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Studies on Preferred Growth of Sea Ice Grain*

by

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Abstract

Experiments were performed to study preferred growth in sea ice by growing sea ice uniaxially from an artificial polycrystalline seed with a known arrangement of crystallographic orientations. The seed was produced by welding rectangular blocks of single ice crystal. The growth direction was chosen parallel to the grain boundary in the seed, that is, the plane of welding (Plane W). The grain boundary formed during growth was generally a plane (Plane G). The angle β between W and G was measured for two typical arrangements of c-axes of neighboring grains: In the first arrangement, both the axes lay on a plane (Plane V) which is parallel to the growth direction and vertical to Plane W, while in the second, one of the axes lay on Plane V and the other on a plane which is parallel to Plane W. We investigated relations between the angle β and the angles α 's made by the horizontal direction and each of the c-axes. Two relations depending on α 's were established in the first arrangement, while a relation was found in the second arrangement. The experiments were made in seawater with salinity ranging from 8 ‰ to 32 ‰ and in a growth rate ranging from 0.5 mm/h to 2.0 mm/h. It is concluded that at least in these ranges neither salinity nor growth rate affects these relations.

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Contents

I . Introduction.....	3
II. Observation of crystallographic structure of sea ice grown at Saroma Lagoon	4
III. Laboratory experiments	9
III. 1. Simplification	9
III. 2. Procedure	9
III. 3. Experiments with the seed of type 1	11
1. Geometry	11
2. Results and analysis	12
3. Discussion	15
III. 4. Experiments with the seed of type 2	19
1. Geometry	19
2. Results and analysis	19
3. Discussion	24
III. 5. Other arrangements	25
IV. Conclusions	26
Acknowledgments	28
References	29

I. Introduction

It is well known that during polycrystalline solidification of a material from melt, the grain boundaries are generally not parallel to the growth direction. This means that in successive cross sections vertical to the growth direction the grain boundaries change their positions, that is, they move horizontally. For convenience, in cases of unidirectional growth, growth direction is hereafter referred to as vertical and cross sections as horizontal. Since the direction of the movement is determined by the crystallographic orientations of neighboring grains, some grains decrease their horizontal area and eventually disappear as growth proceeds. The process continues as grains encroach on and wedge out the neighboring grains in a phenomenon generally called preferred growth in polycrystals.

As many properties of polycrystals depend on the crystallographic orientations of their grains, an understanding of preferred growth is important in casting metal. Another interesting material is water, because unidirectional solidification of water occurs in nature on a very large scale in lakes and oceans.

There are many observations on preferred growth in ice solidified from pure water (pure ice) and saline water (sea ice) (Perey and Pounder, 1958 ; Harrison and Tiller, 1963 ; Pounder, 1963 ; Ragle, 1963 ; Knight, 1966 ; and Gow, 1986 for pure water ; Shumskii, 1955 ; Tabata and Ono, 1957 ; Perey and Pounder, 1958 ; Weeks and Assur, 1963 ; Langhorne, 1980 ; Weeks and Gow, 1980 ; Weeks and Ackley, 1982 for saline water). In these studies the common procedure was to measure the distribution of crystallographic orientations of grains surviving at the end of growth. Though there have been a few contradictory results in the case of pure water, a predominant conclusion is that the more horizontal the c-axis of a grain is, the more likely will the grain survive.

More elaborate studies on preferred growth in ice solidified from pure water were done by Ketcham and Hobbs (1967) and Ramseier (1968). In their method two horizontal sections were cut from ice to investigate the relation between the direction of movement of boundary and the crystallographic orientations of neighboring grains. As neither worker used seed polycrystals composed of regularly shaped grains with desired orientations, their analyses were statistical because the direction of movement depends also on the direction of the boundary. Their results are consistent with the above mentioned predominant conclusion.

It should be noted that a few essential differences exist between the growth of pure ice and sea ice :

(1) When sea ice forms, some of the concentrated saline liquid is trapped not only along grain boundaries but also in individual grains, which hence develop a peculiar structure, as will be described later. While the remainder is excluded into the underlying seawater. Therefore, concentration of salinity occurs at the interface between solid and liquid, making a salinity gradient in melt.

(2) Because normal seawater has a salinity greater than 24.7 ‰, therefore possessing a freezing point higher than its temperature of the maximum density, surface cooling creates an unstable vertical density distribution, causing convective mixing. At the time of initial ice formation an upper layer of the seawater will have been lowered to or slightly below the freezing point. A macroscopic temperature gradient, therefore, is not present in freezing of natural seawater.

With some exceptions, all the observations reached the same conclusions on pure ice and sea ice as mentioned earlier. Their results indicate that the differences (1) and (2) have little effect on preferred growth in ice. Laboratory experiments to freeze sea water uniaxially are desired to confirm this assumption. Furthermore, as the conclusions by Ketcham and Hobbs and by Ramseier are somewhat ambiguous and qualitative because of their statistical nature, more detailed quantitative analyses are desired.

In the present study, the author first observed in detail a sample of naturally grown sea ice to show how preferred growth occurred in it (Kawamura, 1982). The results of the observation are presented in Chapter II. Then he froze saline water in a unidirectional manner using an artificial seed crystal of known simple arrangements of orientation of neighboring grains relative to the direction of grain boundaries (Kawamura, 1985). The first section of Chapter III presents a general geometrical description of preferred orientations. The second section explains the experimental procedure, and the third and fourth sections present the results, analysis and discussion of the first and the second type of seeds, respectively, described in the first part. In these experiments three simple empirical linear relations between the angles defined in the first part of each section are presented together with some speculation of the occurrence of these relations. The last section of Chapter III discusses the possibility of extending these relations to explain other arrangements.

II. Observation of crystallographic structure of sea ice grown at Saroma Lagoon

Crystallographic orientations of grains were measured in a representative sample of sea ice grown in calm conditions (Kawamura, 1982). The sample was collected from sea ice grown for two days in an artificial pool (1.5 m × 1.5 m across) made on a fast ice sheet of about 200 mm thick covering Saroma Lagoon, of which the salinity of the water is about 32 ‰ due to its connection with the Okhotsk Sea through narrow channels.

A vertical cross section of the sample is shown in Fig. 1. Excluding the several-millimeter-thick surface layer due to snow, the thickness of proper sea ice in the sample was about 53 mm, in which the grain boundaries were generally inclined, that is, one of the neighboring grains encroached on the other during the growth of the sea ice. The bubble layer found at a depth of 36 mm was probably caused by the reduced growth rate in daytime. As the layer only scarcely affected the crystallographic structure, there was almost no effect

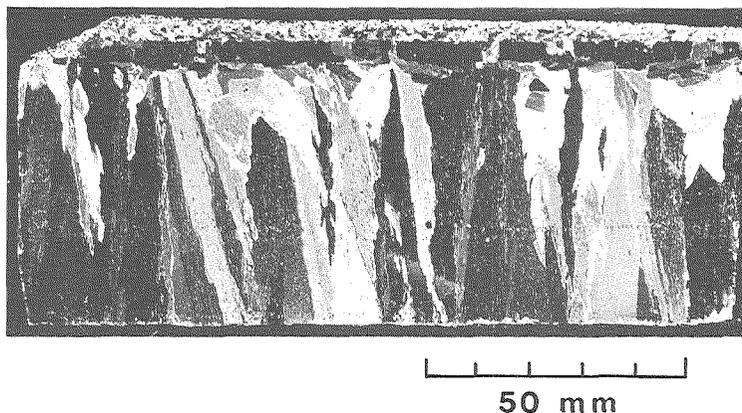


Fig. 1 Vertical thin section of sea ice (53 mm in thickness) grown freshly on an artificial pool in Saroma Lagoon.

on grain boundary as seen in Fig. 1.

The process of the encroachment appears in a series of horizontal cross sections as the change of the position of the boundary. The sample was sliced into five horizontal sections, each having a surface at depths of about 10, 20, 30, 40 and 50 mm measured from the top of proper sea ice, respectively. From these slices, the grain boundaries of each of the depths were determined optically under polarized light and the crystallographic orientations of each grain were measured with micro Laue photography. The sketches of grain boundaries at the depths of 10, 30 and 50 mm are shown in Figs. 2 (a) to 2(c), respectively, where grains whose *c*-axis made an angle larger than 75 degrees against the growth direction were hatched. Most of the grains that appeared at 50 mm depth could be traced back to upper sections. Of these grains, the most important ones are numbered in the figures.

As mentioned in the introduction, sea ice grains have a peculiar structure (e.g., see Tabata and Ono, 1957). Each grain is composed of layers of platelets, each about 0.5 mm thick, with brine pockets distributed between them (Fig. 3). In these figures hatching was done in such a manner that its line was aligned with each platelet. Hence, the projection of the *c*-axis of a hatched grain is perpendicular to the hatched line because the *c*-axis of the platelet is perpendicular to its plane.

