CRYSTALLOGRAPHIC ORIENTATION IN LAKE AND ARTIFICIAL ICE*

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Introduction

Most lake ice consists of an interlocking aggregate of vertical columnar crystals. In some ice pads the long dimension of these columns coincides approximately with the crystallographic c-axes, but in other lakes, the c-axes are sub-normal to the columns. A distinctive phenomenon in some cases (Ragle, 1958) is a progressive increase in the relative abundance of horizontally-oriented c-axes with depth and a decrease in number of crystals with vertical c-axis orientation. Lake ice pads with c-axis orientations other than the predominantly sub-vertical or predominantly sub-horizontal (or combinations of these two) are apparently rare.

The varying crystallographic orientations in lake ice pads are of interest because of their relationship to the strength characteristics of melting ice. High arctic lakes often freeze to depths of 10 feet or more, and provide useful landing sites over a large portion of the year. The melting and ablation of this ice often extends over a period of several spring and summer months, during which time the ice progressively deteriorates into an unsafe condition. Observations and strength tests carried out during the 1959 summer by Barnes and Leavitt (verbal communication) on such lake ice at Lake Peters, Alaska, have shown that melting lake ice with horizontal c-axis orientation rots much more deeply and is considerably weaker than ice with vertical c-axis orientation. In other words, the crystallography of the lake ice aggregates ultimately becomes a controlling factor in determining the useful age of the landing platform.

The process of ice crystallization in pools of undisturbed water is reasonably well documented. When the water surface has been sufficiently supercooled (generally to a few tenths of a degree below zero in natural waters) nucleation commences about an impurity, and a dendrite or needle spreads over the water surface along one of the 3 a-axis directions of ice. Offshoots along the other 2 a-axes are common, and large plates or dendrites spread over the water surface, gradually aggregating to a thin sheet of coarse-grained ice in which the c-axes are predominantly vertical. Deviations from this orientation are relatively rare, and in most cases under our observation, less than 25 degrees.

If there is growth of a dendrite or needle along one a-axis in a horizontal plane, there is no a priori reason why this needle must have a vertical c-axis. However, if one or two additional a-axes develop, the crystal will then float with c-axis vertical. The beginnings of ice nucleation are frequently limited to a very thin supercooled surface layer. Few centers of nucleation develop; platelets are free to float, and a

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strong preferred vertical c-axis orientation results. This is the most common situation in lakes and artificial ice.

Previous Work

The fact that orientations other than the sub-vertical are commonly observed in lake ice as well as interest in the kinetics of crystallization have prompted innumerable studies of ice growth. Among the more interesting of these, from the point of view of orientation, are the experiments of Brill (1957), who grew ice from distilled water in a relatively shallow but well insulated container (Fig. 1), fitted with a stirrer at the bottom. Heat loss was vertically upward, and cooling was induced by placing a dry ice container a short distance above the water. The clear crystalline ice grown by this method consisted of an aggregate of horizontally radiating needles, with horizontally oriented c-axes. Brill at first attributed this orientation to edge effects, but in subsequent experiments he prevented crystallization at the container walls by heating them electrically, and still obtained the same crystallographic orientations. This is a point of some significance; it implies very strongly that the horizontal c-axis orientation must be explained in terms of the kinetics of grain growth and is definitely unrelated to the thermal properties of ice. We suspect that the reasons for Brill's orientations are due to a combination of (1) a thick layer of supercooled water, and (2) possible fragmentation of the earliest formed ice skim. These points are discussed at some length in the section describing some of our experiments.

A laboratory study of the causes of the varying crystallographic orientations in natural ice sheets has been reported recently by Perry and Pounder (1958). Their experiments consisted essentially of growing blocks of artificial ice in cylindrical plastic containers well insulated at the sides and bottom, so that the thermal flux was entirely vertical.

In studying horizontal sections cut at progressive depths in the cylinders it was found that the fraction of the horizontal area covered by crystals with horizontal c-axes increased with depth (Fig. 2a). If the area of the crystals was not taken into consideration, they could find no preferred orientation. The explanation of the increased area taken up by crystals with horizontal c-axes is well summarized by Fig. 2b; it is hinged essentially to the well-verified (Hillig, 1958), more rapid velocity of crystallization in the basal plane of ice, and to the geometric possibilities of the more steeply oriented basal platelets cutting out the flatter ones.

