CRYSTAL ORIENTATIONS IN FLOATING ICE SHEETS

W. F. Weeks[1] and J. S. Wettlaufer[2]

1. Geophysical Institute, University of Alaska
Fairbanks, AK 99775-7320
2. Applied Physics Laboratory, Box 355640
Department of Physics
University of Washington, Seattle, WA 98195

Abstract

A review of the striking and varied c–axis orientations that are observed in undeformed sheets of lake and sea ice is presented from three points of view [laboratory, field and theory] with the goal of tying seemingly contradictory observations together into a consistent overall explanation.

Introduction

The development of strongly preferred crystal fabrics (c–axes orientations) in glacier ice has received considerable attention in the literature [1–4] as the result of the effects of crystal orientation on the rheological properties of ice. The equally strong fabrics that develop in undeformed sheets of sea and lake ice, although of similar importance in affecting the properties of these materials [5–11], have received somewhat less attention. It is these fabrics and the field observations and experiments concerning their development, that will be discussed in the present paper.

Fabrics in glacial ice develop as the result of deformation and recrystallization. In contrast, although deformation and recrystallization do occur in sea and lake ice, they are primarily secondary phenomena and do not produce the primary fabrics that are characteristically observed in these materials. These primary fabrics form during the growth of the different layers of ice and are the result of the fact that, during the essentially 1–dimensional growth characteristic of such ice sheets, crystals in certain preferred orientations have a growth advantage over less favorably oriented neighboring crystals. This growth advantage allows the favored crystals to expand their position at the advancing interface with the result that, with continuing ice growth, the less–favorably oriented crystals are ultimately cut out. The result is an ice–water interface that only contains crystals having the favored orientation. A schematic diagram illustrating this process in sea ice is shown in Figure 1. This general process has been referred to in the crystal growth and solidification literature as geometric selection and is commonly observed during the 1–dimensional solidification of a wide variety of both natural and man–made materials [13–16]. In general, geometric selection is usually the result of anisotropic growth of single crystals of the solidifying material. As will be seen later, this is clearly the case during the formation of sheets of lake and sea ice.

In attempting to unravel the observations on geometric selection as it occurs in ice, we will, after some initial background considerations, review the literature in the following order: initial crystal formation, experimental observations, field observations and theory.
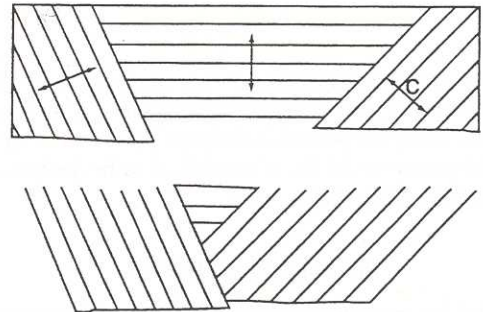

Figure 1. A schematic drawing illustrating the process of geometric selection; particularly as observed in sea ice [12]. The platy structure of the individual crystals indicates the orientation of the basal (0001) planes. Note that the favored crystals are indicated as having a growth advantage (i.e., they extend farther into the liquid at the ice–water interface).

Initial Considerations

First it is well to remind ourselves of some fundamental differences in the behavior of lake water and of sea water. In pure water (at 1 atmosphere) there is a density maximum that occurs at +3.98°C. Therefore, as water cools toward this temperature its density increases. However, as cooling continues from +3.98°C toward the freezing point at 0°C, the density decreases as the structure of the liquid anticipates the formation of the low density solid phase Ice (Ih). In fact, the water system is one of the very few in which the density of the pure solid is less than the liquid from which it forms. Furthermore, the temperature of the density maximum is a function of composition with the maximum increasingly approaching the freezing temperature as the amount of salt in the solution increases. In seawater the transition from the state where the density maximum is encountered "before" the freezing point is reached to the state where the density maximum only occurs in the supercooled state occurs at a salinity of 24.7‰ (Figure 2). Therefore, when an isohaline layer of water with a salinity >24.7‰ is cooled from above, the density of the near-surface liquid increases producing an unstable vertical density distribution resulting in buoyancy driven free convection. This convection results in a significant thickness (meters to 10s of meters) of the water column being cooled to the freezing point before initial ice formation starts. For salinities <24.7‰, cooling of the surface layer of water to temperatures below that of the density maximum leads to the formation of a stable, low density surface layer which, because the fundamental heat transfer

mechanism in the water column has now changed to conduction, can supercool and freeze quite rapidly. Therefore, at the start of winter it is commonly observed that lake ice forms first, then river ice (where vertical mixing occurs as the result of forced turbulence) and finally sea ice. The importance of these matters to the geometric selection process will be developed later in this paper.
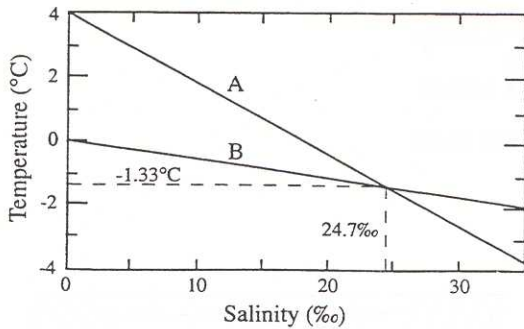

Figure 2. Plots of the temperature of the density maximum (curve A) and of the freezing point of sea water solutions (curve B) as a function of their salinity expressed in ‰ (parts per thousand by weight). The crossing point at 24.7‰ is considered to be the boundary between sea water and brackish water.

Initial Crystal Formation

The initial ice crystals that form in layers of supercooled pure water have discoidal shapes in which the crystal dimensions measured in the plane of the discoid [the basal or (0001) plane] are much greater than those measured perpendicular to this plane [in the direction of the c–axis]. The discoidal growth shape results from both the equilibrium and the kinetic properties of ice, which can be traced to the highly anisotropic surface free energy of the material. In equilibrium, the crystal shape itself is a reflection of the orientation dependence of the surface free energy, $\gamma(\hat{n})$, which can be reckoned with the work it takes to break the bonds per unit area for a given crystallographic orientation, $\hat{n}$. Hence the equilibrium shape is that which minimizes the total surface free energy per unit area for the volume it contains. The *Wulff construction* uniquely determines the equilibrium shape [17–18] which is essentially identical to the shape of a homogeneously nucleated crystal. However, since $\gamma(\hat{n})$ is strictly an equilibrium concept, a complete knowledge of it is insufficient to describe a growth shape [19–23]. A polar plot of $\gamma(\hat{n})$ reveals the interfacial structure for any material with cusps in the plot denoting high symmetry crystallographic planes, or *facets*, that are molecularly smooth. A convenient simplified physical picture of these surfaces is that the change from one phase to the other occurs over roughly the distance that separates molecular planes, that is, the interphase density jump occurs over a molecular scale. Measurements of the differences in $\gamma(\hat{n})$ values in pure ice between the basal plane and an edge plane have recently been obtained by Koo, Ananth and Gill [24] by studying the shape anisotropy of water filled negative crystals. They found an anisotropy ratio of 10^2 which is extremely large.

For ice, the surface perpendicular to the c–axis is a facet at temperatures up to the melting point. Growth on such a flat plane requires an undercooling that is larger than some threshold value sufficient to allow the formation of new 2–dimensional nuclei on the surface of the plane. Other surfaces of an ice crystal possess a structure which results in a gradual interphase variation over the scale of a number of molecular planes. These are termed

molecularly rough or *diffuse* surfaces, and in ice the surface normal to the the basal plane takes this structure at temperatures near the melting point. Growth on such rough surfaces is not subject to threshold supercooling and can apparently proceed at any supercooling [25]. Depending on the orientations present, an equilibrium or growth shape may be fully faceted or completely rough. Measurements of ice growth velocities have been made by Hillig [26], who found that growth parallel to the c–axis is controlled by an activated nucleation process. In addition he observed that at supercoolings of less than 0.03°C, growth in the c–axis direction was zero. He also noted that at small supercoolings it was possible to grow crystals that had dimensions of 25 cm parallel to the basal plane and 5 microns parallel to the c–axis; a ratio of 50,000 to 1 [27].

Characteristically, the first crystals to form during the freezing of lakes on calm, cold, clear nights are needles [28–29] which extend rapidly in the thin supercooled surface water layer. Although supercoolings exceeding 1°C have apparently been measured in the field [30], typical supercoolings of a few hundredths of a degree are more common. These needles have their c–axes inclined at various angles to the vertical with horizontal and near horizontal inclinations being quite common [31]. Once an interlocking network of needles is established, the space between the needles is subsequently filled in by plate–like tabular crystals oriented with their c–axes vertical. These crystals can grow to be quite large with sizes (measured horizontally) in excess of 1 m being reported [32, 58].

If it is windy and wave action is present, in both lakes and oceans vertical turbulence causes the upper layer of the water to become thermally well mixed and cooled to the freezing point (or even slightly supercooled). This allows ice crystals to nucleate within the upper portion of the water column. Wave–induced motions then cause crystal to crystal collisions typically resulting in a fine grained slush that when solidified results in an ice layer in which c–axis orientations are presumably random. We use the word 'presumably' here because, as the result of the very small grain sizes involved, measurements of c–axis orientations are not, as yet, available for this ice type. However considering the nature of the processes involved in the formation of this ice, it is likely that a wide variety of different crystal orientations would be present. In addition, examination of thin sections of such ice under crossed polarizers reveals the full range of interference colors that would be expected to be produced by a random distribution of c–axes. Similar appearing ice can also form as the result of snow falling in the water during the initial stages of freezing. When seawater freezes the results are generally similar to those observed on lakes with the exceptions that needle formation appears to be less frequent and grain sizes seem to be consistently somewhat smaller. It should be noted that c–axis vertical crystals are quite common in both initial sea ice skims [46, Figures 23 and 24] and in skims formed from brackish water [77, p. 10–13]

The important point to be extracted from the above discussion is that all the information available at present suggests that for both lake and sea ice the initial ice skims contain crystals with a wide variety of c–axis orientations including both vertical and horizontal. We are not examining situations where orientation A wins over orientation B because B was simply not present in the initial ice layer. In fact, in sea ice there is good evidence that, even after the initial ice layer has formed and competitive downward growth has started, c–axis vertical crystals are continually being introduced into the ice sheet during growth by the formation of tiny discoidal crystals in the water column that then float up and become attached onto the bottom of the overlying ice. There they are rapidly terminated by geometric selection. If similar situations occur in lake ice, they have not been documented in the literature.