Figures 2 (a) to 2(c) show that during the growth from 10 to 30 mm, the hatched grains encroached on and wedged out almost all of the less horizontally oriented grains and that even during further growth encroachment continued among the hatched grains.

Figures 4 and 5 demonstrate the process of encroachment more quantitatively. Figure 4 shows the distributions of *c*-axis orientations at three depths by standard projections on a Wulff net. It should be noted that at 50 mm depth, 6 of 9 numbered grains were almost horizontal. In Fig. 5, the orientation was arithmetically averaged without any consideration

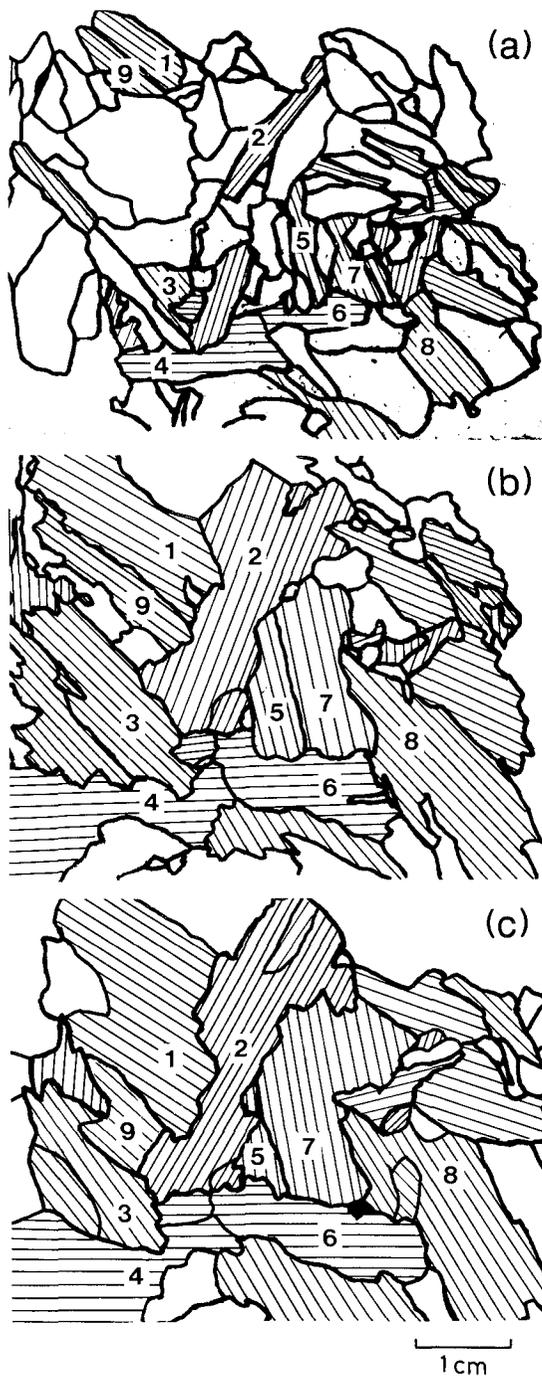


Fig. 2 Horizontal thin sections of the sea ice shown in Fig. 1 from (a) 10, (b) 30 and (c) 50 mm below the sea ice surface. Thin parallel lines indicate platelets or basal planes of sea ice grains, whose c-axis was directed almost to the horizontal plane. Major grains are numbered, each corresponding to the same numbered grain.

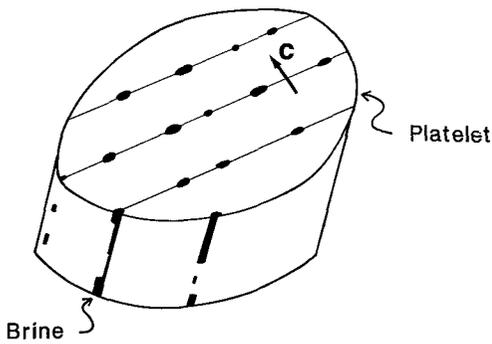


Fig. 3 Schematic illustration showing structure of sea ice grain. Crystallographic c-axis of sea ice grain is perpendicular to platelets, which are parallel with the basal plane of the grain.

of the area of each grain. If weighed by area, the values were expected to be larger. Thus the mean value of 81 degrees at 50 mm depth shown in Fig. 5 confirmed the observations hitherto reported that in sea ice horizontally oriented grains dominate the bottom. It was rather surprising that such domination occurred during growth of as short as 50 mm.

The average cross sectional area of grains increased from 18 to 38 mm² in a similar manner to the average inclination angle during growth from 10 to 40 mm, indicating that more than half of the grains that appeared at 10 mm depth disappeared during the growth. These results demonstrated that this sample of sea ice had ordinary characteristics of general sea ice, that is, grains with an almost horizontal c-axis grew preferentially, increasing in area at the expense of other grains with an inclined c-axis.

Encroachment features of the sea ice grains were recognized clearly because the grains could be traced throughout the speci-

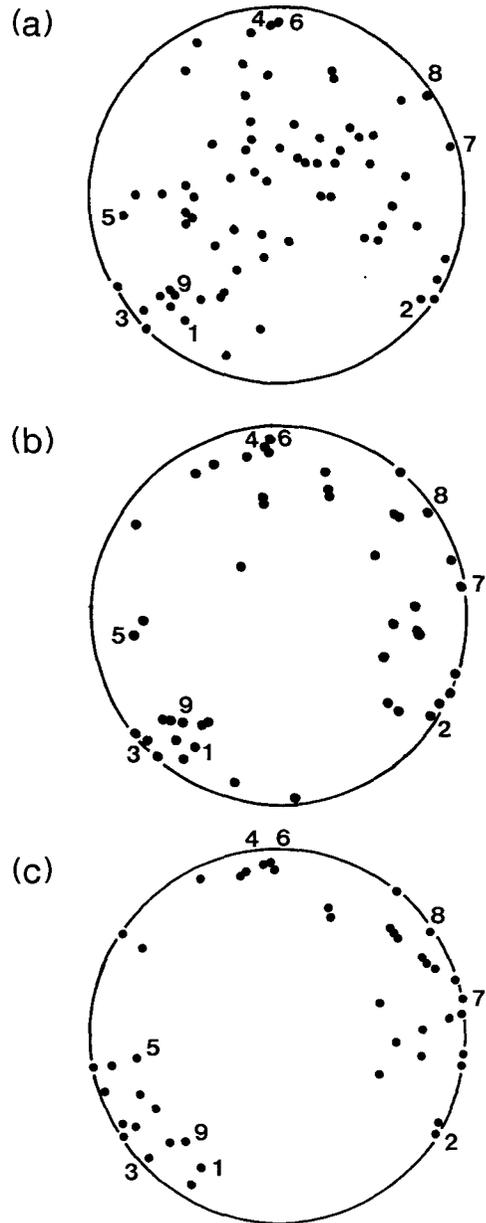


Fig. 4 Orientation of the c-axes on each layer in Fig. 2(a) to (c) plotted on a standard Wulff projection net. The numbers near the dots represent the same numbered grains shown in Fig. 2.

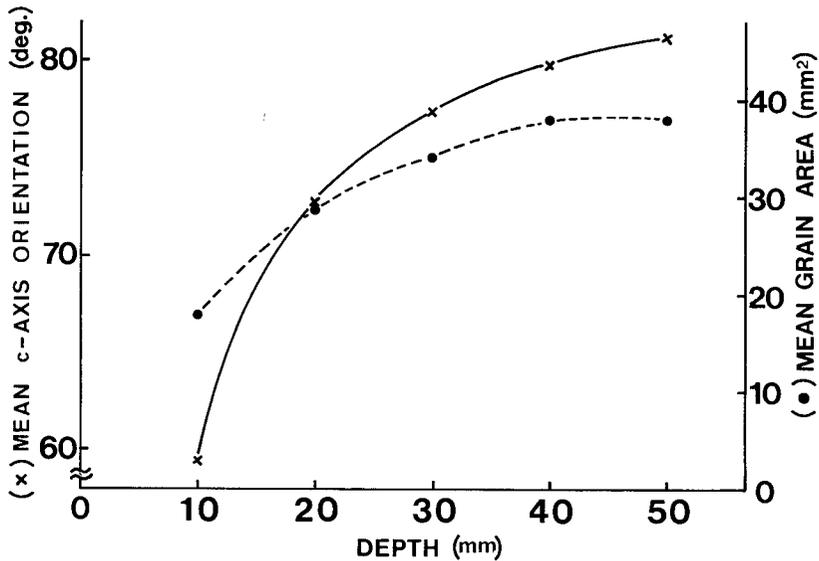


Fig. 5 Changes with depth of average inclination angle of *c*-axes to the vertical direction (solid line) and average cross-sectional area (dashed line) of the grains shown in Fig. 2.

men (Fig. 2); no detailed observations had been carried out. Wedging-out with two simple types of *c*-axis arrangement was noticed:

- (1) In two adjacent grains the *c*-axes were parallel to each other, for example, arrangements were observed between both grains 1 and 9 and grains 5 and 7 in Fig. 2.
- (2) The *c*-axes of the grains were perpendicular to each other, for example, the arrangement between grains 1 and 2.

