STUDIES OF ARCTIC LAKE ICE*

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Abstract. Discussions of possible causes of preferred crystal orientations in fresh-water ice are presented, with data on ice orientations from several Arctic lakes. Evidently, initial ice orientations are determined by wind conditions. Orientation selection during growth at the bottom of the ice also takes place, but in the lake ice examined it is apparently largely unsystematic. Constitutional supercooling can cause *c*-axis-horizontal orientations, but it is not of sufficient magnitude in the lakes examined to have much effect. Striations are locally significant but erratic.

Résumé. On discute les causes possibles d'orientations préférencielles des cristaux dans la glace d'eau douce, avec des données sur les orientations de la glace de plusieurs lacs arctiques. De façon évidente, les orientations initiales dans la glace sont déterminées par les conditions de vent. La sélection de l'orientation a également lieu durant la croissance de la glace à sa base, mais dans la glace de lac étudiée ce phénomène n'est apparemment pas souvent systématique. La surfusion peut causer des orientations horizontales de l'axe *c* mais n'est pas d'une importance suffisante dans les lacs étudiés pour avoir beaucoup d'effet. Les striations ont une signification locale mais erratique.

Zusammenfassung. Die möglichen Ursachen für das Auftreten bevorzugter Kristall-Orientierungen in Süsswassereis werden anhand von Beobachtungen der Eisorientierung in verschiedenen arktischen Seen diskutiert. Die Eisorientierung wird am Anfang sichtlich durch die Windverhältnisse bestimmt. Es tritt auch eine Orientierungsauswahl während des Auffrierens an der Unterseite des Eises ein, doch ist sie bei dem untersuchten See-Eis weitgehend unregelmässig. Natürliche Unterkühlung kann eine horizontale Orientierung der *c*-Achsen verursachen, doch genügt ihr Ausmass in den untersuchten Seen nicht zu grösseren Wirkungen. Stellenweise ist eine deutliche, aber regellose Streifenbildung zu beobachten.

Introduction

The aspect of lake ice which has received most, indeed almost exclusive, attention is the crystal fabric: the presence and character of any preferred crystal orientations. Since crystal orientation is the most important parameter, in conjunction with grain size, for predicting the properties of a given block of lake ice, it receives major attention in this paper as well. It is found that most ice orientation data in the literature, as well as the new data presented here, roughly confirm the theory first clearly stated by Shumskiy (1955, p. 158–64). Exceptions are present, however, and other factors must be considered.

One main class of "other factors" consists of phenomena related to grain boundaries and sub-boundaries. The last sections of this paper discuss these features, mainly the sub-boundaries (striations), which are extremely prominent in all lake ice examined, and have not been studied previously in ice.

Ice Orientations

General considerations

There are two separate problems connected with ice orientation: (1) the start of freezing, and (2) orientation selection or change after freezing has commenced. The best way of studying the start of freezing is to watch freeze-up in the field, but this has not been done; therefore, the discussion must be in terms of later observations. Suffice it to say that the first growth of ice in lakes may be random, or consistently orientated with either horizontal or vertical *c*-axes. In agreement with the experiments of Lyons and Stoiber (1959), an initial *c*-axis-horizontal orientation is always very fine-grained (order of 1 mm.) at the top and randomly orientated in the horizontal. Ice which starts with vertical *c*-axes is generally very coarse-grained (order of centimeters), as would be expected for freezing in quiet water. Ice of initial random orientation starts with intermediate grain size. It is certainly reasonable to

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postulate that wind action is responsible for these varying orientations, as indicated by Lyons and Stoiber (1959).

Observations of the ice on Peters and Shrader Lakes in the spring of 1961 support the idea that wind is the main factor. When all the snow had ablated and the ice had candled, different surface orientations over the whole lake could be determined by inspection (Figs. 1–3). The *c*-axis-vertical ice was white and the *c*-axis-horizontal ice was darker, because of the detailed mechanism of candling. (The same phenomenon is reported by Barnes (1961), also at Peters Lake.) Candling in the fine-grained, *c*-axis-horizontal ice is simply grain-boundary melting, while the whiteness of the *c*-axis-vertical ice is attributable to tubules (Ragle, unpublished) and air bubbles formed when solar radiation causes internal melting in large crystals of this orientation.*

Patterns of orientations suggested wind action: breaking of an initial ice skim and re-freezing between the "pancakes" or in tears in an initial skim.

Fig. 1. Candled ice surface of Peters Lake, Alaska (Shrader Lake in distance). The light-colored ice has vertical c-axes, whereas the dark-colored ice has horizontal c-axes. Note frozen lead traversing the lake

* This brings up the interesting question of whether orientation or grain size is the "real" cause of the different modes of deterioration (Barnes, 1961). Observations of some ice from ARLIS II indicate that grain size is the important cause. Extensive, dike-like bodies of ice in the glacial portion of ARLIS II generally consist of two ice "facies" : one ". . . weathers out as a very resistant, cellular, white ice that produces knobs 2 to 2·5 m. high. The other weathers to a low, rounded ridge with a smooth, almost velvety surface texture—it retains a faint bluish color even when weathered. The latter comprises 70–80 per cent of the bodies observed." (Personal communication from David D. Smith.)

The present writer examined specimens of both types of this ice in thin section and found the only difference between them was crystal size. The "velvety", blue ice was even-grained with grains 2-5 mm. in diameter and contained no vapor bubbles. The white ice was also even-grained but with grains 2-3 cm. in diameter and contained many irregular air bubbles evidently caused by internal melting and drainage of the melt water. In neither case did the grains show any elongation or crystallographic orientation.

The question arises why ice with different grain sizes responds so differently to radiation. Since the direct cause of the "whiteness" of coarser-grained ice is the presence of irregular air bubbles, perhaps the answer simply lies in the geometric distribution of internal water, and its ease of drainage in the two different cases.

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Fig. 2. Close-up of the surface of Peters Lake showing frequent orientation changes

Fig. 3. The surface of Peters Lake showing patches of c-axis-vertical ice in c-axis-horizontal ice. Note the track of a taxiing DC–3 airplane; the wheels dug grooves about 20 cm. deep in candled, c-axis-horizontal ice but they made no impression on the c-axis-vertical ice

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Although about half the surface ice on both Peters and Shrader Lakes was orientated with the *c*-axis vertical and half horizontal, all of the ice more than 60 cm. beneath the surface in Peters Lake and below 15 cm. in Shrader Lake was *c*-axis horizontal. This was determined from 10 cores in Peters and 5 in Shrader Lake, taken through surface ice of the various orientations and surroundings. Evidently, phenomena occurring during growth of ice at the bottom of an ice sheet can be more important to the orientation of the bulk of the ice than the initial ice formation.