Experimental Observations

Lake Ice

The experiments relating to the primary mode of geometric selection in ice have primarily been carried out using pure water. The two main experiments are by Ketcham and Hobbs [33] and by Ramseier [34–35]. They are experimentally rather similar in that both studies are of ice growth into a water column that was either at 0°C or possibly very slightly supercooled. Figure 3 shows the experimental arrangements used by Ketcham and Hobbs. Ramseier's proceedure (a floating zone) was similar to the setup in Figure 3A except that his sample was continually rotated during growth as in the Czochralski technique. Note that in the cases of freezing fresh water from the bottom up there is continual free convection induced by the density decreases in the liquid associated with cooling at the freezing interface. In such cases the water column would, as suggested by the authors, be expected to be isothermal and at the freezing point. The second experimental setup used by Ketcham and Hobbs (Figure 3B), although freezing from the top downward, maintained isothermal conditions in the water column by surrounding the column with an ice–water bath. The purpose of both sets of experiments was to establish the preferred orientation that forms under these growth conditions and also to develop specific rules describing crystal encroachment along specific grain boundaries. It is not necessary to describe the details of the resulting rules here except to note, not surprisingly, that the later paper by Ramseier builds on the Ketcham and Hobbs work and provides rules that are somewhat more general. From our viewpoint the results of both experiments are essentially the same. As stated by Ketcham and Hobbs, "...the larger the angle between the c–axis of a grain and the growth direction the greater the probability that the grain will be preferred. Therefore, as a piece of polycrystalline ice grows from a melt, those grains in which the c–axis makes a large angle with the growth direction will become increasingly dominant". The conclusion to draw from these observations is that all sheets of lake ice should rapidly develop crystal orientations in which the c–axis is oriented in the plane of the ice–water interface. We also note that the encroachment rules developed in these papers are similar to the rules developed by Kawamura [59] for sea ice which we will describe later.

In addition, experiments to evaluate the effect of seeding and the thermal regime in the water column on crystal orientations in fresh water ice have been carried out by Gow [31] using a 7×7 m refrigerated tank that was filled with 1.2 m of water. Both seeded and spontaneously nucleated ice sheets were formed. Water temperatures were set to several different temperatures between 0 and +4°C and then the cooling system above the tank was turned on, lowering the air temperature to –20°C. The results of these experiments were as follows. When the ice sheet was seeded, columnar–textured ice with substantially horizontal c–axes (so–called S2 ice) always developed regardless of the thermal condition of the water prior to seeding [initiated by covering the surface of the water with frozen droplets formed from a high pressure nozzle]. On the other hand, when ice growth nucleated spontaneously, c–axis vertical orientations were invariably observed resulting in S1 type ice with the thermal regime of the water apparently exerting no significant control on the resulting crystal orientation. He concluded that, to within his ability to control other parameters, nothing mattered except whether or not the ice sheet was seeded; a situation that we have already dismissed as a probable cause. Whether or not this is an effect of whatever mechanism(s) controls orientation changes remains to be considered. Incidentally, the S1 and S2 shorthand for designating the structure of different naturally occurring ice
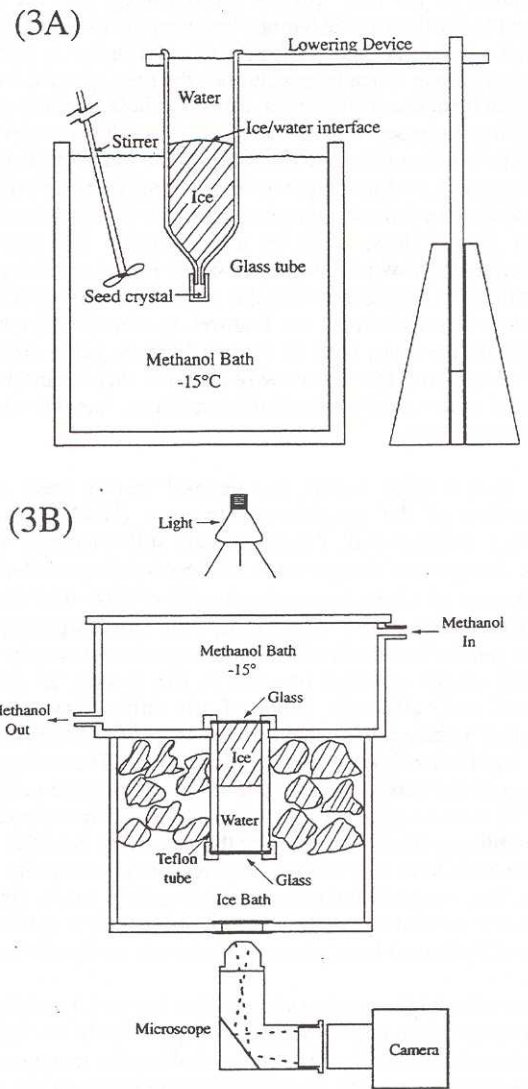

Figure 3. Two different experimental freezing arrangements utilized by Ketcham and Hobbs [33].

types is from the classification suggested by Michel and Ramseier [32] and will be used at times later in the present paper.

Two additional sets of experiments relating to selective growth in lake ice should be mentioned. Although the general experimental approach of both sets of experiments was similar in that the ice was grown in small cells that allowed high resolution optical observations of the freezing interface, the geometric arrangements of the experiments were quite different. The first group of experiments was by Harrison and Tiller [36–37]. The substances frozen included pure water and sea water as well as a variety of other solutions and the orientations of the resulting crystals were determined by optical methods. The procedures for all the runs were the same in that ice was grown from distilled water for about 4 hours at which time the other solutes were added to the remaining water. Typical growth rates were 1 cm/hr and temperature gradients in the ice were both very high (15°C/cm) and constant. The ice grown from distilled water had a smooth, glass-like interface. Although grain boundary and sub-grain boundary grooves were observed in the fresh water runs, they were not noted as being either atypical or of more than one type. The presence of solutes at the growth front has drastic

consequences for the growth morphology and is solely responsible for the vast difference between the overall fabrics of lake and sea ice. As the solubility of salts in ice is very low, during the growth of ice from solutions the salts rejected from the solid build up at the growth front. Since the bulk freezing point of the solution decreases with an increase in the solute concentration, the solute build up creates a decrease in the local freezing point and, depending on the temperature gradient in the solution, can give rise to *constitutional supercooling* of the fluid adjacent to the growth front. Thus, there is a propensity for interfacial disturbances to grow into the supercooled liquid, resulting in the formation of a corrugated /cellular solid–liquid interface. This qualitative description of the features responsible for sea ice substructure has been with us for nearly forty years [38], but a quantitative theory that shows why and how this hallmark fabric is created, under nearly all natural conditions, has only recently been presented [39].

When solutes were added, the general results were similar independent of the specific solute used (NaOH, Na_2SO_4, K_2CrO_4, t–butyl alcohol, dioctyl sodium sulfosuccinate and sea water). As expected, the presence of these solutes resulted in the development of a interface consisting of $<11\bar{2}0>$ dendrites that grow perpendicular the c–axis. Perhaps the most surprising result of these studies was the fact that some crystals were composed of dendritic arrays oriented parallel to the c–axis. It was also observed that, although some of the initial crystals were eliminated by geometric selection, the majority of the surviving grains had their origin in the initial ice layer. The two primary surviving orientations consisted of either basal plane cells or c–axis cells with no apparent indication that one orientation had an appreciable growth advantage over the other. We note that arrays of c–axis cells have not, to date, been reported in naturally grown sea ice. This suggests that although such growth can be forced to occur in the laboratory, under naturally occurring conditions the more readily formed basal plane dendrites are always dominant.

The second set of experimental studies has just recently been published by Wilen and Dash [40] who grew ice in the form of a thin disk as shown in Figure 4. By controlling the temperatures at both the center of the disk and around the perimeter of the growth cell, it was possible to independently vary both the radius of the ice disk and the radial temperature gradient. Ice growth was nucleated at the center of the cell. Two very different types of grain boundary grooves were noted as schematically shown in Figure 5. Grain boundary groove (b) is "classical" in that it correctly corresponds to the capillary length and is typically rounded (see the discussion in [40 and 41]). On the other hand, grain boundary groove (a) not only has linear dimensions that exceed the expected 'capillary length' values by a factor of 30 but is comprised of facets of the basal (0001) plane. Furthermore, the facet size was not a single-valued function of the temperature gradient but showed considerable hysteresis in size as the ice–water interface advanced and retreated. Finally, the facetted grooves were not rare, typically comprising 10 to 20 % of the total number of grain boundaries.

In order to understand the essential concepts for interpreting the Wilen and Dash experiments, we distinguish two relevant growth regimes: *interface controlled* and *diffusion–limited*. In the former case, the interfacial growth velocity is controlled solely by local surface parameters and is decoupled from diffusional or other long--range influences. In the latter case, the removal of either heat or impurities limits the motion of the interface.
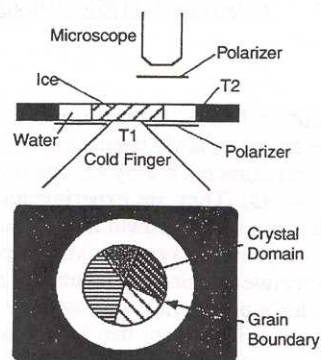

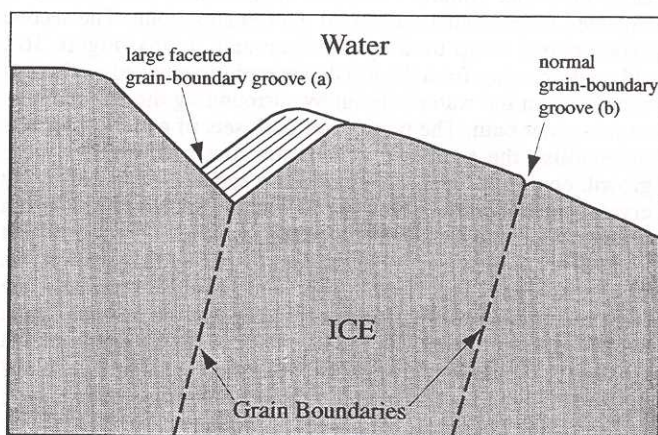Figure 4. The freezing arrangement utilized by Wilen and Dash [40]

Figure 5. A schematic drawing of a facetted grain boundary groove (A) and a typical rounded groove (B) occurring at adjacent grain boundaries. Although the drawing is based on a photograph presented by Wilen and Dash [40, Fig. 2], here the exact positions of the grooves have been rearranged slightly for a clearer presentation. The size of the imaged area is 0.35 x 0.23 cm.