The grain boundaries in the former case moved in a normal direction to their platelets; on the contrary, in the latter case, the platelets of grain 1 that came laterally in touch with those of grain 2 tended to encroach on grain 2. Therefore, experimental studies were performed mainly on the above two types of *c*-axis arrangements.

The observations of sea ice collected at Saroma Lagoon confirmed the general information on the preferred growth of sea ice grain and furthermore revealed the encroachment features of the grains.

III. Laboratory experiments

III.1. Simplification

To study the phenomena of preferred growth quantitatively, we need to simplify the situation so that the results can be easily analyzed.

We choose an orthogonal coordinate system in which freezing proceeds along z -axis upward. The interface of melt and solid is then parallel to x - y plane. Let the region between $z=0$ and $z=h$ be a bi-crystal with a grain boundary G . The problem to be investigated is stated as follows : When the crystallographic orientations of each grain of the bi-crystal are given, what is the direction of the newly formed grain boundary as the bi-crystal grows upward?

Now the grain boundary appears on an x - z plane as a curve $y=f(x, z)$. Then the direction of the grain boundary at a point $(x, f(x, z), z)$ is given by a normal vector $\mathbf{n}(x, z)$. The problem can be restated to find $\mathbf{n}(x, h+d)$ when the growth direction, grain directions and vector $\mathbf{n}(x, h)$ are all given.

The dependence of $\mathbf{n}(x, h+d)$ on $\mathbf{n}(x, h)$ will be in general nonlocal, that is, at a point $\mathbf{n}(x, h+d)$ will depend on the values of $\mathbf{n}(x, h)$ for some range of x . Or, in other words, $\mathbf{n}(x, h+d)$ will be a functional of $\mathbf{n}(x, h)$, thus complicating the problem. Therefore, for simplicity, we chose a grain boundary which $\mathbf{n}(x, h)$ is independent of x in the following experiments. Then, $\mathbf{n}(x, h+d)$ become independent of x . And for greater clarity, we selected the grain boundary at the start of the growth experiment, or the grain boundary in the seed bi-crystal, as the plane of $y=0$. This means that the z -component of $\mathbf{n}(x, h)$ is zero. It is not yet clear whether $\mathbf{n}(x, h+d)$ depends on the z -component of $\mathbf{n}(x, h)$ or not, but the results of the experiments seem to indicate that it does not.

Even with this restriction on the grain boundary in the seed, there are many conditions related to the crystallographic orientations of the grains. In the present experiments, we mainly used two types of seeds : In the first type, the c -axes of both the grains lay on the y - z plane, and in the second type, one of the c -axes lay on the y - z plane while the other lay on the x - z plane.

III.2. Procedure

The seeds were prepared in the following manner (Kawamura, 1986 ; Wakatsuchi and Kawamura, 1987) : A plastic washbowl about 50 cm in diameter and 15 cm in depth, with a thermal insulator on its sides and bottom, was filled with pure water and placed in a cold room at a temperature of about -5°C . After one day or so, a clean piece of polycrystalline ice of a few centimeters thick was obtained. The grains of the ice were usually large with horizontal dimensions of several centimeters or more. The crystallographic orientations of

each grain were then determined with the aid of etch pits produced on its surface (Higuchi, 1958).

Then, firstly the grain was sliced into plates, each being about 10 mm thick and having the desired crystallographic orientation relative to its surface. The inclination of *c*-axis to the surface was decided as 0 to about 35 degrees. Secondly, each plate was cut into a few blocks, each about 50 mm × 30 mm × 10 mm with the relative orientation of the *c*-axis to the 30 mm × 10 mm side being the same as that to the grain boundary in the desired seed. Thirdly, the would-be grain boundary sides of two blocks were melted slightly and joined together. Care was taken not to allow air bubbles to form between the contacted surfaces. Then, the contacted blocks were kept in a cold box at a temperature slightly below the freezing point so that the contacted surface froze slowly and annealed. Several ice blocks were welded to make a polycrystalline seed to obtain the desired data.

We considered that the steps at both the grain boundary and the edge of the seed affected further growth in sea water, therefore the welded polycrystal was floated first on pure water and grown so that it was enclosed on its side by newly grown pure ice grains, making a disk, which was then removed, and both its top and bottom were planed and smoothed to a thickness of about 7 mm.

The growing apparatus is shown schematically in Fig. 6. A plastic tank, 50 cm in top and 42 cm in bottom diameter and 85 cm in depth, was set in a wooden box, in which the temperature was kept at the freezing point of used saline water in order to ensure uniaxial downward growth and placed in a cold room. Both the box and the tank had collimated windows through which the growth of the ice in saline water could be observed. To prevent pressure increase during ice growth, an escape pipe was attached to the bottom of the tank. About 110 liters of saline water of salinity 32, 16 or 8 ‰ were used to fill the tank. The water of salinity 32 ‰ was sea water collected from Saroma Lagoon, and less saline water was obtained by diluting the sea water. The growth rate was kept constant for one experimental run of a growth of about 100 mm at 0.5, 1 or 2 mm/h by controlling room temperature.

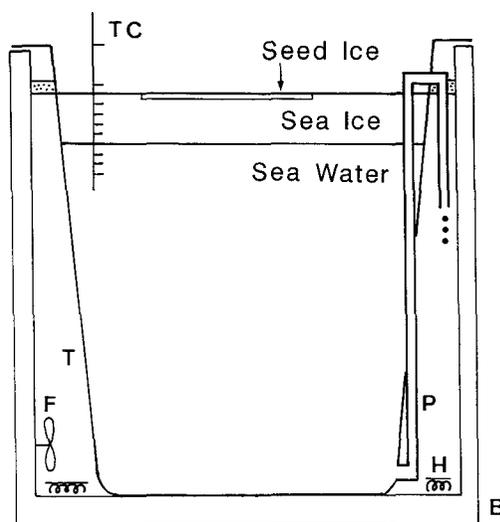


Fig. 6 Illustration of tank for growing sea ice from seed.

T : tank, B : insulated wooden box,
H : heater, TC : thermo-couples,
P : pressure escape pipe, F : fan.

After its removal from the tank, a vertical section of about 7 mm thick along the center line of the welded polycrystalline seed was made and necessary measurements were carried out on it. However, in some cases, a series of horizontal thin sections was made. The crystallographic orientations, which had been determined with etch-pits in preparing the seed, were reexamined with micro Laue photography using the appropriate section to the accuracy of one degree.

III. 3. Experiments with the seed of type 1

III. 3. 1. Geometry

Figure 7 schematically shows an arrangement of c -axes of seed of type 1. Crystallographic c -axes of the grains constituting a seed bi-crystal were both arranged on $y-z$ plane, which is vertical to the welded grain boundary. We designated the grain on the right side of the grain boundary as grain 1 and that on the left as grain 2. The c -axis direction of each grain could be determined by giving the angles α_1 and α_2 , which can vary from -90 to $+90$ degrees. The range tested was actually from -35 to $+35$ degrees as stated before. The $y-z$ section of the result of the experiment is shown in Fig. 7(b), where the z -axis is directed downward. The newly grown grain boundary was approximately straight as shown in the figure. We measured the encroachment angle β , which was made between the grain boundary and the z -axis, on vertical sections. In some cases, the newly grown boundary was a noticeable zigzag line with two alternative directions. In this case, we measured two encroachment angles. The positive sign of angles α 's and β was taken counterclockwise.

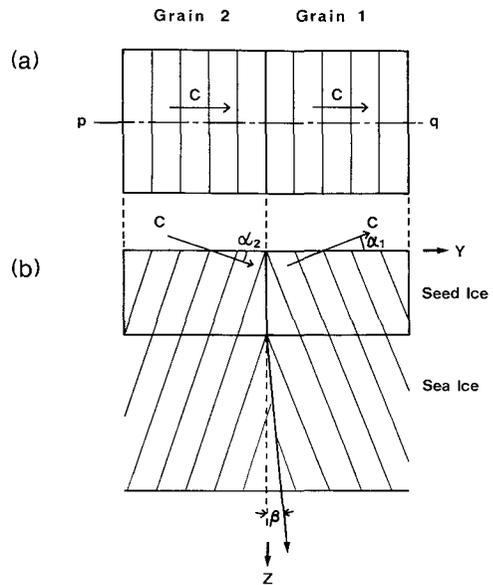


Fig. 7 Schematic diagram of type 1 seed ice with c -axis arrangement and sea ice grown from it. (a) top view of seed ice and (b) cross-sectional view of line $p-q$ ($y-z$ plane). Thin lines show the platelets of sea ice, which are perpendicular to c -axis indicated by the arrows. Inclination angle of c -axis to the horizontal plane and the angle between the vertical line and the resultant grain boundary are given by α and β , respectively.