In the consideration of ice growth at the bottom of a sheet of ice, there is again a convenient two-fold sub-division of the subject. First, as grain size increases with depth in the ice, some grains are wedged out, and this process is an orientation mechanism in so far as it is selective; and secondly, there may be the introduction of new orientations as conditions of freezing change. The second consideration may be ruled out of the discussion, because the ease of supercooling of water makes discrete re-nucleation in the process of freezing extremely unlikely, except in conditions of most rapid freezing, which cannot occur in nature at the bottom of an appreciable sheet of ice. No unequivocal cases of nucleation of new crystals during freezing of the ice were found, except in the upper 6 in. (15·2 cm.).

As a third possibility, it is not inconceivable that a crystal may change its orientation as it grows, with the introduction of certain types of dislocations, but this effect was specifically looked for and not found. Therefore, the process of wedging out and its results are the subject of the remaining part of this paper dealing with orientations.

Historical

The literature on ice orientations is quite extensive, surprisingly so, in view of its usual inconclusiveness. The work up to 1938 is completely reviewed by Dorsey (1940, p. 407–12) and is not further referred to here.

The best attempt at a comprehensive theory of ice orientation to date is that of Shumskiy (1955). (Perey and Pounder (1958) discuss ice orientations in a somewhat similar fashion and list several additional references.) Shumskiy's theory is also restricted to the wedging out process and considers the fast growth direction of ice in relation to temperature gradients in the water. If supercooling decreases away from the freezing surface, the ice crystals whose fast growth directions (*a*-axes) are parallel to the freezing surface are thought to wedge out ice crystals of other orientations, and a preferred orientation develops with *c* parallel to the heat flow direction (perpendicular to the ice/water interface). Similarly, as freezing progresses, impurities concentrate in the water near the interface and lower its freezing point, causing supercooling to increase away from the interface, and crystals with *c* parallel to (*a* perpendicular to) the interface are favored. (Shumskiy does not explicitly mention impurities but he deals directly with temperature or supercooling gradients.) No measurements of the concentration of impurities at the ice/water interface have been reported, and consequently the theory has no direct confirmation, but the general orientation trends are in agreement with its predictions. The crystals in sea ice are generally orientated with their *c*-axes horizontal (Weeks and Lee, 1958; Schwarzacher, 1959). Lake and artificial fresh-water ice may have either orientation, but where there is a transition, the vertically orientated ice is normally above, as predicted (Perey and Pounder, 1958; Lyons and Stoiber, 1959; the author's observations).

The argument for constitutional supercooling causing *c*-axis-horizontal grains to wedge out others seems quite clear and reasonable. The first grain to reach the supercooled layer will grow sidewise at the expense of the others, and this grain will have an *a*-axis most nearly vertical. The argument for *c*-axis-vertical grains being favored when supercooling decreases away from the interface is not so clear at all, when one thinks of the details involved. Certainly, if it occurs, it must be very slow.

One theory of ice orientation has been based on measured or assumed anisotropy of thermal conductivity (Weeks, 1958). Anisotropy of fresh-water ice is very small (Landauer and Plumb, 1956), and the fact that fresh-water ice (ice with no visible liquid inclusions) can orientate either way, seems to rule out this theory. It is intuitively much less appealing to the present author than Shumskiy's theory, especially for thick sheets of ice in which lateral temperature gradients at the bottom must be very slight.

Melt-pond data and discussion

Frozen melt ponds on Arctic pack ice provide some striking visual confirmation of Shumskiy's theory. The water in these ponds comes from rain, melted snow and melted old sea ice, and is consequently quite fresh, usually with a salinity less than 1‰. These ponds are only one or two feet (0·3—0·6 m.) deep and as freezing progresses the concentration of salt in the remaining water increases rapidly. A study of the ice reveals the response of the crystals to the continuously increasing impurity level of the water from which they freeze. As expected, as the water becomes more salty, the *c*-axis-horizontal crystals commence growing dendritically (that is, they start growing downward by means of discrete blades or platelets, extending into the liquid) and very rapidly wedge out the vertical crystals (Fig. 4b). An unexpected effect was that, as dendritic growth started, the grain boundaries became irregular in a rather periodic fashion—doubtless reflecting the platelet structure, and further verifying Shumskiy's theory (compare Figs. 4a and b). Up to the point where the grain boundaries of the horizontal crystals became irregular, there was little consistent selection between vertical and horizontal crystals. Both, however, would tend to wedge out tilted crystals.