The Perry-Pounder mechanism is probably significant in determining ice orientation under some circumstances, particularly if a means is available for producing random orientations in the early-formed ice skim. It should be pointed out, however, that lake ice petrographic diagrams, in general, appear to lack the intermediate crystallographic orientations predicted by the theory (Ragle, 1958). Our experiments (see below) also indicate that the probable cause for the histogram of Fig. 2a is not the mechanism of Fig. 2b.

Laboratory Studies

We have grown approximately 20 blocks of laboratory ice in cylindrical plastic containers with a depth of 22 cm, and 18 cm diameter. Tap water was used, and

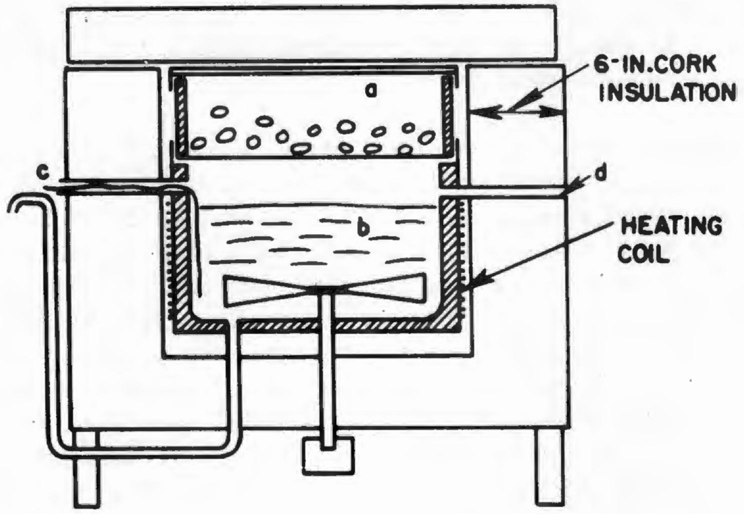

Fig. 1. Schematic drawing of device for preparing samples of ice (after Brill).

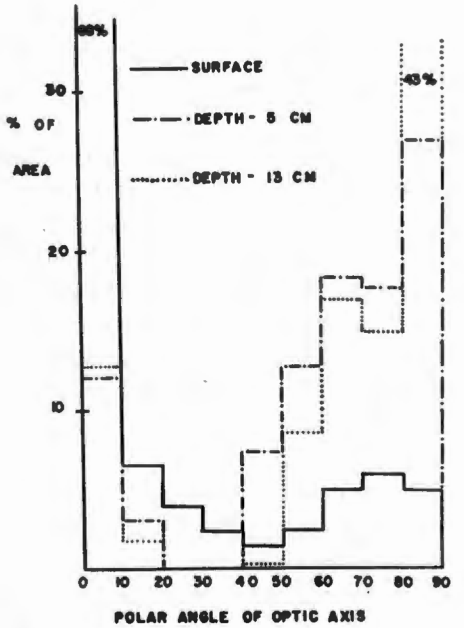

Fig. 2a. Perry and Pounder histogram for artificial ice showing fraction of horizontal area covered by crystals of a given orientation at depths of 0.5 and 13 cm below surface of ice sheet.

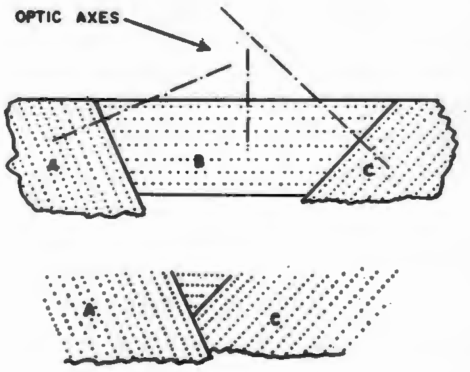

Fig. 2b. Proposed explanation for preferred growth of crystals with inclined optic axes, and gradual cutting-out of vertically oriented crystals. Lower sketch represents a later stage of freezing (after Perry and Pounder).

the ice crystallized in a cold room maintained at an ambient temperature of -10° C. Except when otherwise desired, insulation was provided by a one-inch covering of foam rubber, and several inches of vermiculite. The direction of heat loss and freezing was varied, the blocks being allowed to solidify from the top, the bottom, or from all directions simultaneously.