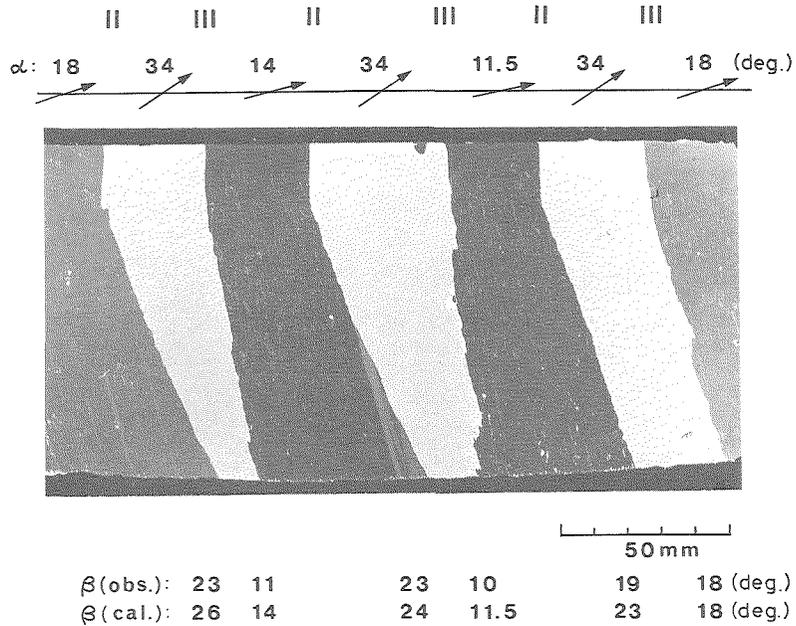


Fig. 8 Photograph of vertical thin section of sea ice grown from type I seed. Arrows indicate c-axis orientations included in the section. Values of c-axis inclination angle α and observed and calculated encroachment angles β are presented. Roman numerals over the values correspond to zones defined by values of α , which will be described afterwards.

III. 3. 2. Results and analysis

A representative vertical section of sea ice grown from seed ice with the c-axis arrangement of type I is illustrated in Fig. 8. The grain boundaries were regarded as straight in spite of the presence of some irregularities. The values of the encroachment angle β measured in the photograph were given on the first line under it. The values of the c-axis inclination angle α were shown above the photograph.

Experimental data thus obtained were summarized in Fig. 9 at a respective salinity of 32 ‰ and a growth rate of 0.5 mm/h. Similar values of the angle β as a function of both α_1 and α_2 were obtained in other combinations of salinity and growth rate.

Next we examined data in the vicinity of $\alpha_2 = -\alpha_1$. When $\alpha_1 > 0$, the basal planes or the platelets of both the neighboring grains advanced with growth away from the grain boundary at the same angle. Under this condition the angle β tended to show a value close to 0, which equals the mean value of α_1 and α_2 . On the contrary, when $\alpha_1 < 0$, where the platelets of the two grains encounter each other at the grain boundary, experimental values of β were

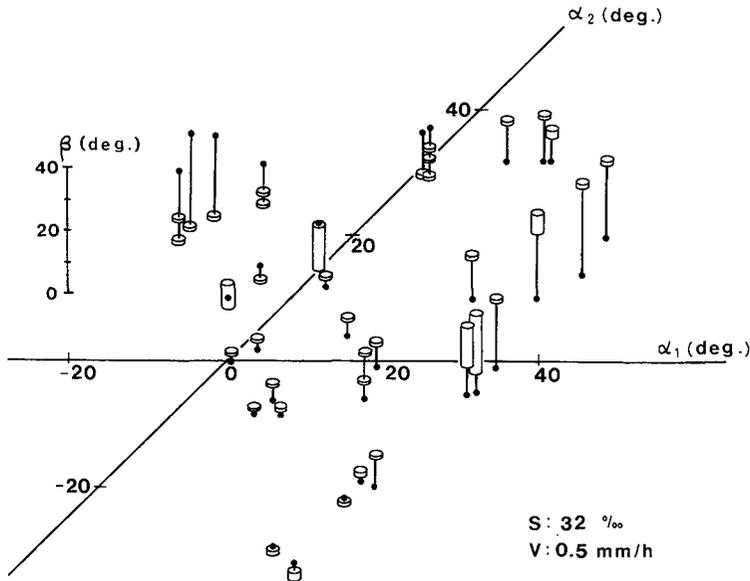


Fig. 9 Three-dimensional representation of values of angle β as a function of angles α_1 and α_2 . Values of β corresponding to values α_1 and α_2 , indicated by dot on α_1 - α_2 plane, are shown by the cylinders connected to the dots.

distributed near the value of α_1 , and also near α_2 in some cases.

The above described conditions were considered to be applicable to all the points in the data region of α_1 and α_2 . This suggests that the region can be divided into four zones, I to IV, as shown in Fig. 10. There are no essential differences between zones I and II and between zones III and IV, as will be described later. The experimental data out of zones I to IV could be re-plotted in the corresponding zones, taking advantage of symmetry. Ketcham and Hobbs (1967) explained qualitatively the preferred growth of pure ice grain in zones I to III, which agreed with the present experimental data.

Diagrams of a vertical section in each zone are shown in Fig. 10 along with contact features of the basal planes of neighboring grains at a grain boundary. Zones could be clearly distinguished from each other by the contact manners as follows: If a groove was formed at the grain boundary in zones I and II, both of the neighboring grains can expose their basal planes at the groove, thereby minimizing the surface energies, since the basal plane of ice is a low energy surface. In zones III and IV, on the contrary, not both of the basal planes of the neighboring grains can be exposed at the grain boundary groove, even if the groove was formed, and accordingly, at least one surface probably possess higher energy.

This clear difference led us to examine further the experimental data of the two groups.

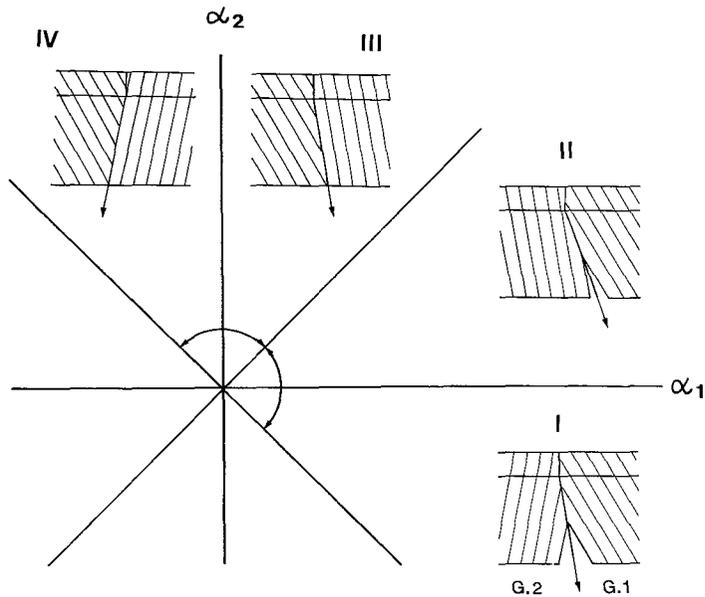


Fig. 10 Division of data region into four zones, I to IV, on the basis of values of both α_1 and α_2 , and schematic illustration of contact features of basal planes of the two grains at the grain boundary added to each zone. Thin parallel lines represent the basal planes projected on the vertical section, and the arrows indicate the direction of grain boundary movement.

A multiple regression analysis was made on the data obtained to examine a relation between the encroachment angle β and the inclination angles α 's. In zones I and II, the angle β in Fig. 9 was expressed by

$$\beta = 0.47\alpha_1 + 0.61\alpha_2 + 1.31 \quad (1)$$

with a multiple regression coefficient of 0.91. This result shows that both the c -axis inclination angles contributed almost identically to the determination of the encroachment angle. On the other hand, in zones III and IV, the angle β was given by

$$\beta = 0.81\alpha_1 - 0.24\alpha_2 + 5.97 \quad (2)$$

with the coefficient of 0.83. It was suggested that the angle β was controlled principally by the angle α_1 .

Since similar equations were derived from the data with other salinity or growth rates, no noticeable dependence of the encroachment angle β on them was recognized. Therefore, it was concluded that neither salinity nor growth rate is important in determining the relation between α 's and β .