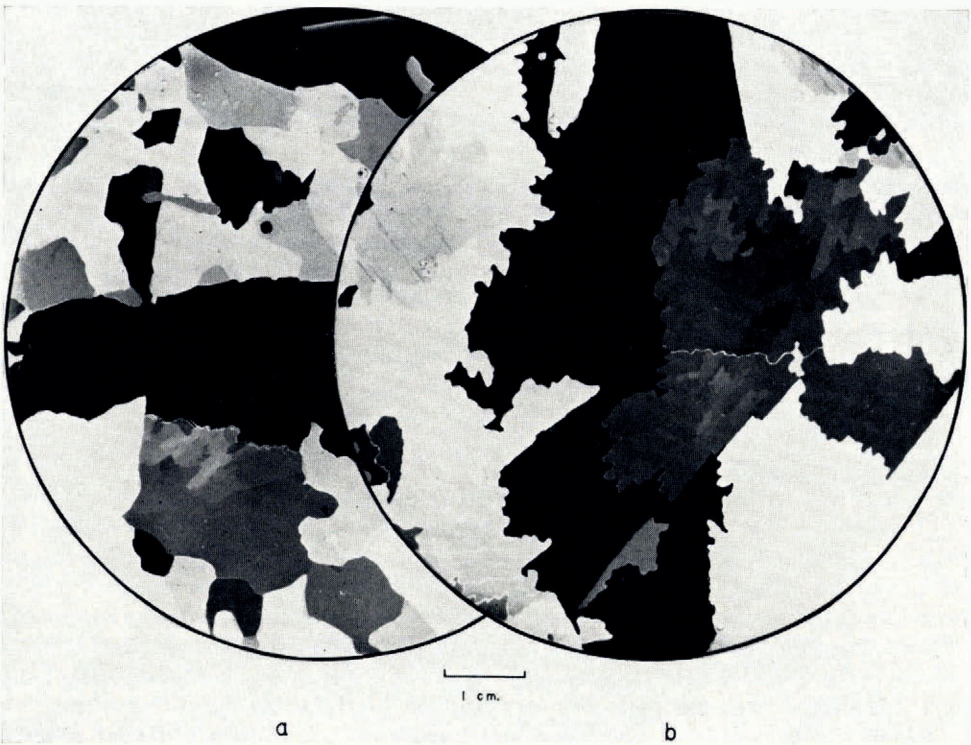

Fig. 4. Horizontal sections of melt-pond ice under crossed polaroids. Both contain a single c-axis-vertical crystal surrounded by c-axis-horizontal crystals. (b) is in a zone of dendritic growth but (a) is not. Note the crystal with striations being wedged out in (a). The c-axis-vertical crystal in (b)—the black one—is being wedged out by all its neighbors

Melt-pond ice also shows clear evidence that appreciable freezing takes place upward from the bottom of ponds. The ice which forms the bottom in most ponds, being originally

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sea ice, is polygonized (Knight, 1962). Overgrowths on these crystals are detected by their lack of polygonization. This proves the presence of constitutional supercooling during the last stage of freezing and further confirms Shumskiy's theory. ("Constitutional supercooling" is the term used in metallurgy for the condition in which supercooling increases away from the freezing interface.) A good review of constitutional supercooling and dendritic growth in metals, and other related effects, is given by Rutter (1957).

It is concluded that Shumskiy's theory is correct in principle, but it is questionable whether impurities build up enough at the ice/water interface in deep, "fresh" lakes for it to apply in these more important situations.

In two ponds *a*-axis orientations were measured. In both cases the initial crystals were very small and "perfectly" *c*-axis-horizontal. In both ponds *a*-axis orientation was also "perfectly" horizontal, as determined by inspection of orientated etch pits formed by the method of Higuchi (1958). This parallels the findings of Lyons and Stoiber (1959) on artificial ice frozen on a water surface agitated by wind. The same etching technique was tried with sea ice, to compare its *a*-axis orientation with that of the pond ice, but difficulties were encountered. The etchant did not work properly, presumably because of a salt-water film on the ice surface. However, overgrowths of fresh ice could be produced on sea ice, with fair crystal continuity, and orientations were determined on these overgrowths. Seventy-one crystals were "measured" by inspection of etch pits on horizontal sections. Sixty-three were judged to be most nearly *a*-axis vertical and eight were most nearly *a*-axis horizontal. In many cases considerable judgement was exercised but the trend seemed definite. In addition, the trend was checked qualitatively by measuring the orientations of crystals in several vertical thin sections, using a straining technique described elsewhere (Knight, 1962). There is no question of these orientations being the result of initial growth; they must be the result of wedging out, since the sea ice used in these determinations was taken near the bottom of one- or two-year-old pack ice (about 2 m. down).

It is interesting that a perfect horizontal *a*-axis orientation was found in one case, and an imperfect vertical *a*-axis orientation in the other, clearly of two different origins. Since the *a*-axis direction is the direction of fast growth, an imperfect vertical *a*-axis orientation resulting from a wedging out process is to be expected according to Shumskiy's theory. The horizontal *a*-axis orientation in initially orientated ice is explained by Lyons and Stoiber (1959) in terms of mechanical considerations in ice formation on a wind-blown water surface.

To the author, it seems odd that, if the mechanical effect of the wind is important, no orientation of *c* with respect to wind direction is found. In his experience *c* is entirely random in the horizontal plane. However, no better explanation can be offered.

Lake ice data and discussion

In late spring of 1960 a series of orientation profiles was measured in Ikroavik and Imikpuk (also called Fresh) Lakes, and single orientation profiles were measured in Malikpik, Peters and Shrader Lakes. The first three lakes are near Barrow, Alaska and the last two are in the Brooks Range just south of Barter Island, Alaska. In the spring of 1961 orientation profiles were repeated in Ikroavik and Fresh Lakes, and in Peters and Shrader Lakes as mentioned above. The data are presented in Figures 5–9. Conventional thin-section techniques were used throughout, the sections being spaced originally 15·0 cm. apart along the 7·6 cm. diameter cores, and closer together when needed to follow an orientation transition.

In 1960 the cores in Ikroavik and Fresh Lakes were taken in a rather restricted area in the center of each lake—within a radius of approximately 50 m. In 1961 the cores were purposely taken farther apart, except for two (Fresh Lake, 1961, e and f), which were taken within 1 m. of each other to check a specific feature. The sequence in the figures is not significant.

In 1960 the initial orientations in both lakes were more or less random in all the cores, as indicated by the dotted lines. In 1961 a sharply defined, bubbly layer of ice was usually found at the top, possibly representing a flooding of the original ice surface from beneath because of a weight of snow (Ragle (unpublished) calls this "snow ice"). Beneath this layer there was ordinarily a sharp transition to some preferred orientation.

The vertical, horizontal and tilted (V, H and T) orientations indicated on the figures were completely distinct in almost all cases. On the few occasions when there was doubt the arbitrary definition for T was taken as more than 15° deviation from H or V.

Grain size increased downward, and below about 60 cm. in the ice it was rare to find one grain completely enclosed in a 7·6 cm. diameter thin section, though it was also unusual to find a section composed of one single crystal. Grain-size measurements were not made. Thin sections of a larger area would be necessary for studies of this kind.

