13] had found to exhibit a "normal" quartz-crystallization in parts of east-central Sutherland, and to become progressively "abnormal" westwards, as they approach the outcrop of the Moine thrust-plane, along which the Moines have

[*] Seligman's conclusion, from alpine glaciers, that the higher the rate of movement of glacier ice the smaller is the crystal size, has been confirmed in Sweden (Ahlmann and Droessler, p. 274[1]). Note that, in connection with glacier motion, such expressions as "lines of fastest flow" and "the higher the rate of movement" refer, by implication, to regions where *differential movement* is most pronounced (*cf.* Perutz, p. 132[10]).

been thrust westwards over other rocks for at least ten miles. The "abnormality" was thus produced by conditions of marked shearing stress in the vicinity of Scotland's major thrust-plane, which has a gentle inclination eastwards.

In "normal" Moines the quartz is tessellate, that is to say it forms * a mosaic of more or less equidimensional crystals with relatively smooth mutual junctions. In "abnormal" Moines the quartz appears as a highly sutured, interlocking, inequigranular mosaic of crystals that show pronounced optical anomalies due to strain.† The average grain-size of the inequigranular sutured and strain-shadowed mosaic gets smaller on close approach to the Moine thrust; that is to say, grain-size decreases with increasing shearing stresses.

To the writer there seem to be striking resemblances between (a) these two contrasted styles of quartz-crystallization known to be due to differences in shearing stress (Figs. 1 and 3, p. 567), and (b) two contrasted styles of ice-crystallization illustrated in glacier publications of Seligman and Perutz, and of others, viz. the tessellate (equidimensional and unsutured) mosaics of firn and of the upper layers of ice in the *névé* region; and the sutured inequigranular ice crystals of the main body of the glacier (Figs. 2 and 4, p. 567; see also Ahlmann and Droessler, Fig. 2, p. 270 [1]).‡

Tessellate ice characterizes a region at the head of a glacier where shearing stress is at a minimum, and crystallization goes on under conditions of compression due to the weight of overlying firn and snow (Perutz and Seligman, p. 335, 340 and Plate 17 [11]; Seligman, Plates 24, 25 [14]).

Highly inequigranular sutured ice crystals characterize the ice of the glacier tongue (the main body of the glacier); and abnormally small sutured crystals have been observed along shear-planes in glaciers, and in the Grindelwald ice tunnel *situated not far down-stream from an ice fall*. Seligman has consequently made the tentative suggestion that abnormally small ice crystals (which his illustrations show to be sutured) are formed as the result of the operation of abnormally great shearing stresses.

Published statements by Seligman and Perutz regarding the genetic significance of the abnormally small ice crystals are at first sight incompatible. To clarify Perutz's difference of approach to the problem it is necessary to summarize, in the first instance, his explanation of the general increase in size of ice crystals, near the surface of an active glacier, from bergschrund to snout (Perutz, p. 133–34 [10]). He suggests as a working hypothesis that deformation and growth in glacier ice are interconnected in the following manner: "Crystals having the right orientation for yielding to stresses by glide along their basal planes would have a higher energy than others which cannot yield; the former would therefore have a tendency to grow at the expense of the latter by molecular exchange across the crystal boundaries. In glaciers the change in crystal orientation brought about by intra-crystalline gliding and the alterations in stress to which the ice is subjected in the course of its flow to the valley would continuously give rise to fresh energy-differences between neighbouring crystals, and to consequent crystal growth." Perutz states also that (a) the ice crystals of the glacier tongue (*i.e.* of the main body of the glacier) are often of very complex shape and always closely interlocked; (b) it is not certain whether growth follows or accompanies deformation; and (c) it appears certain, as a result of glacier observations, and of laboratory experiments by Tammann and Dreyer, that increase in average crystal size is invariably to be observed after strain has taken place.