III. 3. 3. Discussion

Based on these results, we considered the relation between the contact features of the basal planes at a grain boundary and the value of β . When both the basal planes of the grains were exposed at the grain boundary groove in zones I and II, it was expected that the two exposed planes would advance at the same rate of $V_1 = V_2$ (where V_1 and V_2 are growth rates parallel to c-axis of grains 1 and 2, respectively) as a first approximation without consideration of thermal conditions, since the planes are equivalent (Fig. 11). With the progress of the two exposed planes, accordingly, the grain boundary will proceed toward the bisector of the opening angle at the groove. Since an inclination angle α can be regarded as the angle between the basal plane and the vertical line as shown in this figure, the angle between the resultant grain boundary and the vertical line, which is identical with the encroachment angle β , was given by

$$\beta = (\alpha_1 + \alpha_2) / 2. \tag{3}$$

This equation means that the encroachment angle takes the mean value of the two c-axis

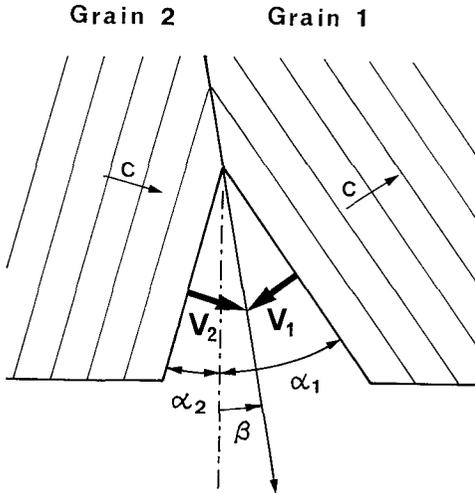


Fig. 11 Schematic representation of grain boundary groove in zones I and II, in which the basal planes of both grains can be exposed. Two exposed planes advance at the same growth rate (V_1 and V_2) in their c-axis directions. Grain boundary proceeds in the direction of the arrows with ice growth.

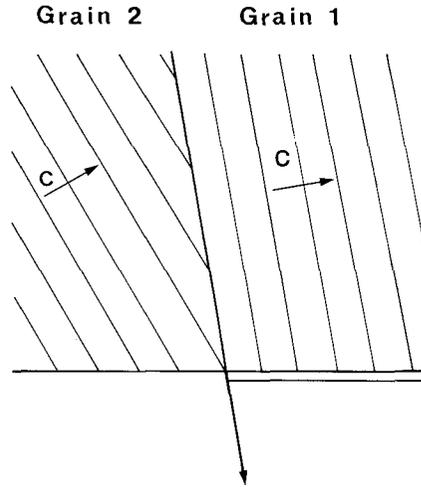


Fig. 12 Schematic diagram of contact features of basal planes at the grain boundary in zone III. Preferred grain 1 advances with step ahead of the other grain.

inclination angles, showing close agreement with Equation (1). Therefore, for simplicity, we adopted Equation (3) to express the data in zones I and II.

In zone III, if it is assumed that grain 1 with c-axis which is more horizontally oriented grows ahead of the other grain 2, grain 1 can protrude further into water beyond the neighboring grain 2, forming invariably a step as shown in Fig. 12. This may suggest that the basal planes of grain 1 will grow to maintain their direction, since the step inhibits grain 2 to advance beyond them. Accordingly the grain boundary direction will be determined by the c-axis inclination angle of preferred grain 1, that is,

$$\beta = \alpha_1 \quad (4)$$

Because this equation is qualitatively in accord with Equation (2), which shows that the angle α of grain 1 contributes greatly to the control of angle β . Equation (4) is considered to explain the relation between β and α 's in zone III, in spite of a slightly rough treatment. It is reasonable to consider that microscopic steps can be produced, although no visible steps were noticed on the decanted interface.

In zone IV, in an exactly similar manner as that observed in zone III, it was presumed

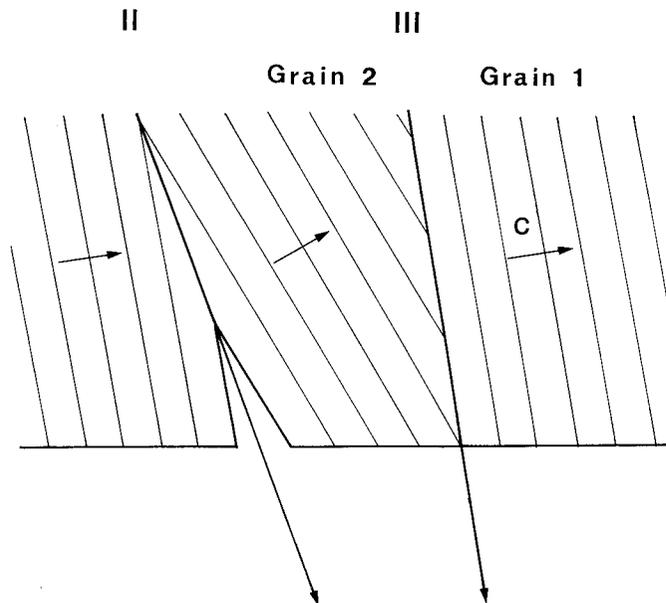


Fig. 13 Schematic diagram of a vertical section in which grain 2 in Fig. 12 is touched on the left-hand side by the same grain as grain 1. Two grain boundaries correspond to those in zones II and III from the left, respectively. Arrows indicate direction of grain boundary movement predicted.

that the preferred grain, whose c-axis is closer to the horizontal plane, grows with a step at the interface, thus controlling the grain boundary direction. Accordingly, the direction of the grain boundary (β) is determined by the inclination angle of the preferred grain (α_1). Thus, since Equation (4) holds true in zone IV also, the value of β should be reversed discontinuously from negative to positive across the line $\alpha_2 = -\alpha_1$ in zone IV. Therefore, experimental data near the line in zone IV can take various values, that is, either positive or negative, or become close to 0 due to the symmetry of the neighboring grains. We must pay attention to this singular belt in zone IV.

The most important fact in zone III is the direction of its grain boundary movement. In this zone a grain with a smaller c-axis inclination angle (grain 1) was observed to be wedged out by one with a larger angle (grain 2), as shown in Fig. 12. This contradicts the common knowledge that the c-axis of the preferred grain in sea ice grown from melt generally shows a horizontal direction.

This result is valid when we consider the movement of this grain boundary alone. However, when grain 2 was touched on the left-hand side by the same grain as grain 1, the present grain boundary corresponded to that in zone II, as shown in Fig. 13. Grain 2 was then wedged out conversely by grain 1 at this boundary at the encroachment angle $\beta = (\alpha_1 +$

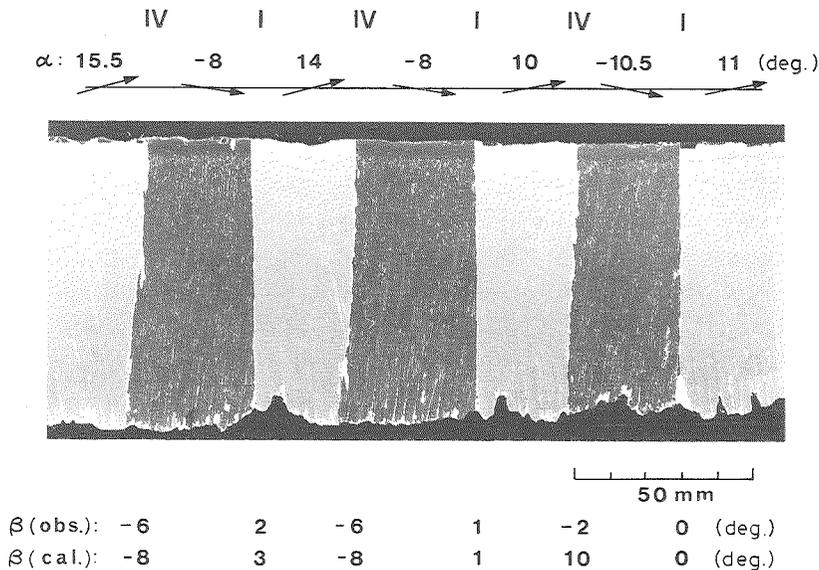


Fig. 14 Photograph of vertical thin section of sea ice grown from type 1 seed. Arrows indicate c-axis orientations included in the section. Values of c-axis inclination angle α and observed and calculated encroachment angles β are presented. Roman numerals over the values correspond to zones defined by values of α .

$\alpha_2)/2$, given by Equation (3), which is larger than that on the right-hand side ($\beta = \alpha_1$). Accordingly, as the interface advanced, the middle grain disappeared due to differences in these encroachment angles between the both sides, although the grain encroached on the right-hand grain. This result agrees with the commonly observed experimental ones in sea ice, in which the grains having a more vertical *c*-axis tend to disappear, being cut off ultimately from melt. It is thus important to distinguish clearly between movement of a grain boundary and extinction of a grain.