A look at the graphs of orientations (Figs. 5–9) shows that when vertical and horizontal ice occur in the same core, the vertical ice tends to be above, with some exceptions. This is compatible with Shumskiy's theory, but some other features are not. In the first place, in only one case grain boundaries became noticeably irregular in the manner which reflected dendritic growth and accompanied rapid wedging out in melt-pond ice; this was 84 in. (2·13 m.) down in Fresh Lake (1961, e). It is true that the bottom interface, when the *c*-axis of the ice at the interface was horizontal, always exhibited a system of approximately 1 mm. high ridges 2 or 3 mm. apart, orientated with the basal plane; but it seems doubtful if this growth is sufficiently dendritic for Shumskiy's mechanism to apply. Indeed, one observation of the bottom surface contradicts it. The bottom surface from one core in Fresh Lake (1961, c) intersected several horizontal crystals which for the most part surrounded one tilted crystal. These horizontal crystals had ridges which extended about 1 mm. below the relatively flat surface of the tilted crystal, yet the tilted crystal was evidently in the process of wedging out the others with exceptional rapidity. This was the only time a bottom surface containing crystals of differing

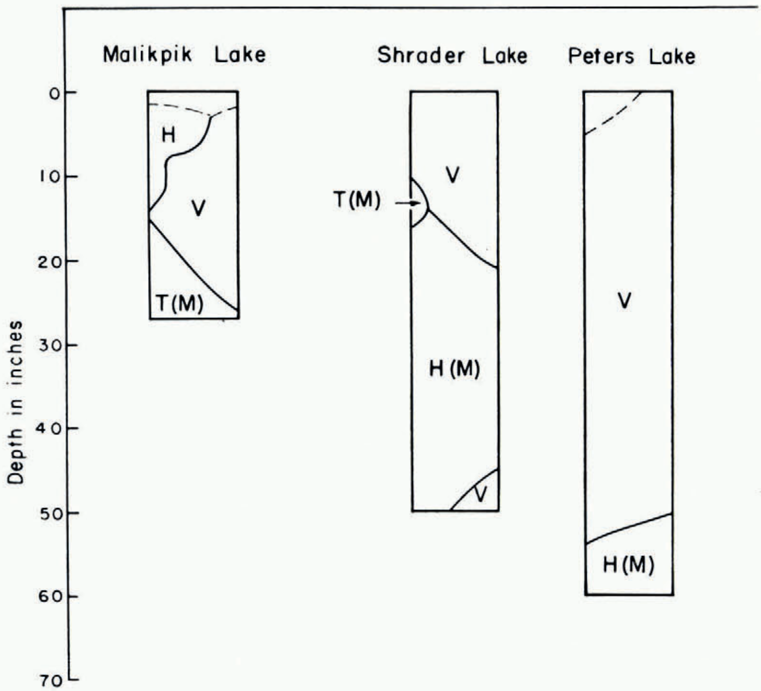

Fig. 5. Profiles of crystal orientations; spring, 1960. H, V and T stand for horizontal, vertical and tilted c-axes. Malikpik Lake was frozen to the bottom

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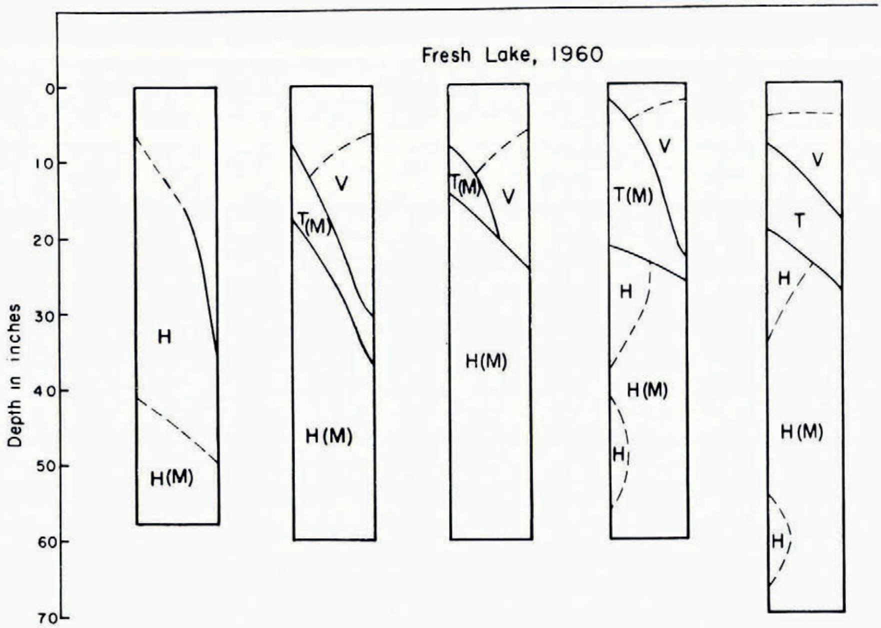