Wilen and Dash's experiments indicate that both of these growth types can occur simultaneously, in analogy to the partially facetted growth of convex single crystals [23]. Growth normal to facets by addition of monomolecular layers occurs primarily by the lateral motion of steps across the surface [42–43]. Hence, the normal growth rate is limited by the generation of step sources for new layers, and defect and dislocation free facets have available only one step generation mechanism; the two-dimensional nucleation of solid clusters. (Normally, other step generation mechanisms such as screw dislocations, or Frank-Read sources may also be important.) The formation of a nucleated step source requires the coalescence of molecules in a cluster, or pillbox, for which the edge to surface free energy ratio will favor spreading at a given undercooling. The generation of new layers is a thermally activated process with a nucleation frequency I per unit facet area A of the typical Maxwell-Boltzmann form, $I = \exp\left(\frac{-\gamma_n}{\delta T}\right)$ where γ_n is related to the free energy of a critical nucleus on the facet, and δT is the undercooling (for more detail see [40]). Thus, for a lattice plane spacing of $\hat{a}$, the normal growth rate at faceted orientations is $V_f = \hat{a} I A$. In experiments on the growth rate of ice perpendicular to a dislocation–free basal plane, Hillig [26] observed this growth mechanism in a range of undercooling from 0.03°C to 0.2°C. For $\delta T < 0.03$°C there was no measureable growth. At

molecularly rough surface orientations, steps are already present so that growth occurs by random incorporation of molecules from the liquid onto the solid surface. In this case, the entire interface continuously advances normal to itself in the presence of *any* finite supercooling, and the velocity is linearly related to the supercooling; $V_r \propto \delta T$ [42–43]. In the initial stages of the Wilen and Dash experiments, the supercoolings are below the threshold value for nucleated growth, and therefore growth can only proceed in the 'rough' direction parallel to the basal plane. In this manner the overall radius of the polycrystalline disc increases as does the length of the basal oriented grain boundary facets. As growth proceeds, the size of the groove becomes sufficiently large to push the undercooling at the vertex beyond the threshold value for nucleated growth normal to the basal planes. Once growth perpendicular to the basal planes ensues, the maximum groove size is achieved with the groove advancing at the same velocity as the bulk interface. When their experiments were repeated using different temperature gradients, it was found that the maximum facet size was inversely proportional to the temperature gradient and that the apparent threshold temperature was in the range of the value determined by Hillig [26].

The fact that the geometry of the Wilen and Dash experiment caused each facet to be bounded by both a foreign substance (the cell window) and the other facet allowed an examination of the question of whether the facet faces were growing via homogeneous or heterogeneous nucleation. To within the experimental resolution, the maximum supercooling was the same for both faces. Therefore, the velocity ratio of the two faces determined the direction of advance of their intersection. If it is assumed that the velocity of each face is given by an independent nucleation process and that the prefactor multiplying the exponential is the same for both faces, this velocity ratio is given by

$$\frac{V_1}{V_2} \propto \exp^{\frac{(\gamma_1 - \gamma_2)}{\Delta T}}$$

However, because of the configurational entropy associated with the reorganization of molecules from the parent phase to the solid surface cluster, there remains the possibility that an undercooling dependent prefactor will differ between the facets [44]. In the above, γ_1 and γ_2 are related to the specific nucleation barriers on the individual facet planes. If homogeneous 2–D nucleation is occurring $V_1 = V_2$ and a specific direction of facet growth should occur. For heterogeneous nucleation, $\gamma_1 \neq \gamma_2$ and the velocity of one of the planes should predominate resulting in the intersection between the facets moving in a different direction. The experimental results are shown in Figure 6. It was found that when the temperature gradient was increased rapidly resulting in a fast advance of the interface, the facets grew in a purely radial direction; the expected result for a growth rate limited by the dissipation of latent heat. For slow growth the growth direction veered toward a new direction which appeared to be rate independent. However, the direction is not the value that would be obtained by assuming that either pure homogeneous or heterogeneous nucleation dominates the process. As a result Wilen and Dash speculate that the growth process for each plane is not independent of the other and is in some way controlled by their common boundary. The question of how the motion of the groove depends on the common boundary between the facets is tied to understanding the detailed structure of the grain boundary itself [45]. Whether the nucleation on one facet is coupled to that on the other is the focus of current research (Wilen et al., pers. comm.).
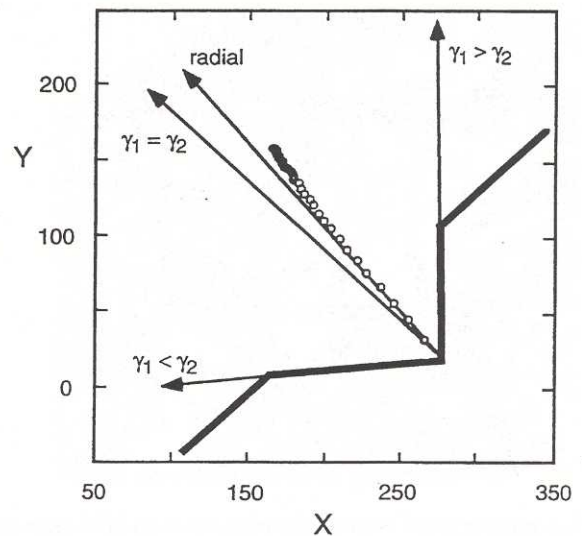

Figure 6. The position of the vertex of a faceted grain boundary groove plotted at equally spaced time intervals [40]. Also indicated are the theoretical directions for homogeneous nucleation ($\gamma_1 = \gamma_2$) and for heterogeneous nucleation ($\gamma_1 \neq \gamma_2$). Although the position of the vertex initially moves rapidly in the radial direction, as growth slows the motion of the vertex, it gradually changes to a new direction.

Sea Ice

Experiments relating to simple geometric selection in sea ice are less common in spite of the fact that this is a fascinating feature of this ice type; that it posesses such uniformity of crystal fabric. Clearly the primary growth orientations that develop are less varied than in lake ice with the elongated crystals that survive geometric selection invariably having their c–axes oriented parallel to the plane of the growing interface [i.e., the easy growth direction parallel to the basal plane is always aligned parallel to the direction of heat flow]. This was first pointed out by Perey and Pounder [12] and by Weeks [38] with the general process being schematically as shown in Figure 1. In this figure c–axis horizontal crystals are shown as growing significantly ahead of competing crystals that have more nearly vertical c–axis orientations. These differences can reach several millimeters in thin ice skims. A demonstration of this phenomenon can be seen in Figure 7 which is a simple soft pencil and paper rubbing of the underside of an ice skim. The tick marks represent locations where the paper encounters the edges of the basal platelets of ice that combine with the interplatelet films and pockets of brine to comprise the individual sea ice crystals. The blank spaces represent the locations of crystals that have their c–axes oriented nearly vertically and are therefore recessed relative to the other crystals [46]. In the context of Figure 7, we note that, as described earlier, the morphological instability responsible for the substructure formation actually enhances the geometric selection process because it allows the highly anisotropic growth of ice single crystals to work in concert with the competition between crystals. We will return to this issue when we present our own theories for fabric development.

In sea ice the interesting problem has not been the development of the primary c–axis horizontal orientation but the fact that after this orientation has developed, a secondary c–axis alignment has frequently developed, particularly in fast ice areas [i.e., not only are all the c–axes horizontal but they all point in the same direction]. The occurrence of these striking alignments as well as of the fact that large areas of sea ice can have similar alignments
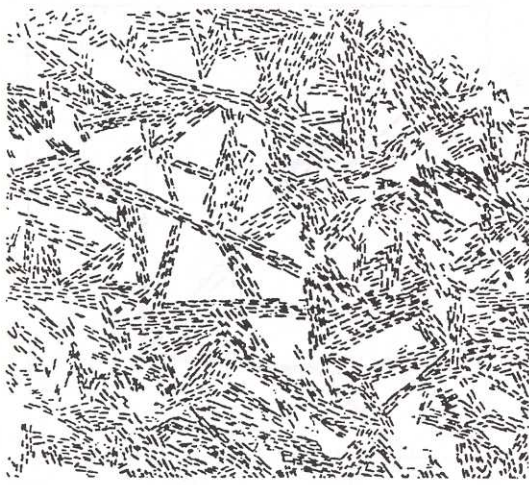
Figure 7. A rubbing of the bottom surface of a 2.5 cm thick skim of sea ice as observed at Hopedale, Labrador, 1955. The blank areas in the rubbing represent the locations of individual crystals that are oriented with their c–axis approximately vertical (⊥ to the plane of the rubbing) and that are recessed relative to the position of the general interface as established by crystals with their c–axes horizontal.

on a spatial scale of tens to even hundreds of kilometers was first reported by Cherepanov in 1971 [47] although the phenomenon had been reported earlier as a local oddity [5, 48–49]. Several different theories have been advanced to explain such alignments. The currently accepted explanation is that the c–axis alignment direction is controlled by the average current direction at the ice–seawater interface through a hydrodynamic mechanism that results in crystals with their c–axes oriented parallel to the current having less solute buildup at the tips of the dendritic plates that comprise the individual ice crystals [50–51]. This, of course, translates into a slight growth advantage for these crystals leading to the development of the alignment as a secondary effect (it commonly requires several 10s of centimeters of ice growth for these alignments to fully develop).

Sea ice related experiments performed in flumes have, to date, focused on attempting to verify the suggested correlation between the c–axis alignment and the current direction. The results have verified the suggested correlation [52–56], although details of the mechanisms involved remain speculative [18]. Of particular interest here is one aspect of the experimental results reported by Stander and Michel [54]. They varied several different conditions in the following ranges (air temperature –5 to –20°C; salinity 0.7 to 32 ‰ (NaCl); nominal flow velocity 0–6 cm/sec). They found that all tests conducted at salinities greater than 1 ‰ resulted in the crystals rapidly increasing in size and developing a pronounced growth alignment with the fastest growth occurring along the basal planes that were oriented perpendicular to the flow direction at the ice–water interface (i.e., c–axes oriented parallel to the current, Figure 8A).