Artificial ice grown under conditions of vertical heat flux consists at the surface of an aggregate of coarse crystals with diameters up to 2 inches and a few finer-grained crystals restricted almost entirely to the perimeter of the block. The coarse crystals have vertical c-axes, and the peripheral crystals horizontal c-axes. At depth there are relatively more crystals with horizontal c-axes. The reason for this becomes apparent when one examines the growth process. Within a short time after crystallization has commenced, the entire column of water in the container is within ±0.15°C of zero, as indicated by thermocouple measurements. The crystals at the perimeter of the block grow downward rapidly, extending dendrites out into the water bath (Fig. 3); in some cases a dendrite may develop into an almost-continuous plate, extending from one wall to the other. Continued growth on early-formed crystals is aided by the fact that the thermal conductivity of ice is approximately four times that of water; it is, therefore, a far more efficient heat sink. The growth and expansion of dendrites and plates in the area below the surface ice cake very probably explain the data in Perry and Pounder's histogram (Fig. 2a) and our observations on differences in orientation with depth, as noted above. There is no new nucleation below the upper surface and the increased proportion of horizontal c-axis ice crystals is due solely to a progressive size increase in those crystals which nucleated at the container walls. Edge effects are apparently controlling factors here, unlike the situation in Brill's experiments.

Omitting consideration of such unknown parameters as surface energy effects between plastic walls and water molecules, a possible reason for the preferred growth of vertical basal platelets (horizontal c-axes) at the upper container edge may be that this is the area most likely to have both vertical as well as horizontal heat flow. If randomly oriented nuclei precipitate on the wall, those basal platelets which are both vertical and normal to the wall will lie parallel to the planes of maximum heat loss. The coincidence of the most rapid growth plane in the crystal with the plane of maximum heat loss soon results in the dominance of grains with this orientation.

This coincidence of rapid growth direction in ice with the direction of thermal flux is also the probable explanation for the orientation patterns in (1) commercially-grown ice blocks (Fig. 4), (2) laboratory-grown ice where there has been no insulation, or (3) laboratory-grown ice where cooling has been restricted to the bottom of the container. Everywhere except near the central upper surface of such blocks the columnar or tabular ice crystals generally have their c-axes sub-parallel to the walls (and the basal planes are normal to the cooling surface). The general textural relationships are identical to those in metal castings, even to the development of the familiar "globular" texture at the center. In metals the long direction of the columns is the direction of maximum thermal conductivity and of maximum growth velocity; in ice only the second of these two conditions is satisfied, but this is the important factor.

Fig. 3. Dendritic ice growth below a 2-inch thick ice cover. Diameter of ice block is 18 cm. Wires protruding from the cylinder are thermocouple leads.

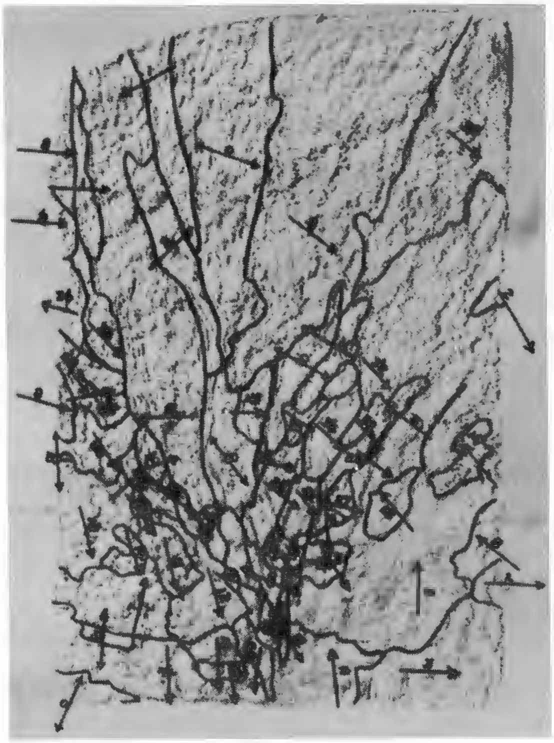

Fig. 4. Orientations of c-axes (indicated by arrows) in typical block of commercial ice. Edges of block toward top and sides of photo. Numbers on arrows indicate degrees of plunge.