Fig. 6. Orientation profiles

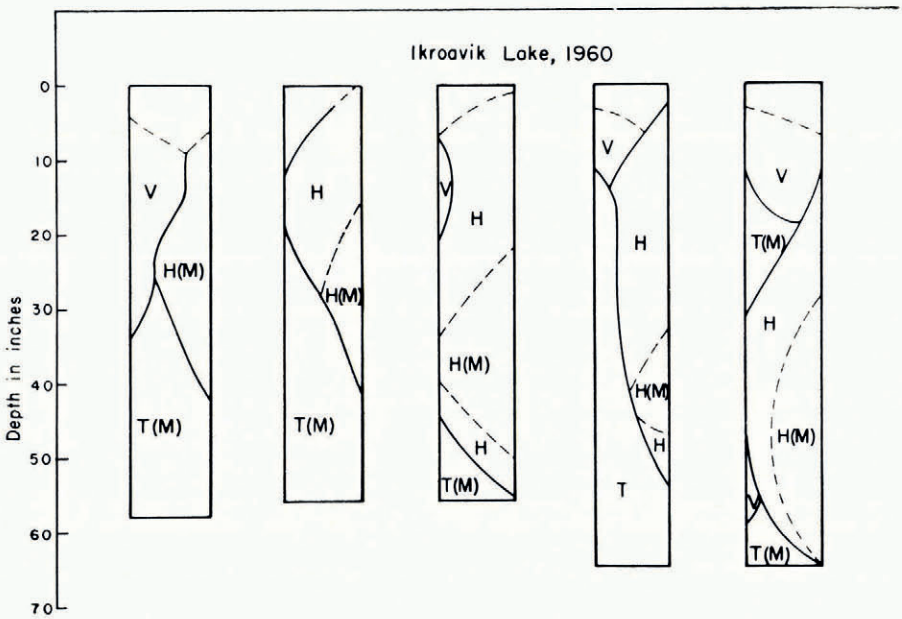

Fig. 7. Orientation profiles

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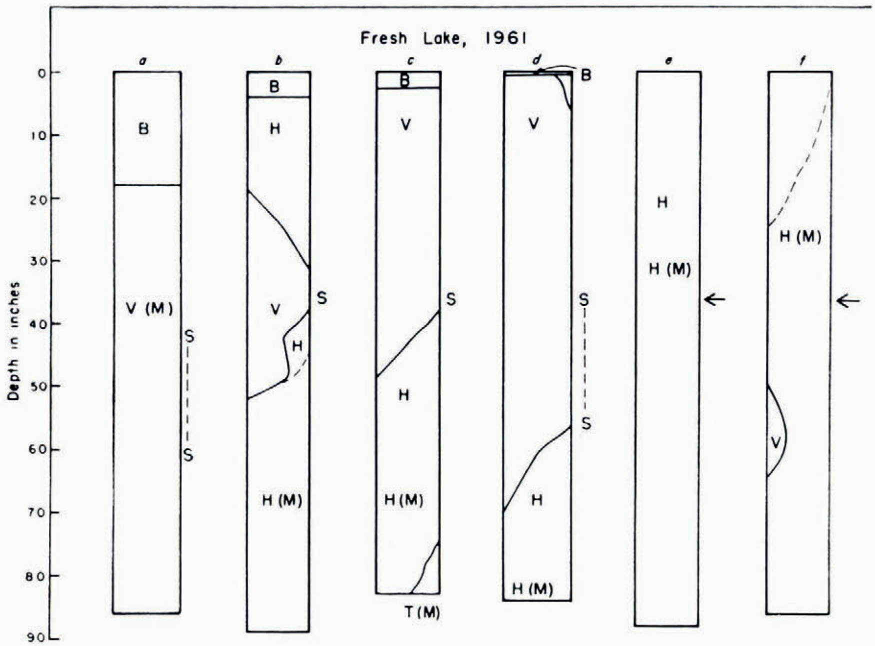

Fig. 8. Orientation profiles

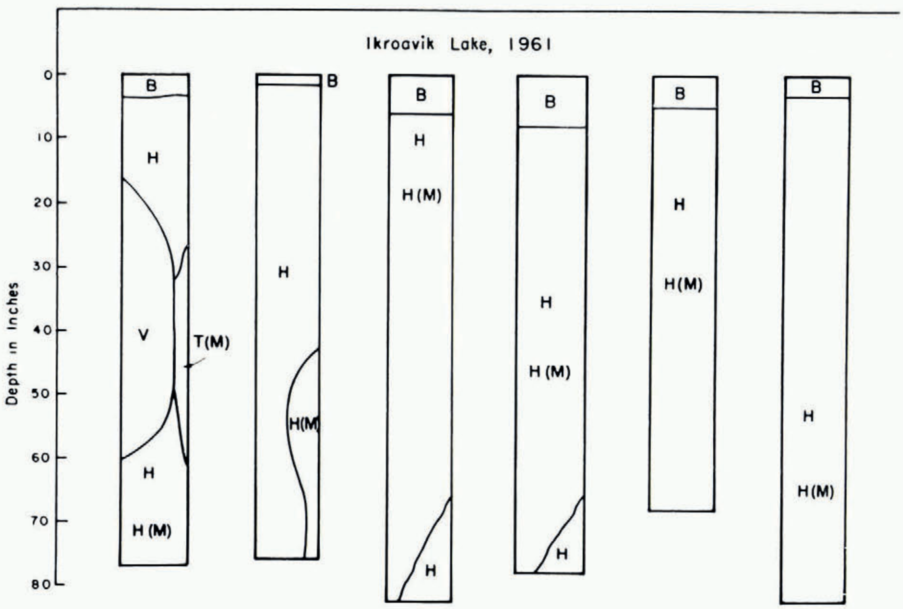

Fig. 9. Orientation profiles

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orientations was encountered, with the exception of the one core from Shrader Lake taken while the ice was melting.

The tilted orientations also appear to contradict Shumskiy's theory. There is a point in the continuum of possible supercooling situations at the ice/water interface at which there is no preference for vertical or horizontal orientations, but it is difficult to imagine any positive principle of selection for tilted orientations. However, just this selection seemed to occur in 1960. It may or may not be significant that all of these cases had initial random crystal orientation.

Whether the tilted orientations represent a real selection, or just an imperfection in the scheme of horizontal and vertical selection, is a question which cannot be answered with the data at hand. The diameter of the ice cores is too small to obtain grain-size data at a sufficient depth in the ice, or to permit one to observe inter-grain relationships with any completeness. While studying the 1960 cores, it was felt that the tilted orientations were distinct enough to imply a selection principle as a cause. Unfortunately, simpler ice was encountered in the more detailed study in 1961 and few tilted crystals were observed.

Another puzzling aspect is presented in the rough layering of orientations observed in 1960. More data are required, again only easily obtainable from larger diameter cores. This layering must be fortuitous if it is to be assumed that nucleation does not occur during the freezing process.

In 1960 several sequences of thin sections spaced 2 cm. apart and closer were made in the lake ice, through the zone where the initial random orientations gave place to a specific orientation. In the winter of 1960–61 similar series of sections were made in melt-pond ice in the zone above dendritic growth, when interesting orientation situations arose. Visible clues of factors significant toward orientation selection were looked for and various photographs and petrofabric diagrams were made. Apart from the obvious fact of an orientation selection occurring, no consistent correlations involving wedging out were observed. As far as could be determined, any grain was capable of wedging out any other, depending on local circumstances, for which no general ordering principles were discovered.

However, in a number of cases specific features of local significance were observed, and apparently several of them have not been previously described. All of these features involved grain boundaries and sub-boundaries (as they must in a monomineralic substance), and many of them are of more interest in themselves than they are in relation to orientations. They are described separately below and their relation to orientation will be only incidentally mentioned here. The wedging out process is, however, fundamentally a grain boundary phenomenon, and any new understanding of grain boundaries is likely to elucidate it. Large-angle grain boundaries will be discussed first, followed by a discussion of sub-boundary (striation) features.

Grain Boundaries

The irregularity of grain boundaries accompanying dendritic growth has been discussed above and needs no further treatment.

In lake ice, in the zone near the top where random orientations give way to selected orientations, a remarkable and unique grain boundary feature was observed, and this is illustrated in Figure 10. In horizontal sections every grain having a tilted *c*-axis develops one side as a straight face. Looking down at a horizontal section in its original attitude, the side developed is the one parallel to the trace of the basal plane towards which the *c*-axis plunges. The opposite side is irregular, as are all sides of crystals with their *c*-axis orientations near vertical or horizontal. (Horizontal crystals in conditions of dendritic growth, as judged by the above-mentioned irregularity of grain boundaries, tend to develop both basal faces. This is a distinctly different phenomenon from that under consideration here, where the growth is not

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dendritic.) As is clear in Figure 10, many of the grains which are orientated near 45° have the one "face" and are quite large—indicating that they have been wedging out other grains. This phenomenon was thought to hold great possibilities for explaining the *c*-axis-tilted orientations found in 1960, but a careful examination of closely spaced sequences of thin sections showed no relationship with orientation selection; one 45° grain will increase its area with depth, while 2 in. (5 cm.) away a similarly orientated grain may decrease in size.

