13. Read, H. H. The geology of central Sutherland. *Mem. Geol. Surv.* 1931.
14. Seligman, G. The structure of a temperate glacier. *Geogr. Journ.*, Vol. 97, 1941, p. 295–315.
15. —— Growth of glacier crystals. *Nature*, Vol. 161, No. 4091, 1948, p. 485. (Letter.)
16. —— The growth of the glacier crystal. *Journal of Glaciology*, Vol. 1, No. 5, 1949, p. 254–66.
17. —— The growth of the glacier crystal: Some further Notes. *Journal of Glaciology*, Vol. 1, No. 7, 1950, p. 378–81.
18. Turner, F. J. Mineralogical and structural evolution of the metamorphic rocks. *Geol. Soc. Amer. Mem.*, No. 30, 1948.

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

By P. G. OWSTON

(Department of Chemistry, University College, London)

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

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

parallel to the crystal face. New layers form from time to time, usually near the centre of the face, but this occurs much less readily than the extension of an existing layer. Substances whose molecules are arranged in layers in the crystal will clearly grow readily in this way.

We would thus expect ice to form flat plates, with the layer-plane of the structure parallel to the principal face: the optic axis would then be perpendicular to the surface. It is, in fact, usually found that sheets of ice on ponds and lakes have their optic axes perpendicular to the surface.

These ice sheets, however, do not form as hexagonal plates, as the simple considerations given above would suggest. They begin as needles, growing out quickly over the surface from the edge, or from dust particles. These join to form a continuous sheet with the optic axis vertical, but with the secondary axes variously directed.

When crystallizing ice in capillary tubes Megaw [4] found that the crystals grew along the a axis. The author has found that crystals grow along the $(11\bar{2}0)$ plane, perpendicular to the principal axis: this direction is at 30 degrees to the a axis, but the direction of growth is not always clearly defined. There is no obvious explanation for the strong preference for a particular direction, but it may be connected with the fact that all the inter-molecular bonds lie in the three $\{11\bar{2}0\}$ planes, and may encourage growth parallel to those planes.

In these crystals, grown in the liquid underneath the surface sheet, the optic axis is perpendicular to the length of the crystal, but is not always vertical. It is usually approximately vertical for crystals lying on the bottom of the dish, but may be horizontal in crystals attached to the underside of the surface sheet.

A pool of rain water caught in a tarpaulin sheet, and thus subject to cooling from both above and below, crystallized differently. The resulting block of ice cleaved easily into needles which were directed nearly vertically. Crystallization had clearly begun at the bottom of the pool, and the crystals grew upwards, carrying dust particles with them. The optic axis was horizontal, *i.e.* roughly perpendicular to the length of the needle.

Lastly, the surface sheets of ice from dishes of water were examined more closely round their edges. It was found that the direction of the optic axis here followed no obvious rule, and was rarely either vertical or perpendicular to the freezing surface.

We may summarize the various observations as follows. The crystallographic orientation of ice is usually described by stating the direction of the optic axis, which is parallel to the principal crystal axis. This direction is limited to being perpendicular to the direction of growth of the crystals: this observed fact is in agreement with the mechanism of growth being by lateral extension of the layers which are known to exist in the structure perpendicular to the principal axis. A crystal growing at a cooled surface will tend to have these layers parallel to the surface and the optic axis vertical: there seems no reason to suppose that gravity has any influence, except to allow flat crystals to remain horizontal. No directing effect on the optic axis has been demonstrated in crystals growing inside a body of cooled water.

The direction of growth of the crystals is presumably along the temperature gradient provided that growth is not too fast: this was certainly the case in Megaw's experiments. In supercooled liquids, however, growth is very rapid once it has been initiated. It is well known that water readily supercools, and the direction of growth would then be less influenced by temperature gradients. This would not apply near the edges of sheets of water, where there will usually be both strong temperature gradients and a plentiful supply of nuclei: considerable variation of orientation is then to be expected.

The chief unexplained fact is that ice grows as long thin crystals, not as broad plates.

So far only crystallization in considerable volumes of water has been discussed. In the formation of snow crystals the supply of material is more limited.

Some interesting work has been reported from America.[5] A cloud of droplets is formed in a refrigerated box kept at a uniform temperature, and is found to remain as liquid droplets down to

about $-39°$ C. Cooling below $-39°$ C., either throughout the box, or locally by putting in a cold object, *e.g.* a little solid CO_2, initiates crystallization. The crystals formed are small hexagonal plates.

The cloud can be seeded at higher temperatures than $-39°$ C., by particles of some dusts, giving plate-like crystals of irregular forms.

The addition of various vapours modifies the shape of the crystals, *e.g.* acetic acid causes complex hexagonal plates, nitric smokes cause trigonal plates, and acetone causes hexagonal prisms to form. Any of these unusual types will seed a cloud of supercooled droplets, at temperatures well above $-39°$ C., which then freeze, as usual, into hexagonal plates. It is to be concluded, therefore, that in these modified crystals only the external shape is altered, the internal structure remaining unchanged. It must always be remembered that every crystal is a distinct individual, and that rare forms, though interesting, do not give a reliable indication of internal symmetry.

In the same work considerable studies of natural snow forms have been carried out, and a useful set of photographs of typical forms published. Here again the smallest crystals, produced under cold dry conditions (below $25°$ F.), were small hexagonal platelets. Warmer, wet snow was found to consist mainly of the larger familiar six-rayed stars. These appear to have begun as small hexagonal plates from whose corners the rays have grown.

These observations suggest that ice does in fact form as hexagonal plates, but that the conditions which allow rapid growth encourage elongated forms. It is well known that rapid growth often results in dendritic crystal forms, such as the rays of stellar snow crystals; but the elongated crystals found in pools of water are not usually of the dendritic type. A possible explanation of their occurrence is that dendritic crystals are, in fact, at first formed in the supercooled water, for long crystals which are too thin to handle certainly do occur. These would then grow more slowly to give more compact crystals and would become, after a time, the crystals of about $5 \times 1 \times 0.5$ cm. which are found. This particular crystal form might then be regarded as an intermediate in the unfinished change from a dendritic crystal grown quickly in the supercooled liquid, and a more compact, uniform, and possibly plate-like crystal.

REFERENCES

1. Wells, A. F. *Ann. Rep. Chem. Soc.*, Vol. 43, No. 62, 1946.
2. *Crystal Growth*. Discussions of the Faraday Society, No. 5, 1949.
3. Lonsdale, K., *and* Owston, P. G. *Journal of Glaciology*, Vol. 1, No. 3, 1948.
4. Megaw, H. D. *Nature*, Vol. 134, No. 900, 1934.
5. Schaefer, V. J. *Chemical Reviews*, Vol. 44, No. 291, 1949.

THE EFFECT OF THE ALTITUDE OF THE FIRN AREA ON A GLACIER'S RESPONSE TO TEMPERATURE VARIATIONS

By G. S. CALLENDAR, Principal Scientific Officer, Ministry of Supply

THE importance of the altitude of the principal accumulation areas of a glacier, when considering its response to temperature changes, has been repeatedly stressed by Ahlmann,[1] Cooper[2] and others, but the reason for the decisive influence of this altitude is not always very obvious to workers in related fields. It may, however, be clearly demonstrated by means of a simple diagram such as the one accompanying this note.