Striking changes in the normal artificial ice orientation patterns are produced when a steady air stream is directed downward toward a water container so insulated that an upward heat flow has been established. At low wind velocities (i.e. 2-3 mph) the basic orientation pattern assumed by the crystallizing ice is the same as that when no wind fans the surface (see Fig. 5), and the major change is a decrease in average grain diameter, particularly for the vertical c-axis crystals.

If the wind velocity is increased to approximately 6 mph the grain size is greatly diminished, and the petrofabric pattern of all grains coarse enough to be optically identifiable show a complete sub-horizontal orientation of the c-axes (Fig. 6). Tyndall and vapor figures (Nakaya, 1956) produced in this ice by infra-red irradiation also show that each crystal has a horizontal a-axis. The wedging out and disappearance of some crystals at depth (Fig. 7) and the concomitant expansion of the persistent columnar units is difficult to explain; there is no indication that it is related to the degree of verticality of the basal directions in the crystals as it should be according to the Perry-Pounder theory, for one can see from Figure 7 that all the columnar grains have c horizontal. The columnar grain which enlarges with depth has the same orientation as the one it cuts out.

Leaving aside, again, the unsolved problem of the extent and effect of possible surface energy changes in wind-blown water, it would appear that there are at least two other major reasons for the preferred horizontal c- and a-axis orientation. One of these may be turbulent mixing of the upper water layers, and the development of a relatively thick stratum of supercooled water. The second effect is mechanical. Rubbings of a wind-blown ice surface show atypical grain-boundary relations: there are a series of discrete shards or flakes (Fig. 8) separated by intervening areas of lower relief. The pattern is doubtless due to fragmentation or brecciation of thin early-formed ice plates, many of which are probably tilted into random position. Continuous jostling of these fragments makes it progressively more difficult for 6-rayed dendrites or sub-circular disks to form. A condition is eventually reached in which surface growth is possible, or likely, only along one of the 3 a-axes, and a series of needle-like crystallites form. Being hemmed in and prevented from spreading laterally, the vertical direction becomes the only possible avenue for further growth of the a-axis rods. Those rods which rotate or nucleate into such a position that the basal plane is vertical grow most rapidly; this type of orientation becomes the preferred fabric within a millimeter below the surface.

It is also possible that the fabric may be due to a combination of continuous fragmentation of the thin surface ice skim as it forms, jostling of fragments into random position, and the operation of the Perry-Pounder mechanism. We do not favor this alternative, largely because we have found that in all the crystals we examined an a-axis is invariably parallel to the surface. This would be extremely unlikely if the crystals commenced at the surface as vertically rotated shards of basal plates; in this case the a-axes should be expected to show all deviations up to $\pm 30^\circ$ from the horizontal.

Discussion

One of the expressions defining the velocity of crystallization in terms of the physical properties of a solid is the following (Saratovkin, 1959, p. 104):