However, once salinities dropped below 1 ‰, quite different results were obtained. Specifically these ice sheets exhibited a 2 to 6 cm columnar zone in which the ice crystals were equiaxed in the horizontal plane. Below this zone, exaggerated growth was observed in the horizontal plane in those crystals oriented with their basal planes parallel to the fluid flow direction at the interface resulting in a strongly preferred orientation (i.e., c–axes oriented perpendicular to the flow, Figure 8B). Crystals not oriented in this direction remained equiaxed. This immediately raises the question, "What happens at salinities of < 1 ‰ to cause

such a change?". It has been shown that, for a given growth velocity, the stability of a planar growth front is enhanced by decreasing the salinity of the solution and by increasing the solutal segregation coefficient (the ratio of the solute in the solid to that in the liquid), which together, suppress constitutional supercooling [39]. This result is embodied in Figure 9. The answer is that, at the growth velocities typically encountered in natural ice sheets, 'sea ice' forms from NaCl solutions more saline than 1 ‰ while lake ice forms from less saline solutions [57]. That is to say that a planar interface appears to be stable if the solution salinities are < 1 ‰ while a cellular interface forms if salinities are greater than this value. Russian field observations concerning the formation of real sea ice place this transition salinity at a slightly higher value of 2 ‰ [58]. As can be seen in Figure 8, the differences in the resulting favored crystal orientations could hardly be more striking. Stander and Michel do not attempt to develop a mechanistic model to explain why this orientation change occurs other than noting that the favored orientation now has the basal plane oriented parallel to the current.
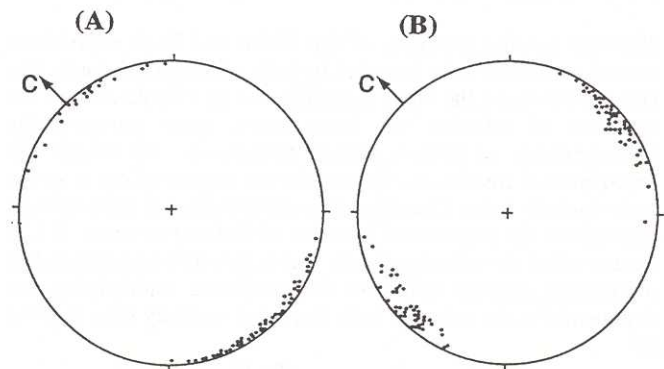

Figure 8. C–axis plots (Schmidt equal area net, lower hemisphere) of the crystal orientations obtained in two freezing runs in a cylindrical flume. The arrows indicate the direction of fluid flow. The ice shown in plot (A) formed from a NaCl solution with a salinity of 25‰ while the ice in plot (B) formed from a solution with a salinity of 0.7 ‰ [54].

The final experimental study that should be mentioned is by Kawamura [59] who studied geometric selection in sea ice crystals by initiating 1-D growth of artificial polycrystalline fresh water ice seeds which were produced by welding together rectangular blocks of single crystals that have known crystallographic orientations. The growth direction was oriented parallel to the grain boundary in the seed. Experiments were carried out with growth rates varying from 0.5 mm/hr to 2.0 mm/hr and salinities from 8 ‰ to 32 ‰. Hence, in all cases morphological instability created a non–planar interface in direct analogy with the typical sea ice substructure. A schematic diagram of the first of three types of c–axis arrangements that were studied is shown in Figure 10A. Here the c–axes were arranged in a vertical plane that was oriented perpendicular to the grain boundary. It was found that for orientations where both crystals could expose their basal planes in the grain boundary groove, (i.e., zones I and II as shown in Figure 10B), the encroachment angle β (the angle measured between the grain boundary and the vertical axis z) was given by the mean value of the c–axes inclination angles α_1 and α_2 of the two grains as shown in Figure 10C. This is the result to be expected if the two exposed basal planes both advance at the same growth rate as measured parallel to the c–axis.
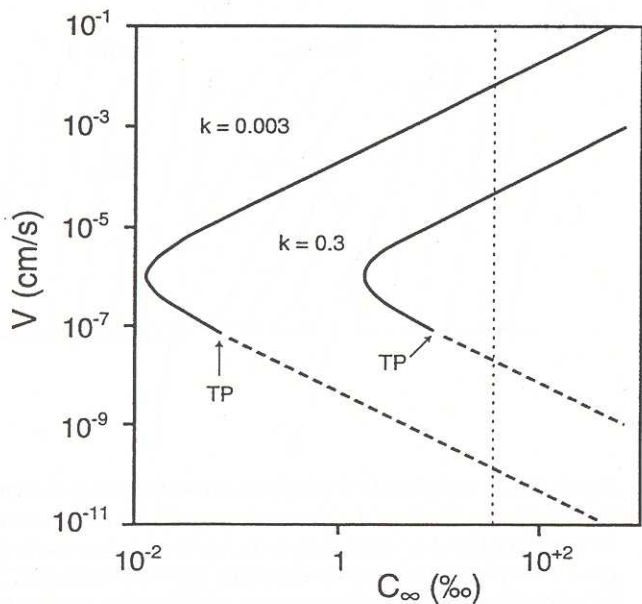
Figure 9. The two theoretical curves represent the boundary between a linearly stable planar ice / saltwater interface and an unstable cellular interface, growing at a mean rate of V (cm/s) into a solution with an initial concentration of C_∞ (‰). Curves are shown for two segregation coefficients, k, which represent the ratio of the solute concentration in the solid lattice to that in the liquid at very small growth rates. For either curve one imagines fixing the salinity and increasing the growth rate. Then, as one crosses the curve, the planar interface undergoes a diffusive instability (see text) and becomes cellular. [The dotted vertical line denotes a typical salinity value of Arctic Ocean surface water, $C_\infty = 35‰$.] Thus, the region to the right of curve depicts the region of instability and to the left stability. If one crosses where the curve is solid, the evolution from planar to cellular is well described by linear perturbation theory, and there is a continuous evolution of disturbances at the interface. If one crosses the dashed region of the curve, there is a "jump" transition, or sub-critical bifurcation, from a planar to a finite amplitude cellular interface that is not well described by linear perturbation theory. The transition point between these behaviors is denoted by TP (for more detail see [39]).

When the basal planes of both crystals were not exposed (zones III and IV in Figure 10B), the situation is somewhat different. However, Kawamura found that the measurements supported the following model. Assume that the preferred crystal (grain 1 in Figure 10D) is the one with its c–axis nearest to horizontal in that in sea ice this is the orientation that places both the easy (0001) growth direction as well as the direction of maximum thermal conductivity oriented parallel to the direction of heat flow. It should be noted that this latter statement is true even though the thermal conductivity of pure ice may be very slightly higher parallel to the c–axis than perpendicular to it [60]. This seemingly odd reversal is the result of the fact that sea ice is a layered composite of both brine and ice [61] and the thermal conductivity of pure ice is significantly higher, by a factor of 4, than that of brine. It then follows that grain 1 will grow slightly ahead of grain 2 thereby limiting its lateral growth. Furthermore, if the lateral edge of the growth step is the basal plane, then the grain boundary direction is specified by the c–axis inclination angle of the preferred grain or simply $\beta = \alpha_1$. It should be noted that, as shown in Figure 10D, the grain boundary is inclined toward grain 1 even though its c–axis is nearest to horizontal. At first glance this would appear to contradict the common field observation that the crystals that survive to the bottom of the ice sheet are those with their c–axes closest to horizontal. However, there are

cooperative effects as also shown in Figure 10D. If a crystal having the same orientation as grain 1 is also placed to the left of grain 2 , thereby forming a zone II type grain boundary with an encroachment angle $\beta = (\alpha_1 + \alpha_2)/2$, the fact that the β for this zone II grain boundary is always greater than for the zone III boundary ($\beta = \alpha_1$) ensures that grain 2 will be cut out.

Experiments were also carried out in which the c–axes of the adjoining crystals were both horizontal and at right angles to each other. In these cases geometric selection occurred with the center crystal being cut out. Even when the platelets of the neighboring crystals were in contact with each other at angles other than 90°, the β values observed were similar to those obtained when the c–axes were at right angles to each other. Within the growth rates and salinity ranges studied, which were always sufficient to produce a sea ice substructure, changes in the environmental conditions did not appear to effect the geometric selection rules. In the theoretical section, we detail the manner in which the Wilen and Dash experiments explain several important features of the Kawamura experiments, and thus represent a natural laboratory for sea ice studies.
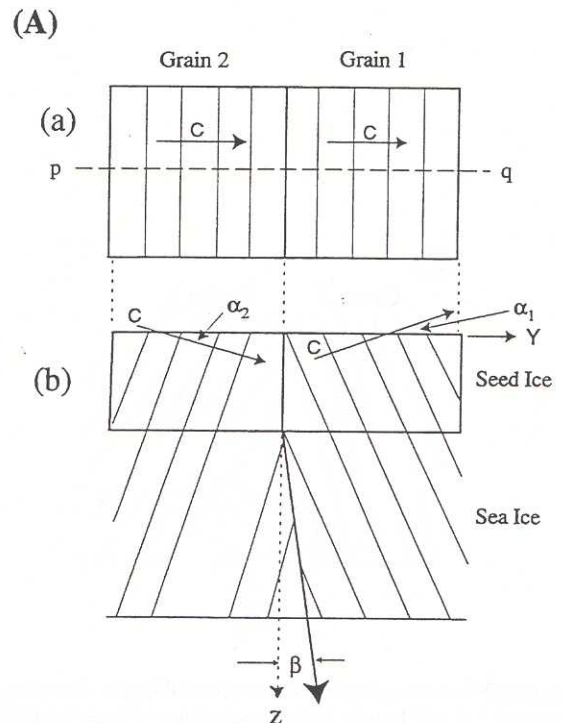
(A)

Figure 10A. Grain boundary encroachment as seen in sea ice [59]. (A) C–axis arrangements in both the seed crystals of orientation type I and in the sea ice grown from the seeds where (a) is the top view of the seed and (b) the cross–sectional view of both the seed and the subsequent sea ice. The thin sets of parallel lines can be taken to represent either the traces of the (0001) planes in the ice crystals or the plate–like substructure characteristic of sea ice. The inclination angles between the c–axes and the horizontal plane and between the vertical and the resulting grain boundary are given by the αs and β, respectively.
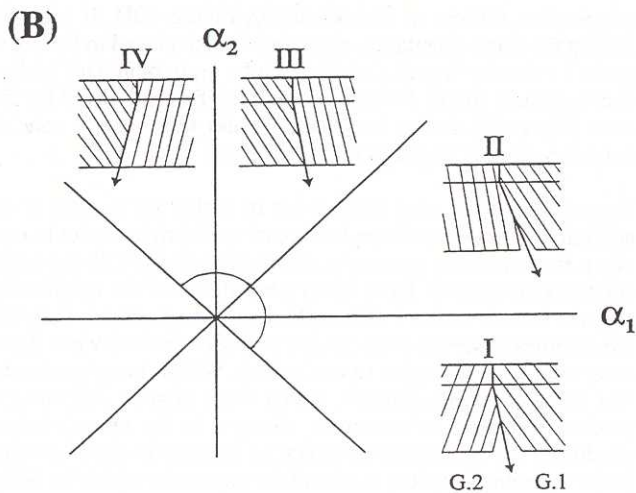
(B)

Figure 10B. The four possible types (zones I to IV) of intragrain contact and the associated direction of grain growth, as indicated by the arrows, based on the values of both α_1 and α_2. As in Figure 10A, the parallel lines represent the basal planes as projected onto the vertical cross–section.
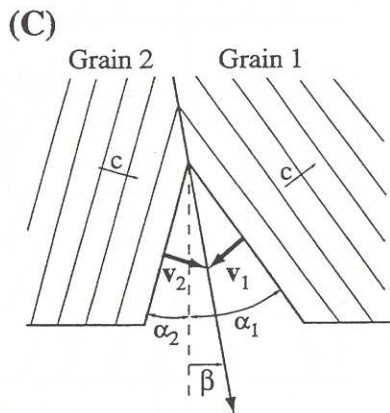
(C)