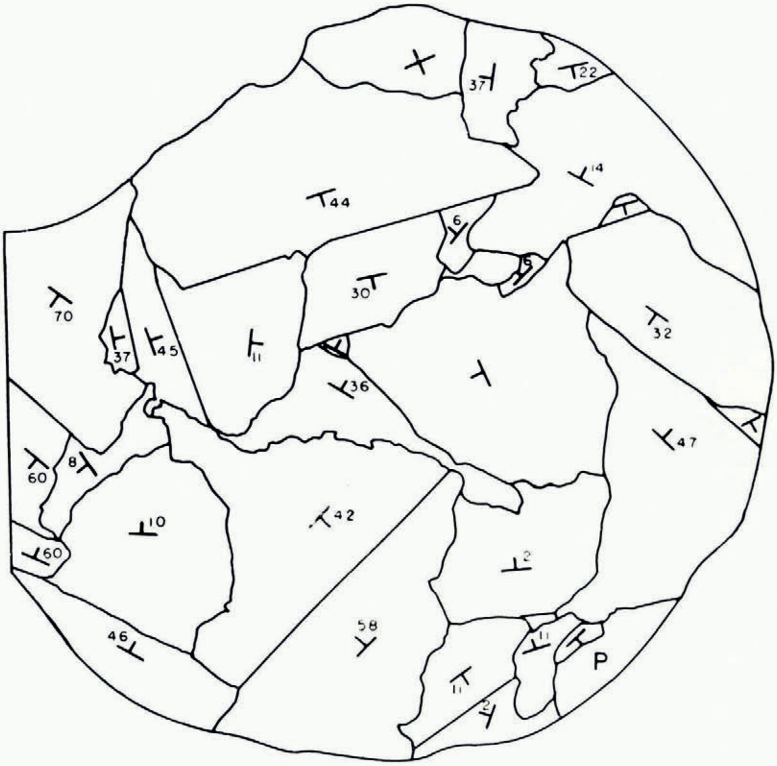

Fig. 10. Map of a horizontal thin section of lake ice 7·6 cm. in diameter. The symbols are the strike and dip of the plane formed by the c-axis and the intersection of the basal plane with the horizontal

The phenomenon of one straight face is interesting in itself but very puzzling, especially so since in the other dimension these faces are not crystallographically controlled, but rather tend to be vertical, as do all of the grain boundaries. This may be explainable in terms of the freezing potential effect discovered by Workman and Reynolds (1950), though the details are not clear. The freezing potential probably develops only across faces perpendicular to *c* (at least mostly across these, though the experiments as reported are equivocal—see Workman and Reynolds (1950, footnote on p. 254), so that one might predict an effect which would be important only in tilted grains, and only at this one "face". Grain boundary troughs about 1 mm. deep were observed at the ice/water interface wherever examined, as shown in Figure 11. At one intersection part of the wall of the trough is nearly parallel to the basal plane, so the freezing potential will operate here and not at the other intersection shown. Perhaps having this "face" straight minimizes an energy resulting from this charge separation. In 1960 every section from near the top of the ice, which showed tilted grains, also showed this one face. In 1961, however, one example (Fresh Lake, 1961, f) was found which "should" have had this feature, but did not. The strength and sign of the freezing potential effect is critically sensitive to the amount and type of impurities, so this exception in a way argues for its significance.

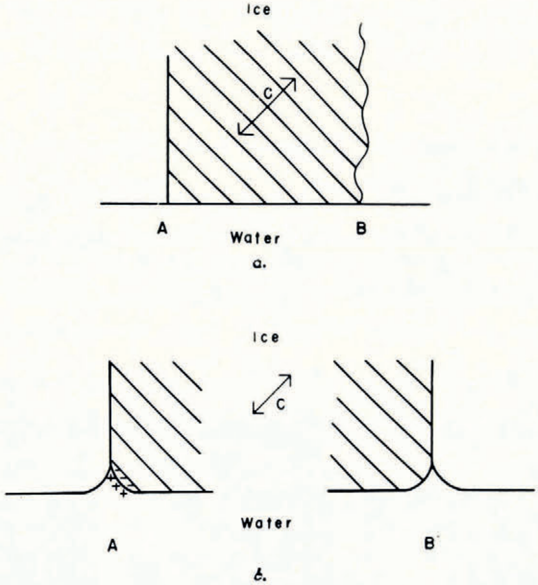

Fig. 11. Schematic relationships of c-axis-tilted grains with one "face" developed. Grain boundary troughs shown in (b), with possible charge separation shown at the one side

A group of possibly important effects concerns interactions between grain boundaries and impurities at the ice/water interface. Thin sections of lake ice, which were allowed to sublimate completely, formed a tracery of precipitate on the glass where the grain boundaries had been, thus proving that impurities are incorporated at grain boundaries either as tiny liquid inclusions or dissolved in the solid. In so far as this may effect constitutional supercooling, it may also effect orientation selection.

Striations

To the investigator studying lake ice by means of polarized light, the most striking feature must be the striations (Figs. 4, 12, 13 and 14). These are usually developed to an amazing degree. Probably in no other substance are striations so prominently displayed and at once so easily observed and studied.

Most work on striations has been concerned with metals and is adequately reviewed in several symposia (e.g. Hirsch, 1956; Rutter, 1957; Elbaum, 1959). Striations have been discussed in terms of dislocations and their forms and orientations have been related to impurities. The present worker has shown that some striations in ice are composed of dislocations, by observing them move under stress (Knight, 1962); and it will be seen below that their forms are also affected by impurities.

The forms of striations in ice also vary characteristically depending upon the orientations of the crystals in which they form. Usually they form nearly parallel to the growth direction but those in crystals with vertical *c*-axes are different from those in crystals of other orientations. In vertical crystals striations are normally present from the very onset of growth, whereas in horizontal and tilted crystals striations appear gradually, and then only in "fairly large" crystals.