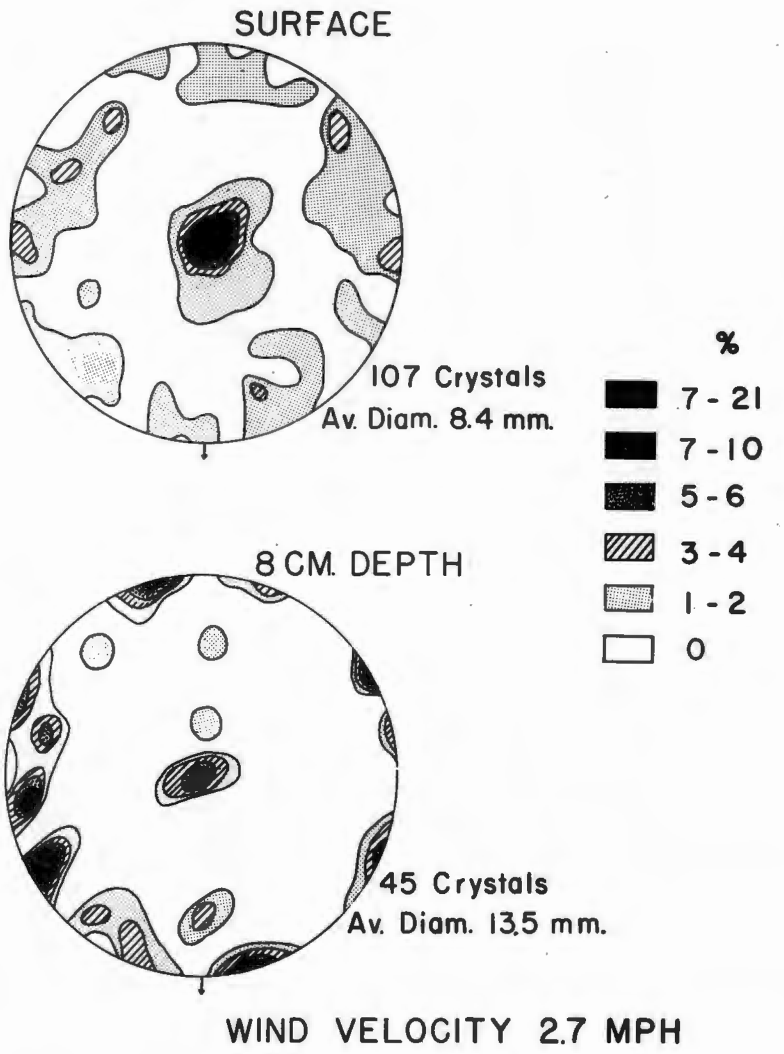

Fig. 5. Petrofabric diagram of c-axis orientations in artificial ice grown in a cylindrical container, with vertical heat flux and at a low wind velocity. Note decrease in percentage of vertical c-axes with depth.

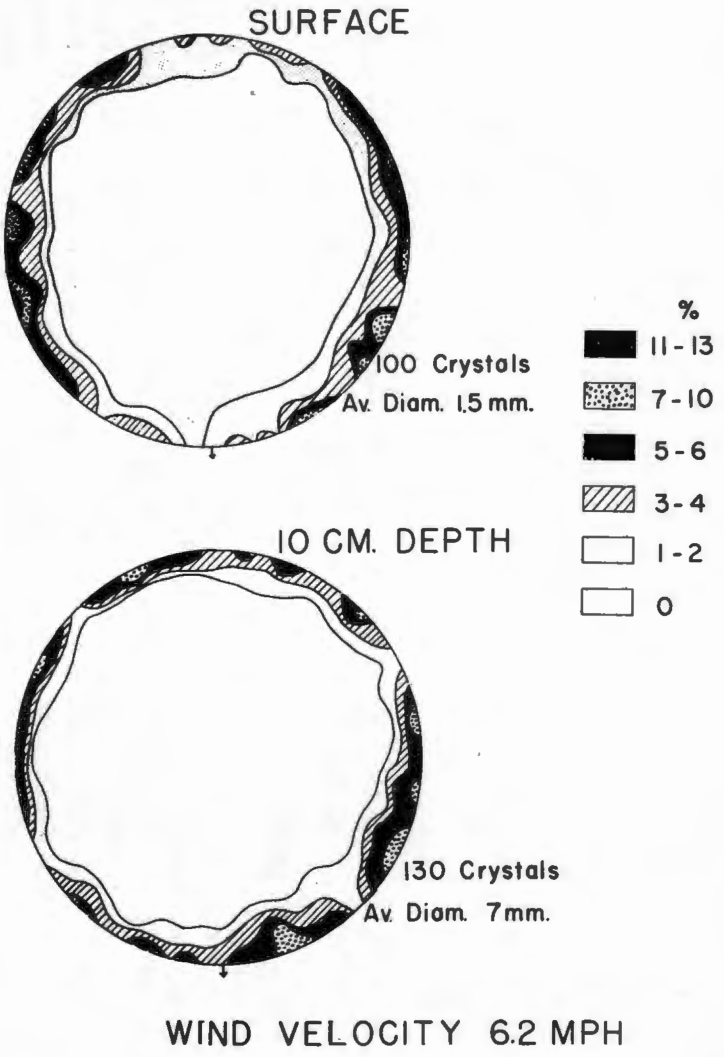

Fig. 6. Petrofabric diagram of c-axis orientations of artificial ice grown in a cylindrical container, with vertical heat flux and high (6.2 mph) wind velocity. Note absence of vertical c-axis orientations.