Figure 10C. A more detailed schematic of the grain boundary groove in zones I and II in which the basal planes of both crystals can be exposed. If it is assumed that the basal planes of both crystals advance at the same rate ($V_1 = V_2$) in the direction parallel to their c–axes, then with subsequent ice growth the grain boundary will advance in the direction of the arrow.
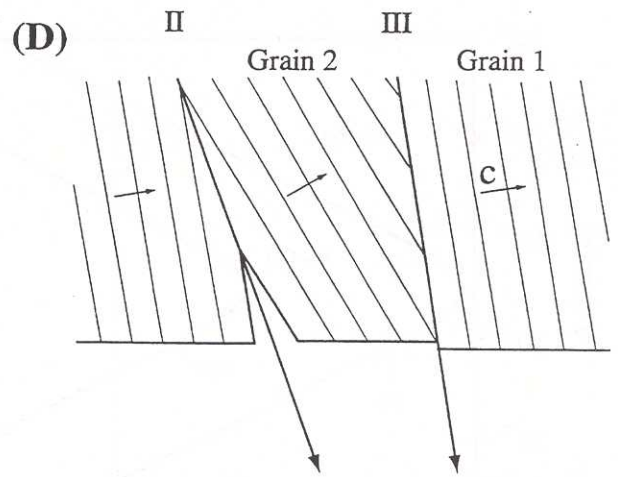
(D)

Figure 10D. The right side of this figure shows the intragrain contact features in zone III. Here, it is assumed that grain 1 is able to advance very slightly ahead of grain 2. Note that grain 2 is encroaching on grain 1 even though grain 1's c–axis is the closest to horizontal. The left side of the figure also shows a grain with the orientation of grain 1 in contact with grain 2 at what is now a type II boundary. Note that grain 2 is being cut out even though it is able to encroach on grain 1 at the type III boundary.

Field Observations

Lake Ice

The literature on the structure of lake ice, although small, is sufficient to tell us what typically occurs in nature. The first extensive study of this subject was carried out on a series of lakes located in Michigan by Wilson, Zumberge, and Marshall [62] who, in contrast to the experimental results of Ketcham and Hobbs and of Ramseier [33, 35] observed that c–axes vertical crystals invariably cut out c–axes horizontal crystals. Their suggested explanation was that pure ice crystals have a higher thermal conductivity parallel to the c–axis than perpendicular to it therefore favoring crystals growing with their c–axes vertical.

Within a few years other workers found that Mother Nature was not so straight forward with Barnes [63] reporting c–axes horizontal orientations at Angiussaq Lake in NW Greenland and Ragle [64] describing similar orientations on Post Pond in New Hampshire. At about the same time, Swinzow [65] found c–axes vertical orientations on a lake near Camp TUTO, Greenland located roughly 60 km to the SSW of Barnes' study site. Work by Knight [66] in 1961 on Peters and Shrader lakes located on the North Slope of Alaska added to the complexity; he clearly demonstrated ice areas with both orientations coexisting in the surface ice layer on the same lake and suggested that these differences were related to variations in wind velocity during the time period when the initial ice skim was forming. This conjecture is strongly supported by his first figure [66, Figure 1] where the spatial distribution patterns of the surface ice types are clearly those that *could* be produced by changes in wind velocity. However, independent of the near–surface crystal orientations, all the ice deeper than 60 cm beneath the surface on Peters Lake and below 15 cm on Shrader Lake were found to have horizontal c–axes. Knight found no indication of the nucleation of new crystals below depths of 15 cm and concluded that the preferred orientation developed by geometric selection. Knight also noted that there appeared to be reasonable agreement between his observations and a growth model initially advanced by Shumskii [67] which will be described in our next section.

344

The most informative study of the crystallographic aspects of natural lake ice covers is the eleven year investigation (1974–1984) by Gow [31] of six northern New England lakes that froze during calm conditions. These lakes included Post Pond that was studied earlier by Ragle. Surprisingly where Ragle had observed c–axes horizontal as the favored orientation, Gow observed c–axes vertical for 11 consecutive years. In fact, of the 58 ice sheets that he examined 48 (83%) possessed c–axis vertical crystal orientations with the remainder possessing c–axis horizontal orientations. Furthermore there was an exact correlation between the ice type and the orientation with so–called S1 ice composed primarily of massive, irregularly shaped crystals demonstrating c–axis vertical orientations and S2 ice composed of vertically elongated crystals showing horizontal c–axes. In addition, as was the case with Post Pond, some of the lakes developed S1 orientations during some years and S2 orientations during other years. Furthermore, it was observed that if the initial ice layer was seeded naturally producing a fine grained, presumably randomly oriented initial ice skim, S2 ice with c–axes horizontal orientations invariably resulted. However, if the ice skim was allowed to nucleate spontaneously, S1 ice with vertical c–axes formed. As noted earlier, Gow concducted laboratory experiments in which the initial temperature of the entire water column was varied from just below +4°C to 0°C concluding that the initial temperature of the underlying water did not appear to exercise any significant effect on either the crystal size or the crystal orientation of the resulting ice sheet.

Russian observations of lake ice structure as reported by N. V. Cherepanov and his associates at the Arctic and Antarctic Research Institute [58, 67–70] are very similar to those of Gow but, as will be seen in the theory section, the explanations of the field observations are very different and to some degree contradictory.

Finally it should be noted that there is one reported field occurrence [71] of horizontal c–axis alignments that are oriented perpendicular to the current direction in a river. This observation is consistent with the experimental observations mentioned earlier by Stander and Michel [54]. The fact that such an occurrence has only been noted once does not necessarily mean that it is atypical of congelation ice formed in rivers. We speculate that the rarity of the observation is more the result of the fact that simple congelation is itself rare on rivers as compared to frazil ice and that observations of c–axis orientations on such ice are even rarer.

Sea Ice

The field observations on sea ice are very consistent. In columnar–congelation sea ice the favored c–axis orientation is always c–axis horizontal. It is also clearly independent of the nature of the initial ice skim. It should be noted that the observations made by Knight [66], that in Arctic lake ice there was no evidence for the introduction of new crystals into the ice sheet after the first few centimeters of ice had formed, does not apply to sea ice. New crystals with a variety of orientations and particularly with c–axes vertical are regularly being introduced into the overlying ice sheet. The process is commonly as follows. These crystals initially form in the water column probably associated with the drainage of cold brine from brine drainage tubes [72]. They subsequently float upward where, after they become frozen to the base of the growing ice sheet, their subsequent growth is terminated by geometric selection as they are rapidly cut out by the surrounding c–axis horizontal crystals that already exist at the base of the sheet.

The only complication is whether the final orientation will have all the c–axes aligned in a specific horizontal direction or randomly distributed in a horizontal girdle. There have now been a fair number of field studies of this phenomenon [47, 50–52, 56, 73–74] and the results are as would be expected in that the c–axis directions correlate with the mean direction of the underlying current. This appears to be true even in regions of pack ice if there is only limited rotation of the floes and the current direction relative to the ice is reasonably constant. However, numerous questions remain concerning this process. For instance, in fast ice areas with an appreciable tide, the current direction at the ice–water interface is definitely not constant. Yet the c–axes alignment directions appear to represent some sort of a temporal average direction. Perhaps more perplexing is the fact that, in almost every field study of this phenomenon, sites are found where alignments might be expected based on the oceanographic setting and yet the c–axis orientations in the horizontal plane are found to be random. Clearly missing to date is one or more field sites where ice growth observations, crystal orientations, and under ice current profiles are observed with sufficient resolution during a significant portion of the sea ice growth season.

Current Theories

Can one provide a consistent explanation of all of the above experimental and field observations? In the following we discuss some of the explanations that have been advanced to explain such phenomena, particularly in lake ice.

1) The favored crystal orientation has its direction of maximum thermal conductivity oriented parallel to the direction of maximum heat loss.
If for pure ice the thermal conductivity parallel to the c–axis is slightly greater than the value measured perpendicular to this direction (Landauer and Plumb were unable to observe a measureable difference [60]) and remembering that in sea ice, because of the layered nature of the incorporation of brine, the bulk thermal conductivity normal to the c–axis becomes larger than the parallel value [61], this combination of changing values can be invoked to explain c–axis vertical orientations in lake ice [62] and the c–axis horizontal orientations in sea ice. However it is unable to explain the occurrence of c–axis horizontal orientations in lake ice.

2) The favored crystal orientation has its easy growth direction oriented parallel to the direction of maximum heat loss.
It is a fact that when ice crystals form in either pure water or in sea water that is either at the freezing point or slightly supercooled, the easy growth direction is in the basal plane. Such an easy growth direction would readily explain c–axis horizontal orientations in both lake and sea ice. However alone it is incapable of explaining c–axis vertical orientations in lake ice. We also suggest that there is no field evidence to support the obvious corollary that would follow from the easy growth direction parallel to the direction of maximum heat loss mechanism; that in lake ice covers, if growth continues long enough, c–axis horizontal orientations will always dominate. Numerous ice sheets have now been described where in the upper part of the sheet c–axis vertical growth not only rapidly cuts out crystals having other orientations but remains the dominant growth mode throughout the complete freezing season. Clearly during the freezing of lakes there are growth conditions under which c–axis vertical growth has a stable advantage. In addition, it appears that the conditions necessary to maintain this advantage can remain dominant for periods of months. Any reorientation requires additional effects.

3) The favored orientation is completely specified by the crystallography of the initial ice skim.

This explanation is suggested by Gow's observations [31] that certain types of initial ice skims uniquely result in certain favored crystal orientations. Although we accept this correlation at face value and we note that it also is supported by Russian observations [58], we do not believe it to be an explanation of the different orientations that are observed in lake ice. Our reasons are as mentioned earlier in that in initial ice skims there is good evidence that a wide variety of crystal orientations exist. This is particularly well documented in S1 sheets of lake ice where the needle–like crystals that form the initial network, within which the c–axis vertical crystals develop, invariably show inclined c–axes. If the favored orientation is already available and if growth parallel to the basal plane is always favored then such ice skims should ultimately result in c–axis horizontal orientations. However, as we have illustrated, this is not the case.

We speculate that there is another way to look at Gow's correlation. This is that the environmental conditions that allow the development of an S1 type of ice skim are exactly those which allow c–axes vertical crystals to become dominant. The question then becomes. "What are these conditions?".

4) The favored crystal orientation is controlled by the thermal characteristics of the underlying water body.