Figure 8 demonstrates clear that although grains with larger α (even grains from the left) encroached on those with smaller α (odd grains) on the right-hand side, the former grains were wedged out ultimately by the latter ones.

We will now compare the values calculated by Equation (3) or (4) and the ones observed for encroachment angle β . Representative movement of grain boundaries in zones II and III is shown in Fig. 8, in which the grains with smaller α and larger α were arranged alternately. According to the values of each grain, the grain boundaries from the left also corresponded alternately to those in zones II and III. The calculated values of β , shown on the second line under the photograph, contrasted with the observed values on the first line.

Some examples of the grain boundaries of zones I and IV are shown in Fig. 14. Here, because of an alternate shift of α from positive to negative, or vice versa, the grain boundaries were changed alternately from zone IV to zone I. The respective observed encroachment angles were shown on the first line under the photograph, while the corresponding calculated ones were shown on the second line.

There is a distinct difference between the two values at the second grain boundary from the right. The angles of α of the grains touching the grain boundary had equivalent absolute values with different signs. The point defined by the two α 's appeared in the singular belt in the vicinity of the discontinuous line $\alpha_2 = -\alpha_1$, as described above, where the platelets of the two grains joined together at the grain boundary at the same angles. Therefore, the angle β of this boundary did not take the value of α_1 predicted in zone IV but a value close to 0 degree. The difference probably occurred for the follows reason. After one grain grew preferentially for some distance, the preference was transferred to the other grain by some mechanism since the inclination angles were quite similar. Continued encroachment of the right grain in the direction of its basal plane was followed by a much shorter encroachment of the left grain. Repetitions of such alternate encroachments resulted in a zigzag pattern, shown in the photograph, which enabled the grain boundary to tilt slightly towards the left grain on the average. Moreover, the zigzag pattern was observed on a larger scale in other sections examined.

All the above results of the *c*-axis arrangement of type 1 were obtained under the *a*-axis condition in which one of the three *a*-axes of two seed grains was directed horizontally. Experiments were also performed with the seed of type 1 in which one of the *b*-axes, but not of *a*-axes, was arranged on a horizontal plane. This result suggested the scarce effect of

a-axis on the experimental results since the present results exhibited similar tendencies to those described earlier. We thus concluded that the c-axis is the primary factor to determine the preferred growth of sea ice grain and that the a-axis produces only the second, if any, effect. A minor difference was also obtained ; values of β near the discontinuous line $\alpha_2 = -\alpha_1$ were distributed more widely between $\beta = \alpha_1$ and $\beta = \alpha_2$.

III. 4. Experiments with the seed of type 2

III. 4. 1. Geometry

An arrangement of c-axes of seed ice grains of type 2 is shown in Fig. 15. The crystallographic c-axis of one grain (referred to as grain 1) is arranged on the y-z section and is inclined at an angle of α to the y-direction. On the contrary, the c-axis of the other grain (grain 2) is oriented parallel to the initial grain boundary and remains unchanged on the horizontal plane. The encroachment angle β was defined as the angle made by the resultant grain boundary and the vertical line, and was considered as a function of the c-axis inclination angle α . Positive signs of angles α and β were arranged counterclockwise.

III. 4. 2. Results and analysis

Figures 16(b) to 16(d) show horizontal thin sections of sea ice grown from seed ice grains with c-axes indicated by arrows in Fig. 16(a). Three seed crystals were connected in this case ; all the c-axes of the grains of either side, being defined as grain 2, were arranged on a horizontal plane. On the contrary, c-axes of the middle grains corresponding to grain 1 were inclined to the horizontal plane ; the inclination angles of the grains were 10 and 2 degrees in the upper and lower parts, respectively. The middle grains appeared to be wedged out by neighboring grains on both sides. The grain boundaries also took the form of a trapezoid in the first stage of encroachment (Fig. 16(c)), altering gradually with depth into a sharply pointed shape (Fig. 16(d)). Therefore, as the observa-

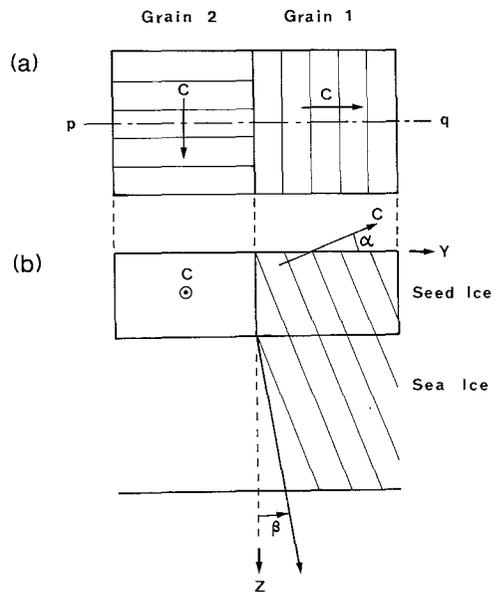


Fig. 15 Schematic diagram of type 2 seed ice with c-axis arrangement and sea ice grown from it. (a) top view of seed ice and (b) cross-sectional view of line p-q (y-z plane). Thin lines show the platelets of sea ice, which are perpendicular to c-axis indicated by the arrows. Inclination angle of c-axis to the horizontal plane and the angle between the vertical line and the resultant grain boundary are given by α and β , respectively.

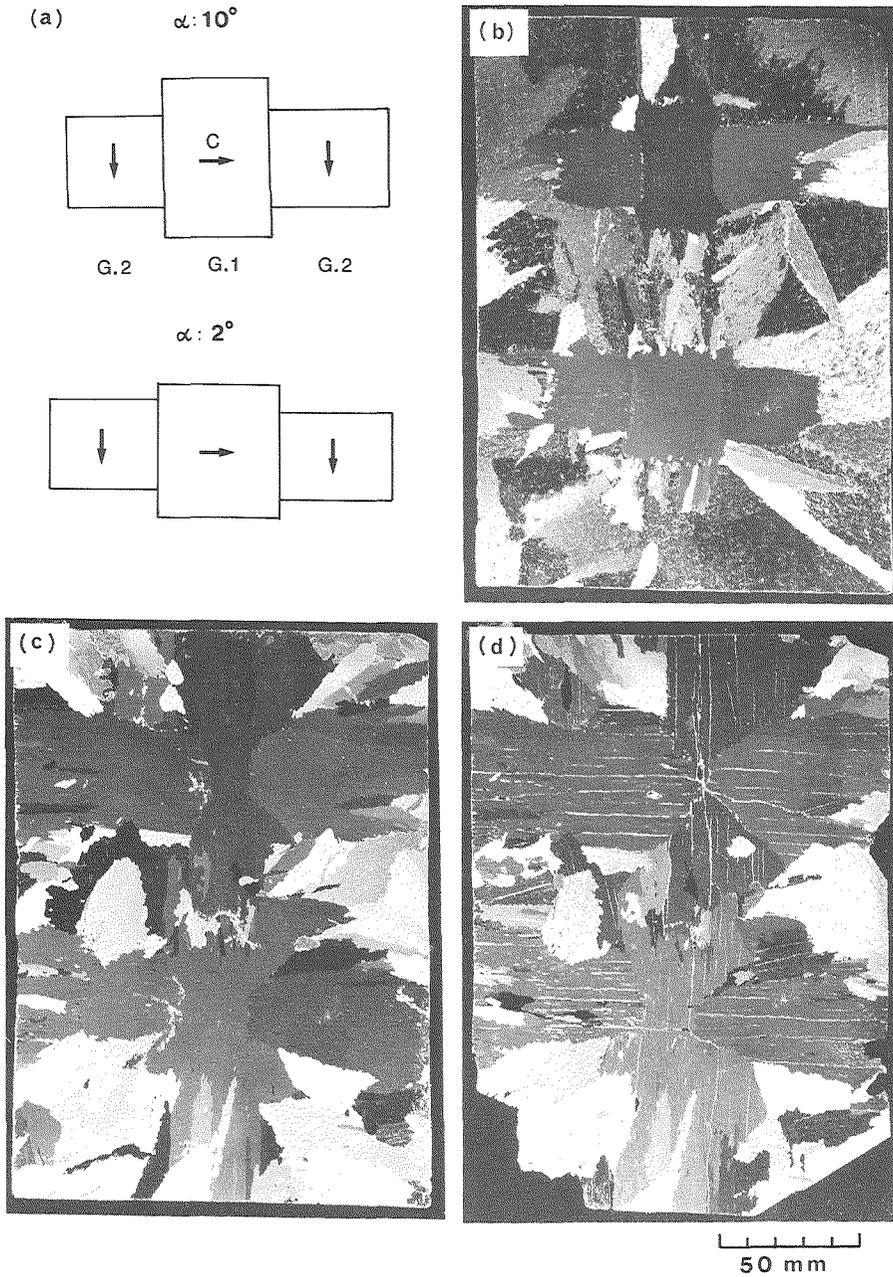


Fig. 16 Photographs of horizontal thin section of sea ice grown from type 2 seed with c-axes indicated by arrows in (a); (b) 14, (c) 42 and (d) 70 mm in depth from the surface. All the c-axes of the grains \nearrow

are in the horizontal plane except the middle grain of the upper part with an inclined c-axis to the horizon. The three connected grains are equivalent to grains 2, 1 and 2, respectively, from the definition.

tions of three dimensions showed, the encroachment had a wedge-like shape. Because wedging-out occurred more predominantly in the central part of grain boundaries, encroachment angle was measured at that point mainly in the vertical sections.