(1) $V = \frac{K}{\rho\delta} \cdot \frac{dT}{dx}$

K = thermal conductivity

$\frac{dT}{dx}$ = temperature gradient; dx = thickness of layer crystallized

ρ = heat of crystallization

δ = density

If the direction of maximum thermal gradient makes an angle φ with the normal to a face, that face then grows with a velocity given by:

(2) $V = \frac{K}{\rho\delta} \cdot \frac{dT}{dx} \cos\varphi$

According to these equations the velocity of crystallization of a substance should be proportional to its vectorial thermal conductivities; most rapid crystallization is along the direction of maximum conductivity and maximum thermal gradient. There are, however, several factors which may cause deviation from the theoretical relation (Saratovkin, 1959). As written, the equations assume heat loss through the crystal. If there is stirring, or heat loss to the melt, $K\frac{dT}{dx}$ cannot be evaluated, nor are equations (1) and (2) valid. Dendritic crystallization —one of the commonest growth forms in ice—is, in the opinion of Chambers (1958, p. 299), always accompanied by heat flow to the liquid rather than through the solid. Hence, ice dendrites need not necessarily show any relation between direction of growth and thermal conductivity vectors in ice.

A more serious consideration upsetting the theoretical relations expressed by the equations is the question of growth kinetics, which is influenced not only by structural and thermodynamic consideration within the crystal, but also by the impurity content of the liquid. There is now a fair degree of agreement among authorities on crystal growth that dendritic, whisker, fibrous, and other habit modifications are due not only to the degree of supercooling of a liquid, but also to the concentration and type of solutes or "poisons"; their rate of diffusion away from an advancing interface modifies both habit and growth rate.

It would appear that in all natural circumstances, and in our experiments using water from a local reservoir, conditions have been such that dendritic growth is favored. This suggests that the impurity content of the water is above a critical minimum level. The velocity of growth in the different crystallographic directions is therefore altered from what it would be in absolutely pure water, and with the ice growing at thermal equilibrium conditions. Evidently in all experiments on ice growth there has either been thermal disequilibrium or excessive (though probably minute) impurity content so that crystallization has never been strictly controlled by the Saratovkin equation.

The predominant control on the rate of crystal growth probably resides within the structure of the solid. As has been pointed out by Frank (1958, p. 9) "a face