The above suggestion has been favored in the Russian literature for a number of years. The initial suggestions along this line appear to have been advanced by Shumskii [67] and, as noted earlier, were favored by Knight [66] in his discussion of orientations in arctic lake ice. The expansion and clarification of Shumskii's ideas as well as the collection of additional ice orientation observations have been carried out by N. V. Cherepanov and co–workers at the Arctic and Antarctic Research Institute [58, 68–70, 75]. The following discussion summarizes their work, particularly as described in reference [58]. They have found that on fresh–water bodies large plate–like crystals with vertically oriented c–axes are particularly common when air temperatures are only slightly below freezing (0.0 to –5.0°C) and when the temperature gradient in the 3 to 4 cm thick surface layer of the water is less than 0.01°C/m. When, during the formation of the initial skim the air temperatures are colder than –10°C and the temperature gradient in the surface water layer is larger, the c–axes orientations in the initial skim tend to be more random and the grain sizes appreciably smaller. Their observations relative to the crystal orientations in initial ice skims are qualitatively similar to Gow's [31].

They suggest that once constrained (orthotropic) growth is initiated, c–axes vertical orientations will form if the near surface portion of the water is stably stratified. Under such conditions the ice–water interface is assumed to be constrained to be both flat and smooth by the position of the 0°C isotherm. This control removes any growth advantage associated with horizontal c–axes orientations as such growth would cause the more rapidly growing crystal to protrude into water that is above the freezing temperature. The grain boundary groove between crystals of differing orientations will then be asymmetric with the crystal that exposes the lower energy surface (the basal plane) to the solid–liquid interface having a lateral growth advantage leading to c–axes vertical orientations. This argument resembles a theory advanced some years ago by Bolling and Tiller [76] to explain preferred orientations observed in metals. In addition, even if the positive temperature gradient (downward) in the water column is quite small (a few hundredths of a °C/m) similar c–axes vertical orientations can apparently result but only when the air/water temperature differences are small (1–4°C). When air/water temperature differences are larger than such values, a slight

roughness begins to develop on the ice water interface and apparently vertical, horizontal or even intermediate c–axes orientations can occur. However, if the water temperature is either exactly at the freezing temperature or perhaps even slightly supercooled, then the thermal restraint on the direction of easiest growth is removed and c–axis horizontal crystals with their basal planes oriented parallel to the direction of heat flow (c–axes horizontal) are able to gain the growth advantage even in lake ice.

There are several interesting aspects to this theory. First it is consistent with the fact that sea ice always shows c–axis horizontal orientations because, as we discussed at the start of this paper, the density–composition variation for water with salinities >24.7‰ always produces water temperature profiles that are either at freezing or slightly supercooled. Furthermore the inclusion of liquid layers of brine into sea ice causes the thermal conductivity of the composite crystal to be greatest parallel to the basal plane which also corresponds to the easy growth direction from a kinetic point of view. These observations are consistent with the horizontal c–axis orientations observed in sea ice.

Although observations on ice that has formed from brackish water with salinities in the compositional range 2 to 24.7‰ are to date quite limited, observations in the low salinity region of the northern Bay of Bothnia [77] as well as experimental studies on the freezing of NaCl solutions in a similar compositional range [57] suggest that, if the composition of the freezing solution is sufficient to result in the development of a non–planar interface and the associated entraping of brine, c–axes horizontal orientations will always result. As noted earlier in this paper, the compositional boundary associated with this change is in the range of 1‰ (for NaCl) to 2‰ (for seawater based on Russian field observations). It would be interesting to check to see if the salt rejected during the freezing process is adequate to drive sufficient local convective activity to destroy any positive temperature gradient in the boundary layer just below the ice thereby producing conditions favoring horizontal c–axes orientations even though these bulk compositions in the 1–2‰ range are well below the 24.7‰ cross–over point seen in Figure 2.

To date the ideas of Cherepanov and his associates have not been widely accepted in the 'West'. This is surprising considering that their ideas offer the possibility of explaining both the consistent orientations in sea ice as well as the odd flip-flops observed in lake ice. Several concerns are as follows. First their results have only been presented in a very general way without a detailed documentation of either their temperature measurements or their resulting crystallographic observations. Second, experiments demonstrating that the postulated changes in temperatures do actually result in c–axes orientation shifts have not, as yet, been reported although we have been informed that such studies are currently underway. However, the biggest roadblock to acceptance is the work of Gow [31] who froze several tanks of water with different initial temperatures and observed no effect on the resulting orientations other than that caused by seeding. However, it should be pointed out that Gow's experiments are equally ambiguous in that the water temperature when the tanks were filled is, in our view, of little importance. What is of importance are the details of the temperature profiles in the water column when and after the initial ice skim forms and the preferred orientation develops. In short, we believe that Gow's observations do not necessarily disprove the Russian explanation. Clearly additional experimental studies are needed.

Conclusions

In the preceeding sections we have attempted a through review of the work on crystal orientations in lake and sea ice. In doing so we have pointed out every apparent inconsistency we could find in the various explanations that have been offered. However, it is only reasonable that the reader ask, "What do you think?". Our attempt to answer this query follows.

As a start, it is helpful to collect the features that the two systems of interest here, lake and sea ice, have in common and share with features observed in entirely different materials. For instance, we know that under certain conditions the initial layer of ice that forms on both lakes and seas can consist of very small equiaxed grains. This layer is analogous to the "chill–zone" found adjacent to the cold walls of an alloy casting mold where the issue of crystallographic structure has captured metallurgical attention for decades [e.g., 14, 78]. Although there is no universal theory that explains the diverse observations of grain refinement, it is a generic growth process that some grains survive and some do not. Those that do survive are often distinguished by an elongated (with respect to the growth direction) columnar structure. Furthermore, there is a gradual increase in mean grain size with increasing distance from the initial layer because crystals in less favorable orientations are gradually eliminated. Although many of the basic growth processes at play in ice sheets have been studied in entirely different contexts by metallurgists [79], we believe that to understand the fabric differences in floating ice sheets, one must be concerned with the manner in which the particular kinetic processes of ice conspire with the thermodynamic growth conditions to either suppress or enhance the probability that a given crystal grain will survive.

Let us think from the perspective of a controlled laboratory experiment which considers the growth of ice from a series of aqueous solutions. Each new experiment will consist of solidifying a solution of a new salinity. In such a series "lake ice" would be considered to be either the zero salinity limit or ice that has formed from a solution containing a sufficiently small amount of impurity so that a planar ice–water interface is stable. It is difficult to conceive of an experiment whereby we could observe the transition from lake to sea ice fabrics as a function of only one variable, for example salinity, while all the other relevant parameters remain fixed. An important reason for this difficulty concerns the coupling between hydrodynamics, especially those driven by compositional changes, and solidification [e.g., 80]. We nevertheless believe that the essential features of the diverse observations we have summarized above can be captured in the context of a simple conceptual experiment.

We envisage an experiment in which one varies the initial concentration of a solution while keeping the overall thermal forcing fixed. We consider the growth of ice from a horizontal boundary with a temperature, T_B, in the classical Stefan scenario, and by a constant thermal forcing we refer to fixing $(T_B - T_m(S)) / T_B$, where $T_m(S)$ is the liquidus temperature of a solution with initial salinity S. Hence, one must reduce T_B as S increases, but over the range of interest we need only vary the former by about 2°C. Although only the initial salinity is varied, observed fabric changes will not be due solely to the kinetic and thermodynamic effects of impurity content, because the mode of heat and mass transport is largely determined by compositional convection.

Lake Ice: As described previously, what is lacking is a systematic investigation of the interaction between the crystallographic orientation of the surface layer and the thermal conditions of the water column. One essential distinction between the lake and sea ice situations has to do with the latter effect because as we have seen from Knight's (1962) work [66], if conditions are sufficiently agitated, a layer of equiaxed crystal grains can form at the surface and horizontal c–axes may develop. Field observations on lakes make it a safe assumption that the most common initial situation is quiescence (initial ice skims commonly form on clear, calm nights that are conducive to large long–wave radiative losses) so that the water surface is seeded by a random distribution of crystals deposited from the atmosphere. The areal density of particular orientations is generally important, and the field conditions determine the initial density. Our argument need only show the advantage of one orientation over the other. Because the temperature of maximum density is +4°C, under calm conditions the surface of a lake is strongly stably stratified, and can therefore become supercooled over a depth, δ, that is primarily controlled by molecular heat conduction. Since below this depth, the water is at or above the freezing point, ice growth is limited by the thickness δ, which is itself controlled by the heat loss to the atmosphere and the heat gain from the underlying water. At a depth $z = \delta$, $T = T_m$ providing the thermal boundary to crystal growth. Such an effect was what limited the growth forms observed by Arakawa and Hallett, and what was alluded to by Cherepanov and colleagues. We view it as a necessary condition for vertical c–axis fabric development. Imagine that the angle that the c–axis deviates from the vertical, ψ, can be drawn from a random distribution. With some probability a nonvertical c–axis crystal will occupy an 'area' (per unit length) $A_\psi = \delta / \tan \psi$. Under typically small supercooling, growth in the basal plane is orders of magnitude greater than that parallel to the c–axis, so we expect a greater percentage of the total area of the initial layer to be occupied by crystals with vertical c–axes. [In the supercooling range $\delta T < 0.03°C$ growth parallel to the c–axis does not occur while for δT between 0.03 and 0.2°C, growth parallel to the c–axis occurs by the kinetically limited birth and spreading of monolayers.] As demonstrated by Hallett, crystals with slight off-vertical c–axes (i.e., finite ψ) grow rapidly into the melt until they reach the T_m isotherm. Hence, although they occupy less (horizontal) area, these latter crystals penetrate to a depth $z = \delta$, but they can go no further. The immersed area is dominated by crystals with basal plane facets exposed to the undercooled liquid. The "needles" observed by Hallett, consisting of crystals growing along their a–axes, separate vertical c–axis domains in the surface layer, and comprise platelet domains throughout the supercooled layer. Under these kinetics the small values of δ constrain any growth advantage a non–vertical c–axis crystal may gain and, as will be shown in detail in a separate publication, during growth through the supercooled region the vertical c–axis crystals can maintain their initial areal dominance. We call this thermally constrained geometric selection, and it requires the absence of mechanical disturbances that would break and ramify the initial ice skim. Once ice has reached the thickness δ, subsequent growth occurs primarily by the removal of latent heat through the ice toward the atmosphere. Hence, the predominantly c–axis vertical orientations are "locked" into the fabric and growth occurs by the continuous creation of additional layers. The overall picture is of the vertical c–axis crystals spreading rapidly to dominate the first layer of the surface, and then maintaining this dominance due to the combination of growth kinetics and the thermal constraint on the vertical growth advantage that an off c–axis vertical crystals may gain. Unless the latter have room to act, geometric selection is held in check by the limited thickness of the supercooled boundary and a vertical c–axis fabric results.