This hypothesis, in which the time-element (length of period of crystallization) seems to be important (*cf.* Seligman, p. 262 [16]), appears to have no obvious direct applications to the problem of quartz-crystallization in metamorphic rocks. To illustrate this statement, let us suppose that shearing stress (up to a certain limiting value) acting on a psammitic sediment, has resulted in

* Usually along with some feldspar, etc.
† Similar "normal" and "abnormal" psammitic granulites have been recognized by others, including the writer, south of Professor Read's Sutherland area, as for instance in Ardnamurchan and Morar (Figs. 1 and 3, p. 567).
‡ The results of Matsuyama's laboratory ice experiments are of great significance in this connection; see addendum, p. 571.
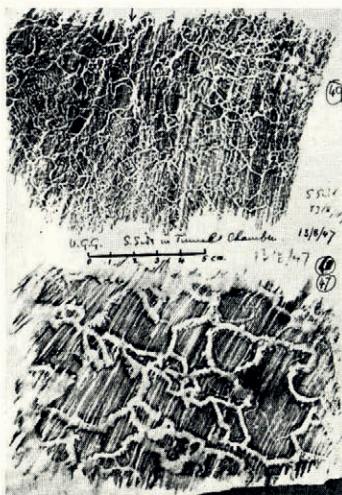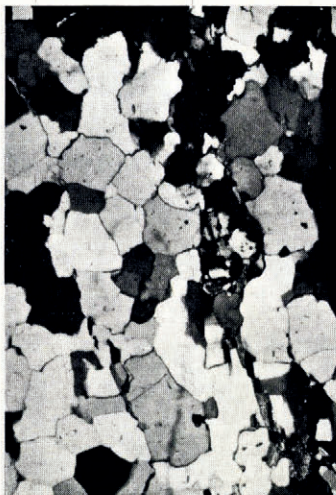
Fig. *1* (*top left*). *Tessellate quartz-mosaic of psammitic granulite, east of Beinn nan Losgann, Ardnamurchan. Mosaic largely quartz, with sporadic alkali feldspar and mica. Nicols crossed.* × *32.* Compare Fig. 2

Photomicrograph by W. Fisher

Fig. *2* (*top right*). *Tessellate mosaic of new ice* (*6 years old*) *at 23 metres, in a crevasse in the Mönchfirn, near the head of the Aletsch Glacier. Dark blebs with high relief represent enclosed air spaces. Nicols crossed.* × *4.1.* Compare Fig. 1

Photomicrograph by M. F. Perutz

Fig. *3* (*bottom left*). *Inequigranular, sutured and strain-shadowed quartz-mosaic of psammitic granulite, east of Mallaigmore, North Morar. Mosaic largely quartz, with subordinate alkali feldspar, mica and epidote. Nicols crossed.* × *32.* Compare Fig. 4

Photomicrograph by W. Fisher

Fig. *4* (*bottom right*). *Outlines of inequigranular sutured ice crystals in tunnel in snout of Upper Grindelwald Glacier. Reduced* (*scale on photograph*). Compare Fig. 3

Photograph of pencil rubbings by G. Seligman

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Recession of the Glacier du Valtournanche

Upper photograph, August 1942
Lower photograph, August 1949

Photographs by Manfredo Vanni

increase of the average size of quartz grains; such an effect would, in general, be impossible to detect because the original size of the quartz grains would be unknown.

Seligman (p. 264 [16]) has however suggested that a similar process, combined with recrystallization due to abnormally great shearing stresses (connected with the presence of an ice fall) may account for abnormally small ice crystals that he found in *relatively deep* layers of ice in a tunnel in the snout of the Upper Grindelwald Glacier; these crystals are shown by his illustrations to be inequigranular and sutured (*see* Fig. 4, p. 567; also Seligman 1948, Fig. on p. 485 [15]; and 1949, Fig. 13, p. 267 [16]). Seligman's tentative hypothesis is thus apparently inconsistent with Perutz's view that *increase* of average crystal size is the invariable result of strain. The two views may perhaps be reconciled by taking into consideration the increase in crystal size that has been observed by Seligman on the upper surfaces of ice-tables carved out in tunnels in the Upper and Lower Grindelwald Glaciers; Seligman attributes the increase in grain-size to relief of pressure (Seligman, p. 380 [17]). We have seen that the grain-size of quartz close to the Moine Thrust was reduced as the result of increasing shearing stress. In this case, of course, relief of pressure took place millions of years later, under conditions that made renewed growth of quartz crystals impossible. It would thus appear that Seligman's ice hypothesis gains support from petrographic evidence.