A representative vertical thin section of such a part (Fig. 17) shows that the middle grain was wedged out symmetrically by the grains on both sides at angles β , which were about 7 degrees. In this case, the c-axis of the middle grain had an inclination angle α of 0 degree, being oriented to the horizon like the c-axes of the grains on both sides. Another vertical section (Fig. 18), in which the angle α of the middle grain was equal to 18 degrees, unlike that in Fig. 17, demonstrated asymmetrical grain boundaries, at which the angles β were 18 and 0 degrees on the left and the right, respectively.

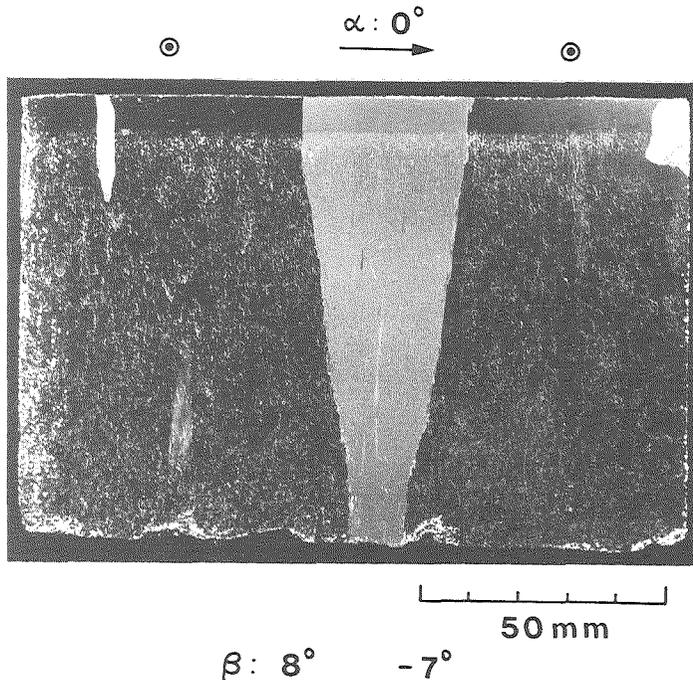


Fig. 17 Photographs of vertical thin section of sea ice grown from type 2 seed. Both arrow and circles with dot represent the c-axes of the grains. The inclination angle of c-axis of the middle grain is equal to 0 degree and is directed horizontally as well as the grains on both sides.

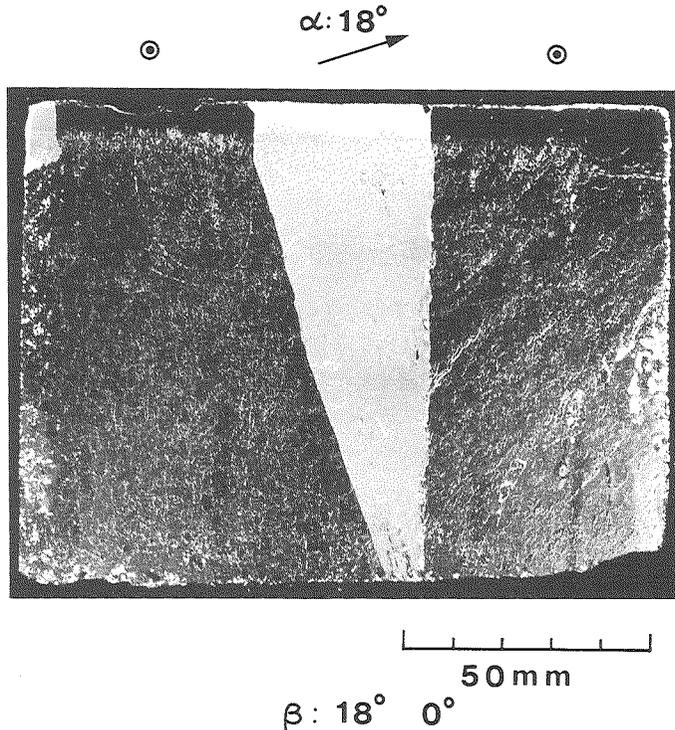


Fig. 18 Photographs of vertical thin section of sea ice grown from type 2 seed. Both arrow and circles with dot represent the c -axes of the grains. The c -axis of the middle grain inclines at 18 degrees to the horizontal plane, whereas that of the grains on both sides is oriented horizontally.

Experimental results obtained at salinity of 32 ‰ were plotted in Fig. 19. It was interesting that angle β did not show 0 degree, even when $\alpha=0$, as seen in Fig. 17. That is, wedging-out occurred even if the c -axes of the two grains were horizontally oriented. Figure 19 also shows that the relation between α and β is linear regardless of growth rate and is given by

$$\beta = 0.4\alpha + 6 \quad (5)$$

over α , ranging from -15 to 10 degrees. Similar results were obtained at salinity of 16 ‰ (Fig. 20), where the relation between α and β was expressed by the same Equation (5). Therefore, when $\alpha=0$, $\beta \neq 0$ also at this salinity. A similar trend was found at the salinity of 8 ‰, as shown in Fig. 21: the values of encroachment angle β of 8 ‰ tended to be slightly smaller than those of other salinities throughout the inclination angle. Thus salinity dependence might appear at 8 ‰, while no noticeable dependence of growth rate was recognized.

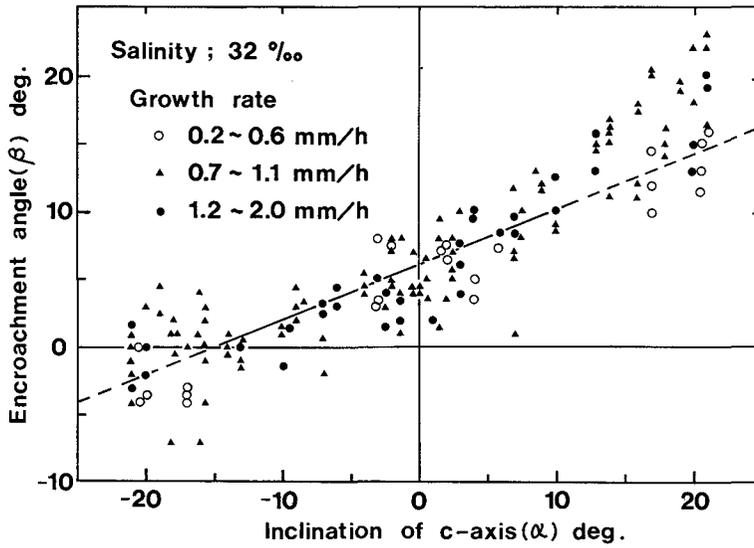


Fig. 19 Relation between c-axis inclination angle α and encroachment angle β of grain boundary at salinity of 32 ‰. The straight line stands for relation $\beta=0.4\alpha+6$.

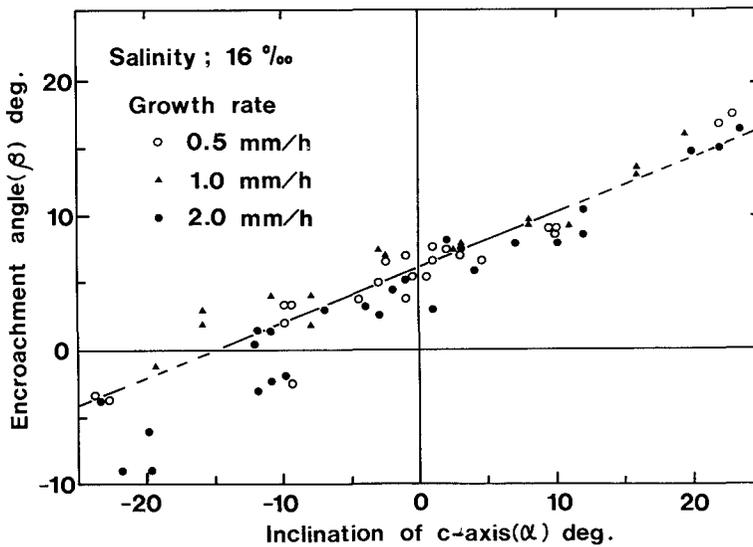


Fig. 20 Relation between c-axis inclination angle α and encroachment angle β of grain boundary at salinity of 16 ‰. The straight line stands for relation $\beta=0.4\alpha+6$.