Once orthotropic growth has started and a continuous skim is in place, the fact that the liquid ahead of the advancing interface is

slightly warmer than the freezing temperature will continue to limit the natural kinetic growth advantage of c–axis horizontal crystals throughout the remainder of the winter allowing c–axis vertical crystals to dominate unless the situation ceases to be one–dimensional (i.e. water at the freezing temperature or even slightly supercooled moves in laterally). However, if during the period leading up to the formation of the ice cover environmental conditions conspire to cool an appreciable thickness of the upper water column to the freezing point, then a fine grained initial skim is favored and the resulting orthotropic growth corresponds to the experiments of Ketcham, Hobbs and Ramseier and a S2 ice sheet results. The effects of the environment just prior to and during the initial freezing not only affect the initial ice sheet as noted by Gow, Knight and Cherepanov but can continue as a controlling factor for the rest of the winter.

Sea Ice: The gross features of the unidirectional freezing experiment described above are similar to those considered in Tiller's (1957) heuristic theory [14] of the orientation changes observed during the growth of face-centered-cubic (fcc) metals. The observations that motivated his study were a transition from (111), to equiaxed, to (100) columnar zone orientations as the impurity content increased from zero [the (111) mode] to trace amounts [the equiaxed mode] to amounts sufficient to induce a cellular substructure [the (100) mode]. Although his arguments are compelling, we are unable to interpret them as regards the role of the thermodynamic growth drive, since no account was taken for that aspect in the observations he aimed to explain. The experiment we have outlined above would be capable of testing the applicability to ice. We know that, for a fixed mean growth rate, an increase in the far field salinity results in a planar–cellular morphological instability (Fig. 9). There is a substantial salinity range between the lake and sea ice regimes, and the morphological stability boundary lies between, so we are guaranteed at least one fabric transition as S increases. Here, we need only supply the sufficient conditions for the development of horizontal c–axis fabric above a critical salinity. The argument turns out to be trivial because the morphological instability facilitates geometric selection by enhancing interfacial breakdown on crystalline grains that abut the melt with the easy growth orientation. In the ocean, there is a very narrow range of salinities in which sea ice forms, so we consider it fixed. What does vary is the rate of growth. As it increases, the boundary between planar and cellular growth modes is crossed. Therefore, we consider as an initial condition a thin zone of fine grained equiaxed crystals. We have two reasonable scenarios.

(*i*): If the growth rate is below the threshold for interfacial instability, geometric selection operates efficiently, for there is always a compositional boundary layer adjacent to the interface of sufficient thickness to allow one crystal to gain an advantage over another. Just as in metals, growth is preferred parallel to the close-packed planes in both high symmetry (e.g., fcc) and low symmetry (e.g., hexagonal close-packed) materials. The melt offers no constraint to the fast grain seeking an advantage. In effect, each competing crystal is accompanied by a constitutionally supercooled boundary layer through which it may gain an advantage over its neighbors.

(*ii*): Imagine that time has yet to give geometric selection operating room and the growth rate exceeds the instability threshold, thereby creating equiaxed cellular grains. At this stage the growth drive is roughly the same for all grains. However, due to the highly anisotropic growth rates, the tips of the c–axis horizontal cells grow much more rapidly than their c–axis vertical neighbors. This provides a kinetic motivation for the

c–axis horizontal cells to maintain their orientation.

The Hillig [26] and Wilen and Dash [40] experiments showed that growth parallel to the c–axis requires overcoming an activation barrier for a two-dimensional nucleus. Hence, nucleated growth must occur between platelets if their width is to increase. This creates a "kinetic supercooling" in the intercellular–interplatelet regions of the grains with horizontal c–axes. Turning that argument on its side, consider a cellular grain with a vertical c–axis. The individual platelet experiences a kinetic supercooling parallel to the overall growth direction that causes its growth to lag relative to more nearly horizontal c–axis grains. Furthermore, since a cellular grain with a vertical c–axis experiences rough growth in the horizontal, this might tend to smooth the grain out, slow the overall growth and allow the horizontal c–axis grains yet another advantage. Finally, the c–axis horizontal cells can further enhance their growth rate by pushing solute toward c–axis vertical grains. Thus, geometric selection and morphological instability work in concert, and leave no option for sea ice other than to create a fabric dominated by horizontal c–axis grains.

River Ice: Finally we would like to suggest a possible explanation for the change in the c–axis alignment direction from parallel to the current in ice posessing a typical sea ice cellular substructure to perpendicular to the current for river ice sheets posessing a planar interface. As long as a cellular interface is stable ($S > 1–2‰$), its topography favors the removal of solute from the advancing cell tips when the cells are elongated perpendicular to the current direction [50, 81]. However, when growth conditions are such that a planar ice–water interface becomes stable ($S < 1–2‰$) this large-scale (i.e., encompassing many grains) topographic effect no longer exists. What does remain is a grain boundary groove separating each crystal. The effect of the current remains the same in that it selectively decreases the solute buildup via enhanced mixing on segments of the grain boundary groove that face directly into the current. Since, here we are dealing with S2 type ice, we can ask what c–axis direction would allow the crystal surfaces facing into the current to grow most rapidly. The answer is clearly the orientation that places the c–axis perpendicular to the current, because this aligns the easy growth direction (0001) directly into the current. The resulting observation would be an inclined grain-boundary groove due to the expansion of the area occupied by the favored crystal at the growth interface. Once again we can explain a field observation using the anisotropic growth kinetics of ice.

Several interesting issues have not been considered in detail here. For example, as the initial salinity of a solution increases, so does the role of compositional or haline convection. This effect can exert influence on a host of space and time scales [18], and although it may not couple directly to the substructure scale, a detailed consideration of its effects will modify some features of the arguments presented herein. Since the density of seawater is dominated by the salinity, salt rejection also exerts influence on thermal convection which, in turn, controls the rate at which latent heat is dissipated at the interface. The role of anisotropy in the impurity segregation coefficient is a curious issue in itself and may also influence the anisotropy of growth kinetics.

Closure: We stress that more detailed kinetic mechanisms are mostly likely operative, but in the face of a dearth of systematic laboratory experiments we have attempted to piece together the essential ingredients of a sufficient argument. Many of the components have been discussed previously in this and other contexts, but the crucial elements must work in concert as we have described above. The essential differences between lake and sea ice fabric development include a thermal constraint on geometric selection and the interaction between the formation of

cellular substructure and geometric selection. A more detailed treatment awaits advances in experimental evidence.

References

1. H. Bader, "Introduction to ice petrofabrics," J. Geol. 59:6 (1951), 519–536.
2. G. P. Rigsby, "Crystal fabric studies on Emmons Glacier, Mount Rainier, Washington," J. Geol. 59:6 (1951), 590–598.
3. A. J. Gow and T. Williamson, "Rheological implications of the internal structure and crystal fabrics of the West Antarctic ice sheet as revealed by deep core drilling at Byrd Station," Bull. Geol. Soc. Amer. 87:12 (1976), 403–411.
4. W. B. Kamb, "Ice petrofabric observations from Blue Glacier, Washington, in relation to theory and experiment," J. Geophys. Res. 64:11 (1959), 1,891–1,909.
5. H. Peyton, Sea Ice Strength, (Geophysical Institute, University of Alaska Fairbanks), Report UAG–182 (1966), 187 pp.
6. Y. S. Wang, "Crystallographic studies and strength tests of field ice in the Alaskan Beaufort Sea," Port and Ocean Engineering Under Arctic Conditions (POAC'79), vol. I (1979), 651–665.
7. A. Kovacs, "Anisotropic properties of sea ice in the 50- to 150-MHz range," J. Geophys. Res. 84:C9 (1979), 5,749–5,759.
8. A. A. Grigor'yev and M. V. Strakhov, "Anisotropy of the elastic properties of an ice cover with a spatially organized structure," Physical and Technical Problems of Ice Research, eds. V. P. Gavrilo and G. A. Lebedev, (Arctic and Antarctic Research Institute, Gidrometeoizdat, Leningrad, 1991), 18–25.
9. V. A. Borodkin, V. P. Gavrilo, S. M. Kovalev, and G. A. Lebedev, "Influence of structural anisotropy of sea ice on its mechanical and electrical properties," Proceedings, Second International Offshore and Polar Engineering Conference, eds. M.S. Triantafyllou, J.S. Chung, K. Karal, and A.L. Tunik, (International Society of Offshore and Polar Engineers, San Francisco, 1992), 670–674.
10. L. H. Shapiro and W. F. Weeks, "The influence of crystallographic and structural properties on the flexural strength of small sea ice beams," Ice Mechanics-93, (American Society of Mechanical Engineers, Applied Mechanics Division, AMD–163, 1993), 177–188.
11. D. M. Cole and G. D. Durell, "The effect of c–axis alignment on the constitutive behavior of sea ice at low strains," Ice Mechanics-95, (ASCE/ASME(AMD)/SES Joint Meeting, AMD–207, 1995), 189–199.
12. F. G. J. Perey and E. R. Pounder, "Crystal orientation in ice sheets," Canad. J. Phys. 36 (1958), 494-502.
13. A. N. Kolmogorov, "Geometric selection of crystals" (in Russian), Doklady Akademii Nauk SSSR 65:5 (1949), 681–684. (CRREL Draft Translation 509).
14. W. A. Tiller, "Preferred growth direction of metals," J. Metals 9 (1957), 847–855.
15. D. Walton and B. Chalmers, "The origin of preferred orientation in the columnar zone of metal ingots," Trans. AIME 215, (1959), 447–457.
16. A. Hellawell and P. M. Herbert, "The development of preferred orientations during the freezing of metals and alloys," Proceed. Roy. Soc. A269 (1962), 560–573.