Seligman thinks that actual rupture of ice crystals is unlikely to accompany his postulated recrystallization; even if he is right, it would seem that an effect similar to that of mechanical granulation accompanied by recrystallization, might well be produced by a combination of unusually pronounced translation-gliding and the development of shear-planes (*cf.* Turner, p. 252 [18]: explanation of mechanical granulation and concomitant recrystallization of quartz).

It seems probable to the writer that, in psammitic granulites, sutured margins of quartz crystals that show marked undulose extinction due to strain may be accounted for by a somewhat similar mechanism. Although there is as yet no certainty regarding the number and orientation of glide-planes in quartz, undulose extinction has been definitely correlated by petrologists with translation-gliding (Turner, p. 227, 255–66 [18]). It seems reasonable to infer that all suturing of strain-shadowed quartz is due to variable localized pressures and shearing stresses connected with internal differential movement along crystal glide-planes; these physical controls, operating in conjunction with a pore-fluid, may be expected to lead to marginal irregular, highly localized and migratory, solution and recrudescence of crystal growth, involving perhaps, in addition, molecular transfer across crystal boundaries (*cf.* Erdmannsdörffer, p. 283–84 [6]; Griggs, p. 1003, 1009 [7]; Seligman, p. 263 [16]).

Such transient recrystallization at constantly changing positions on mutual crystal boundaries is just what one would expect to produce the sutured, irregularly interlocking and inequigranular quartz-mosaic of psammitic granulites (*cf.* Turner, p. 252 [18]: on mylonites).

The fact that the existence of *similar* glide-planes in ice and quartz has not been established, does not appear to affect the general analogy; the important point is that in each case translation-gliding has been independently inferred. The writer is not aware whether undulose extinction characterizes the inequigranular sutured ice of the Upper Grindelwald tunnel; but even if it is not developed, this may well be due to the fact that shearing stress produces translation-gliding much more readily in ice than in quartz. Again, a general analogy between the behaviour of ice and quartz under shearing stress would not appear to be vitiated by the fact that the scale of differential flow is often much greater in a glacier than it is in rocks undergoing dynamic metamorphism. (See also addendum, p. 571).

2. *Effects of Shearing Stress on the Orientation of the Principal Crystallographic Axes of Crystals of Ice and Quartz*

Observations that appear to have petrological significance have been made on the orientation of the principal crystallographic axes of ice crystals in ice subjected to shearing stress. This evidence

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suggests that extended and more detailed work on ice may go far to settle the present geological controversy regarding the relationship between the direction of tectonic thrust and the orientation of quartz crystals in psammitic granulites (Anderson, p. 122 [2]; Phillips, p. 286 [12]). In this connection (Perutz and Seligman, p. 350–55 [11] *) it has been found that in glacier tongues there exists a general tendency for ice crystals to be arranged with their principal axes perpendicular to planes of shear. Moreover, a study has been made of the orientation of crystals of natural ice, in relation to direction of movement, in an ice-apron on the north wall of the Sphinx ridge, near the Jungfraujoch (Seligman, Figs. 2 and 7, p. 299, 314 [14]). Here, in an ice-grotto pillar distorted by creep, most of the principal axes were found to be perpendicular to the plane of shear, and all principal axes were distributed in a plane normal to the plane of shear and *normal* to the direction of flow. These findings have so far, however, not been reconciled with the results of Bader's study of crystal orientation in a block of artificial ice after it had been subjected experimentally to shearing. Prior to the experiment, the crystals of ice had a random orientation ; after shearing, the grain-size had increased but suturing had not developed. According to Perutz and Seligman,† who have summarized Bader's results, most of the principal axes were found, after the experiment, to have taken up positions perpendicular to the plane of shear, and all principal axes were distributed in a plane normal to the plane of shear and *parallel* to the direction of flow. If we draw an analogy between the behaviour of crystals of ice and quartz, the ice-grotto results appear to support E. M. Anderson's [2] view that the planes of "quartz girdles" in Scottish psammitic granulites are *normal to the direction of movement* (and to the lineation). On the other hand, the Bader-Haefeli experiment apparently supports F. C. Phillips's [12] view that the Scottish "quartz-girdle" planes, although normal to the lineation, are *parallel to the direction of movement*. A satisfactory explanation of the apparently contradictory results of Perutz and Bader may thus be of fundamental importance to tectonic research and to petrofabric studies.