The first striations formed in crystals whose *c*-axes are tilted or horizontal are "tilt" boundaries parallel to *c* and vertical in the ice. Initially these are quite perfect and straight, but as freezing progresses they become more irregular and more numerous, and they come to represent greater misorientations between adjacent sub-grains (Figure 12 is an extreme example). Finally, horizontal and tilted grains develop a sub-structure which in horizontal section appears roughly rectangular, with sub-boundaries parallel and perpendicular to *c*. Vertical sections of striated, tilted grains show these striations compromising between vertical and crystallographic orientation, sometimes descending in steps. Misorientations between adjacent sub-grains were found ranging up to 5° with 2 or 3° being most common.

The transition between the presence of only regular "tilt" boundaries and the rectangular sub-structure with two sets of striations at right angles in some cases correlates with other features. The onset of dendritic growth in melt-pond ice, as shown by rapid wedging out of vertical grains and by major grain boundaries becoming irregular, is accompanied by the striation boundaries becoming irregular in just the same manner (Fig. 4b). The striations evidently move to occupy the troughs between the dendrites.

Two cores (Fresh Lake, 1961, e and f) contained a most striking and sudden change in striations in horizontal grains at the depth indicated by arrows in Figure 12. At the same depth

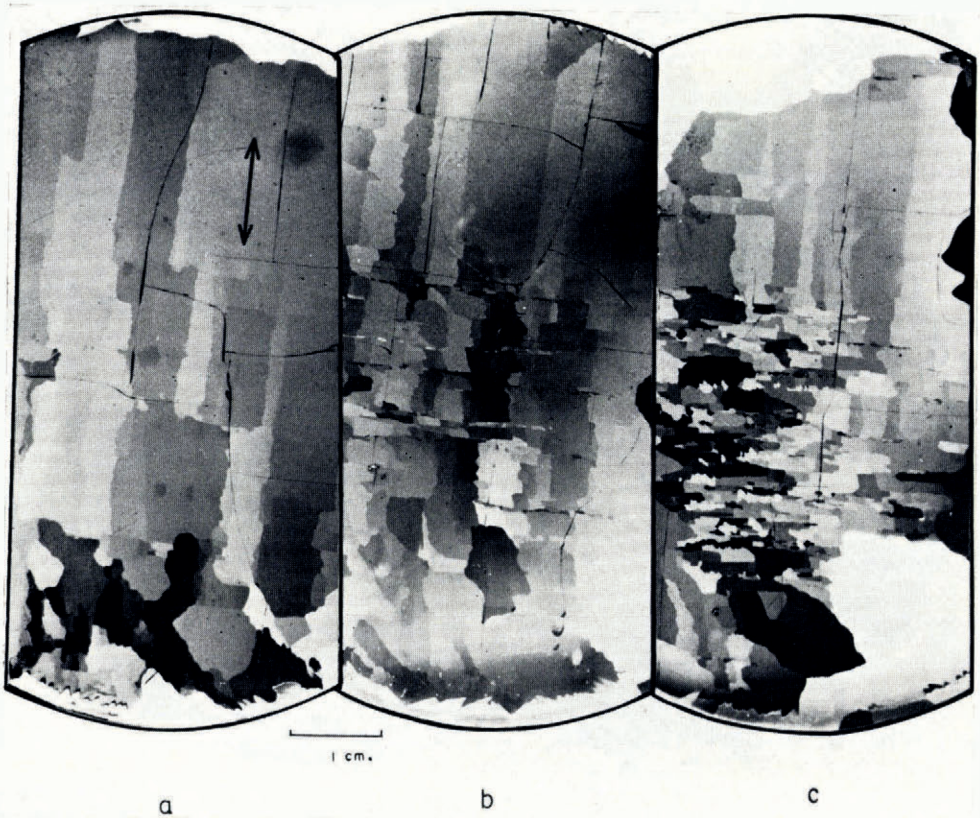

Fig. 12. Three horizontal sections in a core from Fresh Lake (1961, e), at 83·8, 91·5 and 106·5 cm. depths, respectively. The arrow in (a) shows the c-axis direction. Crossed polaroids

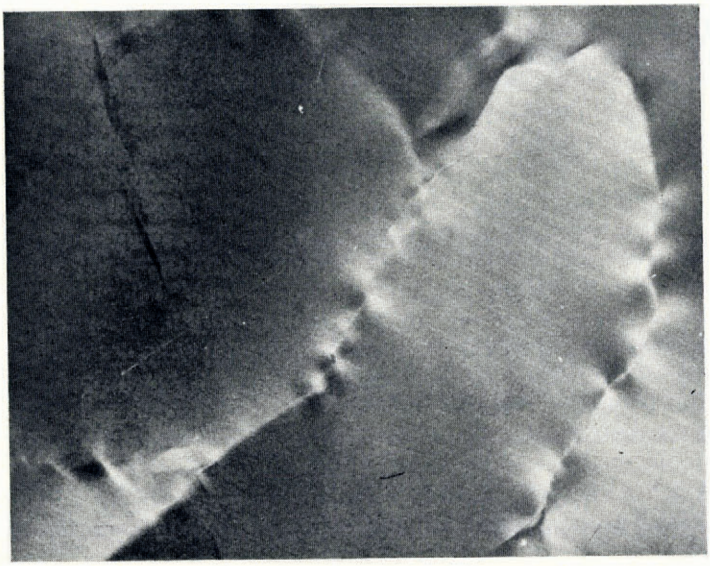

Fig. 13. Strain shadows typically associated with sub-boundaries in c-axis-vertical crystals. The c-axis is perpendicular to the plane of the figure. ×25, crossed nicols