17. J. E. Taylor, J. W. Cahn and C. A. Handwerker, "Geometric models of crystal growth," Acta Metall. 40, (1992), 1443-74.
18. J. S. Wettlaufer, "Introduction to crystallization phenomena in sea ice," IAPSO Advanced Study Institute--Summer School: Physics of Ice--Covered Seas, ed. M. Leppäranta, (University of Helsinki, 1996).
19. F. C. Frank, Growth and Perfection of Crystals, eds. R.H. Doremus, B.W. Roberts and D. Turnbull (Wiley, New York, 1958).
20. A. A. Chernov, Modern Crystallography III, Crystal Growth (Springer, Berlin, 1984), 122.
21. M. Elbaum and J. S. Wettlaufer, "Relation of growth and equilibrium crystal shapes," Phys. Rev. E 48, (1993), 3180-3183.
22. C. K. Bagdassarian and D. W. Oxtoby, "Crystal nucleation and growth from the undercooled liquid: a nonclassical piecewise parabolic free-energy model," J. Chem. Phys. 100 (1994), 2139-48.
23. J. S. Wettlaufer, M. Jackson and M. Elbaum, "A geometric model for anisotropic crystal growth," J. Phys. A 27 (1994), 5957-5968 .
24. K–k. Koo, R. Ananth W. N. Gill, "Tip splitting in dendritic growth of ice crystals," Phys. Rev. A44:6 (1991), 3782-3790.
25. R. Fernandez, and J. Barduhn, "The growth rate of ice crystals," Desalination 3 (1967), 330–342.
26. W. B. Hillig, "The kinetics of freezing of ice in the direction perpendicular to the basal plane," Growth and Perfection of Crystals. eds. R. H. Doremus, B.W. Roberts and D. Turnbull (Wiley and Sons, New York,1958), 350–359.
27. W. B. Hillig, "Kinetics of solidification from nonmetallic liquids," Kinetics of High Temperature Processes, ed. W. D. Kingery, (Wiley and Sons, 1959), 127–135.
28. K. Fujino and Y. Suzuki, "Observations on ice rind formation on the surface of still water," (in Japanese), Low Temp. Sci. A18 (1959), 149–155.
29. J. Hallett, "Crystal growth and the formation of spikes in the surface of supercooled water," J. Glaciol. 3:28 (1960), 698–702.
30. O. Devik, "Freezing water and supercooling", J. Glaciol. 1, (1949), 307–309.
31. A. J. Gow, "Orientation textures in ice sheets of quietly frozen lakes," J. Cryst. Growth 74 (1986), 247–258.
32. B. Michel and R. O. Ramseier, "Classification of river and lake ice", Can. Geotech. J. 8:1 (1971), 36–45.
33. W. M. Ketcham and P. V. Hobbs, "The preferred orientation in the growth of ice from the melt," J. Cryst. Growth 1 (1967), 263-270.
34. R. O. Ramseier, "Zone–melting apparatus for growing ice monocrystals," Materials Res. Bull. 1 (1966) 293–297.
35. R. O. Ramseier, "Origin of preferred orientation in columnar ice," J. Cryst. Growth 3,4: (1968), 621–624.
36. J. D. Harrison and W. A. Tiller, "Controlled freezing of water," Ice and Snow-Processes, Properties and Applications, ed. W. D. Kingery, (M.I.T. Press, Cambridge, Massachusetts 1963), 215–225.
37. J. D. Harrison and W. A. Tiller, "Ice interface morphology and texture developed during freezing," J. Appl. Phys. 34:11 (1963b), 3349–3355.
38. W. F. Weeks, "The structure of sea ice: a progress report," Arctic Sea Ice, ed. W.R. Thurston, (U.S. National Academy of Sciences /National Research Council, Washington, D.C., 1958), 96–98.
39. J. S. Wettlaufer, "Directional Solidification of salt water: Deep and shallow cells," Europhys. Lett 19 (1992), 337-42 .
40. L. A. Wilen and J. G. Dash, "Giant facets at ice grain boundary grooves," Science 270, 17 Nov. (1995), 1184-1186.

41. E. Arbel and J. W. Cahn. "A method for the absolute measurement of anisotropic surface free energies," Surf. Sci. **66** (1977), 14–24.

42. W. K. Burton, N. Cabrera, and F. C. Frank, "The growth of crystals and the equilibrium structure of their surfaces," Phil. Trans. R. Soc. **A 243** (1951), 299-358 .

43. J. W. Cahn, "Theory of crystal growth and interface motion in crystalline materials," Acta Metall. **8**, (1960), 554-62.

44. J. D. Weeks and G. H. Gilmer, "Dynamics of crystal growth," Adv. Chem. Phys. **40** (1979), 157–228 .

45 J. G. Dash, H–Y Fu and J. S. Wettlaufer, "Premelting of ice and its environmental consequences," Rep. Prog. Phys. **58** (1995), 115-66 .

46. W. F. Weeks and S. F. Ackley, "The growth, structure, and properties of sea ice," The Geophysics of Sea Ice, ed. N. Untersteiner, Plenum Press, New York (1986), 9–164.

47. N. N. Cherepanov, "Spatial arrangement of sea ice crystal structure," (in Russian), Probl. Ark. Antark. **38** (1971), 137–140.

48. N. N. Cherepanov, "Structure of sea ice of great thickness," (in Russian), Trudy Arkt. Antarkt. N. I. Institut **367** (1964), 1318.

49. D. D. Smith, "Ice lithologies and structure of ice island ARLIS II," J. Glaciol. **5**:37 (1964), 17–38.

50. W. F. Weeks and A. J. Gow, "Preferred crystal orientations in the fast ice along the margins of the Arctic Ocean," J. Geophys. Res. **83**:C10 (1978), 5105–5121.

51. W. F. Weeks and A. J. Gow, "Crystal alignments in the fast ice of arctic Alaska," J. Geophys. Res. **85**:C2 (1980), 1137–1146.

52. P. J. Langhorne, Crystal Alignment in Sea Ice, Ph.D. Thesis, Cambridge University (1982) 234 pp.

53. P. J.Langhorne, "Laboratory experiments on crystal orientation in NaCl ice," Annals Glaciol. **4** (1983), 163–169.

54. E. J. Stander and B. Michel, "The effect of fluid flow on the development of preferred orientations in sea ice: laboratory experiments," Cold Reg. Sci. Tech. **17**:2 (1989), 153–161.

55. N. V. Cherepanov and M. V. Strakov, "Laboratory studies of oriented growth of ice crystals in a moving stream of water," Electro-physical and Physical-mechanical Properties of Ice, eds. V. V. Bogorodskii, and V. P. Gavrilo, (Gidrometeoizdat, Leningrad, 1989), 125–133.

56. M. V. Strakov, "A study of the influence of currents on the formation of an ice cover with an aligned crystal structure in polar seas," Glaciers–Ocean–Atmosphere Interactions (Proceedings of the International Symposium), eds. V. M. Kotlyakov, A. Ushakov and A. Glazovsky, (IAHS Publ. no. **208**, 1991), 95–103.

57. W. F. Weeks and G. Lofgren, "The effective solute distribution coefficient during the freezing of NaCl solutions," Proceedings of the International Conference on Low Temperature Science. Physics of Snow and Ice, H. Oura, ed. (Institute of Low Temperature Science, Hokkaido University, Sapporo, **1**:1, 1967), 579–597.

58. N. N. Cherepanov, V. I. Fedotov and K. P. Tyshko, "The structure of sea ice," in Sea Ice Structure and Properties, Handbook on the Analysis and Forecasting of Sea Ice, eds. W. F. Weeks and Yu. P. Doronin, (Section **1**, Committee for Marine Meteorology, World Meteorological Organization), in press.

59. T. Kawamura, "Studies on preferred growth of sea ice grain," Contributions of the Institute of Low Temperature Science, Series A, No. **36** (Hokkaido University, Saporro, 1987), 1–29.

60. J. K. Landauer and H. Plumb, "Measurements on anisotropy of the thermal conductivity of ice," Snow, Ice and Permafrost Research Establishment Research Report **16** (1956), 1–4

61. D. L. Anderson, "The physical constants of sea ice," Research **13**:8 (1960), 310–318

62. J. T. Wilson, J. H. Zumberge and E. W. Marshall, "A study of ice on an inland lake," Snow, Ice and Permafrost Research Establishment Report **5** (1954), 78 pp.

63. D. F. Barnes, "An investigation of a perennially frozen lake," Geophysics Research Directorate, AF Cambridge Research Laboratories, Air Force Surveys in Geophysics No. **129** (AFCRL–TN–60–660, 1960), 134 pp.

64. R. H. Ragle, "Formation of lake ice in a temperate climate," Cold Regions Research and Engineering Laboratory Research Report **107** (1963), 20 pp.

65. G. K. Swinzow, "Ice cover of an arctic proglacial lake," Cold Regions Research and Engineering Laboratory Research Report **155** (1966), 43 pp.

66. C. A. Knight, "Studies of arctic lake ice," J. Glaciol. **4**:33 (1962), 319–335.

67. P. A. Shumskii, Principles of Structural Glaciology, trans. D. Krauss, (Dover Publications, 1964), 497 pp.

68. N. V. Cherepanov, "A classification of the ice of natural bodies of water," (in Russian), Trudy AANI **11**:331 (1976), 77–99.

69. N. V. Cherepanov and A. V. Kamyshnikova, "Sizes and shapes of congealed–ice crystals," Studies of Ice Physics and Ice Engineering, ed. G. N. Yakovlev, Israel Program for Scientific Translations (1973), 170–176.

70. V. I. Fedotov and N. V. Cherepanov, "The initial ice layer and its role in the formation of the crystalline structure of the ice cover," Physical and Technical Problems of Ice Research, eds. V. P. Gavrilo, and G. A. Lebedev, (Arctic and Antarctic Research Institute, Gidrometeoizdat, Leningrad, 1991), 7-17.

71. N. P. Lasca, "River ice fabrics: Preliminary results," J. Glaciol. **10**:58 (1971), 151-152.

72. S. Martin, "Ice stalactites: comparison of a laminar flow theory with experiment," J. Fluid Mech. **63**:1 (1974), 51–79.

73. E. J. Stander and B. Michel, "The development of aligned columnar sea ice: a field investigation," J. Glaciol. **35**:120 (1989), 217–223.

74. M. V. Strakhov, "A study of spatially oriented crystal structures of arctic sea ice," The Electrophysical and Physicomechanical Properties of Ice, eds. V. V. Bogorodskiy and V. P. Gavrilo, (The Arctic and Antarctic Research Institute, Gidrometeoizdat, Leningrad, 1989), 134–145.

75. N. V. Cherepanov, "The role of the thermal regime of the water reservoir in the formation of the ice structure," (in Russian), Probl. Arkt. Antarkt. **29** (1968), 55–63.

76. G. F. Bolling and W. A. Tiller, "Growth from the melt: Influence of surface intersections in pure metals," J. Appl. Phys. **31**:8 (1960), 1345–1350.

77. A. J. Gow, W. F. Weeks, P. Kosloff, and S. Carsey, "Petrographic and salinity characteristics of brackish water ice in the Bay of Bothnia," Cold Regions Research and Engineering Laboratory, CRREL Rept. **92–13** (1992), 36 pp.

78. M. Schwarz, A. Karma, K. Eckler and D. M. Herlach, "Physical mechanism of grain refinement in solidification of undercooled melts," Phys. Rev. Lett. **73**, (1994), 1380-1383.

79. G. Tammann, States of Aggregation (D. Van Nostrand, New York, 1925).

80. S. H. Davis, H. E. Huppert, U. Müller and M. G. Worster, eds. Interactive Dynamics of Convection and Solidification, NATO ASI **E219**, (Kluwer, 1992), 113--138 .

81. P. J. Langhorne and W. H. Robinson, "Alignment of crystals in sea ice due to fluid motion," Cold Reg. Sci. Technol. **12**:2 (1986), 197–214.