It may be mentioned in passing that a study of glacier motion has recently been recommended to petrofabric workers as a guide to the definition and interpretation of lineations in rocks (Cloos, p. 22–25 [4]).

In conclusion the writer would record, with gratitude, his indebtedness to Mr. Seligman for the active interest he has taken in this paper, and for his assistance in illustrating it, and to Sir Edward Bailey and Dr. E. M. Anderson for encouragement and helpful criticism.

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* There is a misprint in Perutz and Seligman's paper: on p. 355, and eight lines from the bottom, "xz-plane" should read "yz-plane."

† See also Bader, p. 57–60,[3] and Plate XI, Figs. c and d; Haefeli, p. 135–40,[8] and Fig. 32.

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In a subsequent communication dated 22 April 1951 Dr. MacGregor writes:

ADDENDUM. Since the above paper went to press, the writer has come across striking confirmation of some of the inferences of Section II.1. Thirty years ago a Japanese Professor, while at Chicago University, (*a*) twisted cylinders of ice, and (*b*) bent rectangular ice bars formed of sub-parallel crystals. The behaviour of the ice bars, and their microscopic appearance before and after bending, were described and illustrated in his paper (Figs. 3, 12, 13 and p. 613–15, 624–31).* Ice aggregate with the relatively smooth mutual crystal boundaries of the present writer's "tessellate" type of mosaic was converted, as a result of bending, into recrystallized ice forming a highly sutured and more inequigranular mosaic, *just like that of the "abnormal" Moine granulites.* Faint sub-parallel lines were developed, representing planes said to be parallel to optic axes. These lines had a different orientation in different ice crystals; they started from the angular points of the zig-zag (*i.e.* sutured) mutual crystal boundaries. Sometimes two sets of these lines, nearly at right angles, were seen in a single crystal unit of the new mosaic. Uniform extinction (between crossed nicols) was generally observed throughout each individual new crystal; but in some crystals portions divided by the straight lines showed slight differences in extinction. From all his experimental results Matsuyama inferred that gliding planes parallel to the base of each crystal are not the controlling factor in the deformation of ice and are probably not even an important factor.

THE CRYSTALLIZATION OF ICE

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THE growth of crystals is governed by many factors, and is not at all clearly understood.[1, 2] These factors may be divided into the influence of internal structure and of external conditions, and it is sometimes possible, in a general way, to distinguish the two.

The structure of ice has been recently re-examined.[3] Though it crystallizes in various forms, as do most substances even under constant conditions, ice most usually appears as hexagonal crystals, probably of holohedral symmetry. Examination by X-rays shows that the molecules are arranged in puckered layers, each molecule being bound to three others in the same layer and to one other molecule in a neighbouring layer. The layers are therefore relatively easily separated, and their plane, which is perpendicular to the principal crystal axis, is a plane of easy cleavage and gliding.

It is a general rule, first pointed out by Bravais, that the faces which appear on a finished crystal are parallel to the planes which have the greatest concentration of atoms. More recent studies of growing crystals have amplified this. They show most beautifully that in many cases the crystal is laid down layer by layer. Material is added to the crystal by the extension of the layers

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* Matsuyama, M. On some physical properties of ice. *Journal of Geology*, Vol. 28, No. 7, 1920, p. 607–31.