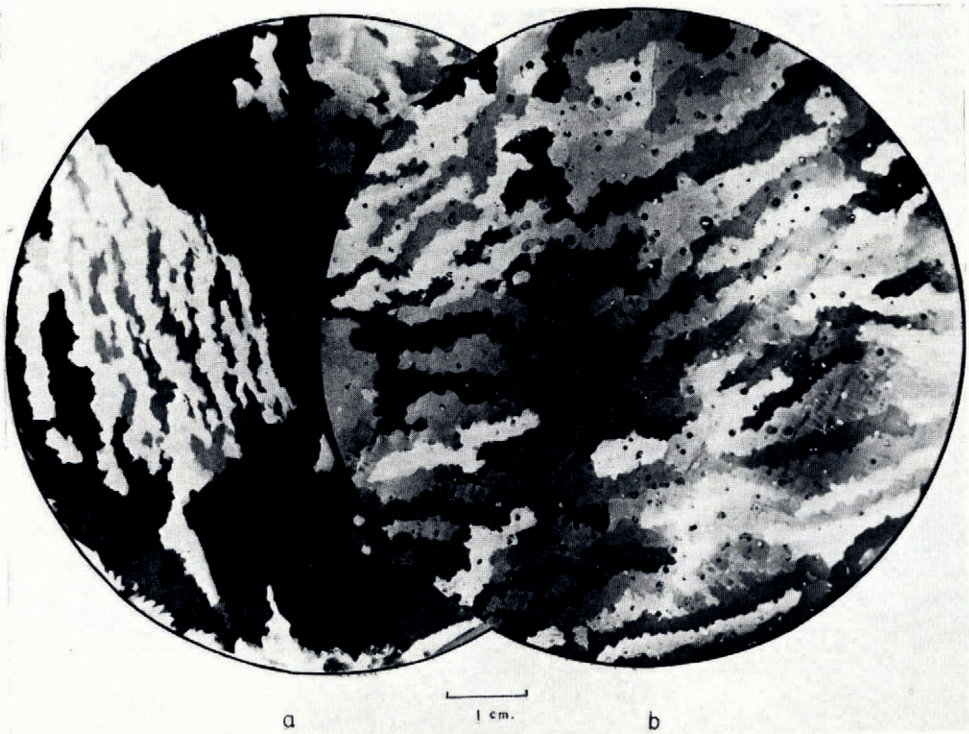

Fig. 14. Horizontal sections of lake ice showing sinuous striations in c-axis-vertical ice. Crossed polaroids

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in both cores (taken within 1 m. of each other), the striations rapidly changed from a fairly regular array parallel to *c* to an extremely chaotic arrangement, which was immediately followed by the grains involved being wedged out by their less-striated neighbors (Fig. 12). This rapid transition correlated with a characteristic striation feature in vertically orientated ice, described below, at approximately the same depth in all the other Fresh Lake 1961 cores.

As mentioned above, vertically orientated ice virtually always contained striations, even at the top of the ice (probably corollary to large initial grain size). These striations ordinarily were irregular and would have been visible only by thermal etching, except that there was strain along them, concentrated at "bends" (Fig. 13). Annealing thin sections for several days at outside temperature usually relaxed the strain, the origin of which is puzzling.

Often the striations in vertical crystals became arranged in orderly patterns, at the same time increasing in misorientation by as much as 7 or 8° (Fig. 14). These orderly patterns are quite unique in that only a very few sub-grain orientations (two to five or six) are involved in a single grain, while the sub-boundaries come to look like the space-filling curves of mathematics. Why these striations act in this way is again a problem, but this appears to have possible significance to orientations.

In 1960 it was noted that usually a vertical crystal was wedged out soon after developing this typical sinuous pattern of striations. In 1961 the pattern appeared in four of the Fresh Lake cores and its approximate extent is indicated in the graph by *S*'s beside each column. In three out of the four cases, the sinuous structure preceded wedging out. It was striking that it appeared at approximately the same level in each core, and at the same level as the rapid transition in the striations in horizontal crystals.

Presumably these striation features are "caused" by the same thing, which must be unique to Fresh Lake and hence must involve impurities, since nothing unusual was noted in the ice of Ikroavik Lake only 4 or 5 miles (6·4 or 8·0 km.) away.

Two cases of heavily striated grains being obviously wedged out as a result of the striations are noted above. One (Fresh Lake, 1961, e and f) consists of normally striated horizontal grains wedging out extremely striated, also horizontal ones; the other consists of horizontal grains wedging out vertical ones with characteristic sinuous striations. In another instance (Fresh Lake, 1961, a) normally striated, vertical grains wedged out sinuously striated, vertical grains; in yet another (Ikroavik Lake, 1961, the middle two cores shown, at the bottom) unstriated horizontal grains wedged out normally striated ones, the wedging out occurring preferentially along the striations. Yet another particularly convincing case was encountered in melt-pond ice, in the upper zone above the zone of dendritic growth. In this core a large vertical crystal was in the process of slowly wedging out the horizontal crystals surrounding it, when one of the bordering crystals developed striations. The wedging out then proceeded several times faster on this crystal than on the others (Fig. 4a).

Thus, it is clear that striations greatly affect the wedging out process and are of importance to orientation selection in so far as striation features are sensitive to orientation in the first place. In terms of one's natural desire to explain the orientations observed, it is unfortunate that striations behave as capriciously as the orientations themselves, and only in the above cases were they found to be related. In the orientation profiles the presence of striations is indicated by *M* following the orientation symbol (the *M* stands for "mosaic"). *V* is always to be understood as including striations.

One interesting problem arose regarding striations, which is a good indication of their unpredictability. Often both pond and lake ice started with an initial, virtually perfect, horizontal orientation ("perfectly" uniform interference color in horizontal section). Often one or two, or several grains would develop full striation patterns, while the rest of the grains in the section would remain perfectly clear. No way was found to predict which grains would develop striations, though one could be sure that the striated grains would be among the largest in the section. Possibly this correlates with the presence of some sort of dislocation-generating imperfections, the incorporation of which might be largely a matter of chance.

Conclusions

With regard to crystal orientation in lake ice the conclusions might be summed up in a series of points.

(1) During the initial freezing of a sheet of lake ice preferred horizontal or vertical, or random *c*-axis orientations may form, as far as is known, in any ratio and in any pattern over the surface of a lake.

(2) Except in the first inch or two of freezing, introduction of new grains must be considered negligible. (This is a major difference from sea ice.)

(3) Orientation selection occurs during the freezing of the bulk of a sheet of ice by the process of "wedging out". Grain boundaries form at an angle to the freezing direction in a manner such as to consistently select for or against certain orientations. The results of this wedging out depend, of course, on the choices of orientations available from the initial freezing.

(4) Perhaps the most significant factor in deciding which orientations are favored is the amount of supercooling in the water as a function of distance from the ice/water interface, an idea most completely formulated by Shumskiy (1955).

(5) Some grain boundary and sub-boundary factors are of demonstrable significance in specific instances but they are of doubtful general significance.

(6) With regard to the practical uses of lake ice, crystal orientation is of first importance to mechanical properties. Orientation depends on such delicate factors that the only practical way of dealing with it is to measure it directly. Prediction in any sense seems highly unlikely.

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