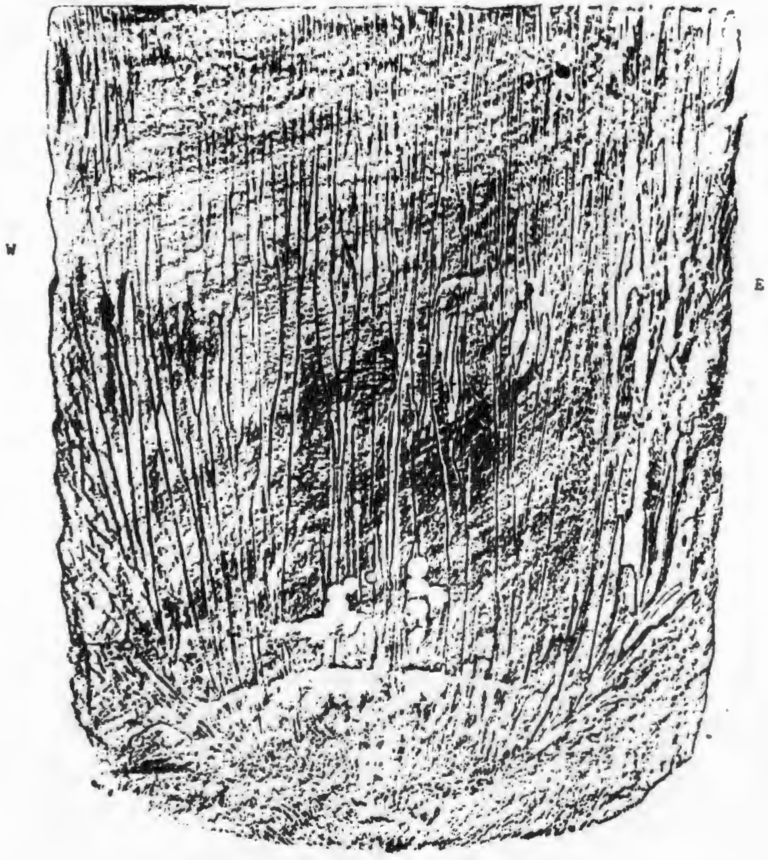

Fig. 7. Vertical rubbing through the center ice crystallized under wind of 6 mph. Each columnar crystal has one of the a-axes and a c-axis sub-horizontal. Note increase in grain size with depth. Width of top of rubbing is 18 cm.

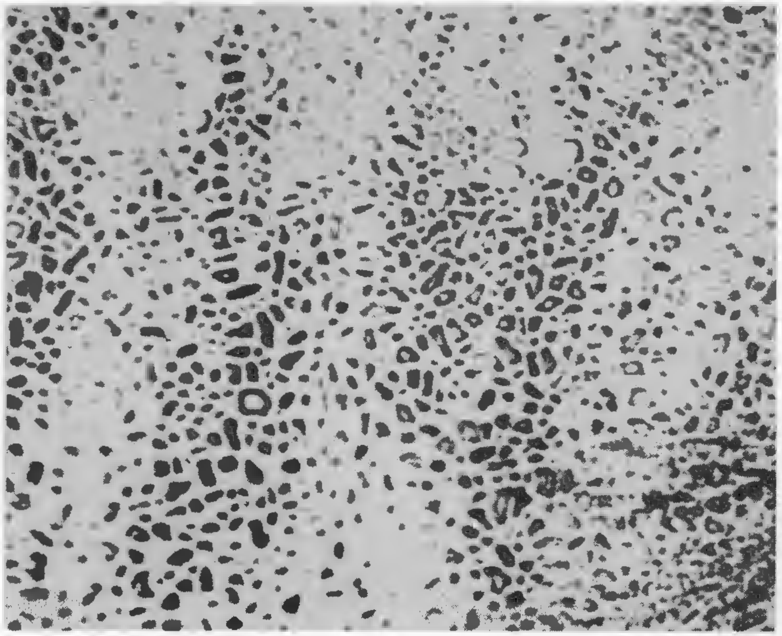

Fig. 8. Rubbing of fragmented upper surface of ice grown at wind velocity of approximately 6 mph; width shown by photo corresponds to 6 cm on the rubbing.

without defects can resist a finite supersaturation without growing at all". Imperfections within the crystal such as screw dislocations, point defects, etc. are necessary if growth is to be perpetuated. Although the nature of structural dislocations in ice is not yet completely known, it is a safe assumption that there is a high probability for them in directions in the basal plane in the ice crystal, and a relatively low probability in the c-axis direction. Only such an explanation allows us to understand why, at a given undercooling, the growth in the basal plane may be of the order of 10 to 100 times more rapid than that in the c-axis direction (Hillig, 1958, Fig. 1). Since the highest thermal conductivity vector in ice is also the slowest growth vector, it is obvious that it plays no appreciable role in controlling growth rates; consequently it also plays an insignificant role in determining preferred orientations in ice aggregates.

The general thesis of this paper is that ice orientation can be best explained in terms of (1) thermal gradients in the growth medium (water), (2) thickness of the supercooled water layer, (3) mechanical effects such as fragmentation of the earliest-formed ice skim, and (4) the undisputed fact that ice, for reasons not yet fully understood, invariably crystallizes more rapidly in the basal plane. None of the known physical properties of ice assists us to understand its orientation patterns. The type of research which would be most helpful in further elucidation of this general problem would be (1) precise measurements of the thickness of undercooled water layers, using the best thermopile equipment, and (2) further studies in the difficult field of crystallization kinetics.

Acknowledgments

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