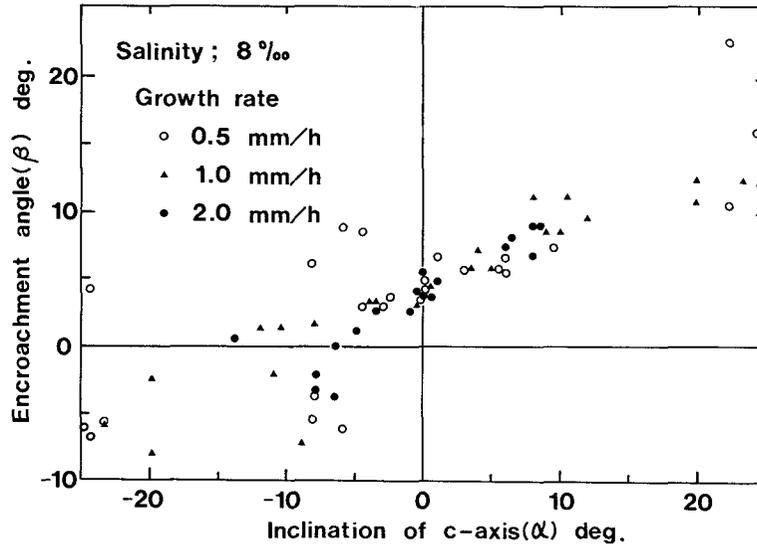


Fig. 21 Relation between c -axis inclination angle α and encroachment angle β of grain boundary at salinity of 8 ‰.

III. 4. 3. Discussion

It should be emphasized again that when inclination angle α of c -axis of grain 1 was equal to 0 degree, one grain was observed to encroach on the neighboring grain at 6 degrees but not at 0 degree, as expressed by Equation (5). When $\alpha=0$, it is reasonable to predict that grains 1 and 2 never encroach on each other, and that there is a stagnant grain boundary, because the c -axes of both the grains are oriented equally horizontally. Nevertheless, the present experiments proved that one grain actually encroached on the neighboring grain, whose platelets were laterally hit by those of the former. This finding has not been reported hitherto. A similar result was observed in natural sea ice collected at Saroma Lagoon, as described in Chapter II.

The above result might be explained in terms of the difference of the horizontal component of growth rate between neighboring grains at a grain boundary groove as follows. Grain 1 cannot encroach on grain 2 unless it grows along its c -axis, whereas grain 2 can wedge off grain 1 only if growth in the basal plane occurs. Summarizing the results of pure ice obtained experimentally by several workers, Fletcher (1970) has shown that the growth rate parallel to the a -axis is always greater than that in the c -axis direction, regardless of total supercooling. Therefore, it is suggested that the horizontal growth rate of grain 2 is greater than that of grain 1 at the grain boundary groove. The grain boundary is expected to move toward grain 1, after which grain 1 will be wedged out.

Finally, let us consider a shape of a grain boundary exposed to horizontal thin sections of sea ice grown from a seed of type 2. The grain boundary possessed characteristic features, being almost identical with the bisector of the angle between the c-axes of both grains, as shown in Fig. 16. This result can be explained as follows. Once the grains on both sides corresponding to grain 2 encroach on the middle grain (grain 1), the reversed crystallographic relationship is generated at the encroaching edges and then grain 2 is wedged out laterally, followed by a balance of encroachment in the platelet direction of both grains.

III. 5. Other arrangements

In the seed of type 2, both the platelets of the two grains joined together at right angles, as described before. We concluded experiments in which platelets of one grain bombarded those of another grain at an acute angle but not at right angles.

Figure 22 (a) shows schematically a top view of seed ice grains with their c-axis orientations indicated by arrows. The c-axes of all the grains on both sides were oriented in the horizontal plane, whereas those of the middle grains were inclined at an angle of α to the horizontal, and their projections onto the horizontal plane were perpendicular to the initial welded grain boundary. The c-axis inclination angle α of the middle grain and the contact angle of the neighboring platelets were 18 and approximately 60 degrees, respectively, as seen in the upper part of the figure. On the other hand, the lower part of the figure shows angles of 20 and about 30 degrees, respectively. In the horizontal thin sections it appeared that the middle grains were wedged out from both sides (Figs. 22(b) and 22(c)). Figure 23 shows tracings of the grain boundaries in the two sections to reveal their movement with depth. This figure revealed that the grains on the left-hand side also encroached more predominantly in the central part of the grain boundaries, as in the case of type 2.

The maximum encroachment angle β was measured at that point along the plane normal to the welded grain boundaries. The observed angles β were 14 and 1 degree at the left-hand and right-hand sides, respectively, in the upper grains. The values of angle β were calculated from Equation (5) obtained in the experiments of type 2. The respective calculated values were equal to 13 and -1 degree, being almost identical with the observed values. On the other hand, in the lower grains, the calculated angles of 14 and -2 degrees exactly equaled the observed angles of 13 and -2 degrees, thus validating the close agreement between the observed and the calculated values. These experimental results led to the conclusion that the encroachment features of the grain boundaries could be fully explained from the results of the c-axis arrangement of type 2, even when the platelets of neighboring grains encountered each other at appreciably different and sharper angles than those of type 2.

The horizontal sections of Fig. 22 also demonstrated that some of the grain boundaries were almost consistent with the bisector of platelet directions of neighboring grains ; this result also agreed with that of type 2.

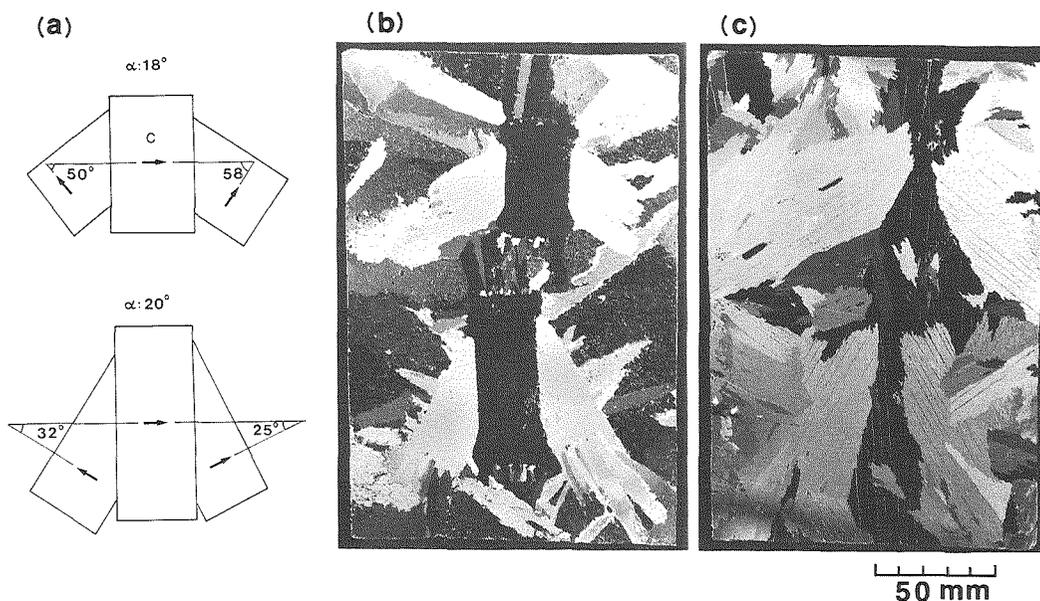


Fig. 22 Photographs of horizontal thin section of sea ice grown from seed ice grains with projection of c-axis on the horizontal plane indicated by arrows in (a) ; (b) 14 and (c) 77 mm in depth from the surface. All the c-axes of the grains on both sides are directed horizontally, whereas the c-axes of the middle grains are inclined at angle α to the horizon.

IV. Conclusions

The characteristics of encroachment of grains with growth were clarified by tracing them on sea ice grown naturally in the field. On the basis of these observations, quantitative experiments were performed on not only two types but also on other modified types of seed with c-axis arrangement of two neighboring grains. Encroachment angles of a grain were examined as a function of the c-axis inclination angles of the grains. The results obtained are summarized as follows :

(1) In the case where both c-axes of the grains were arranged on the same vertical plane, the data region could be divided into four zones, I to IV, based on the contact features of basal planes of neighboring grains at a grain boundary. In zones I and II, where both the grains

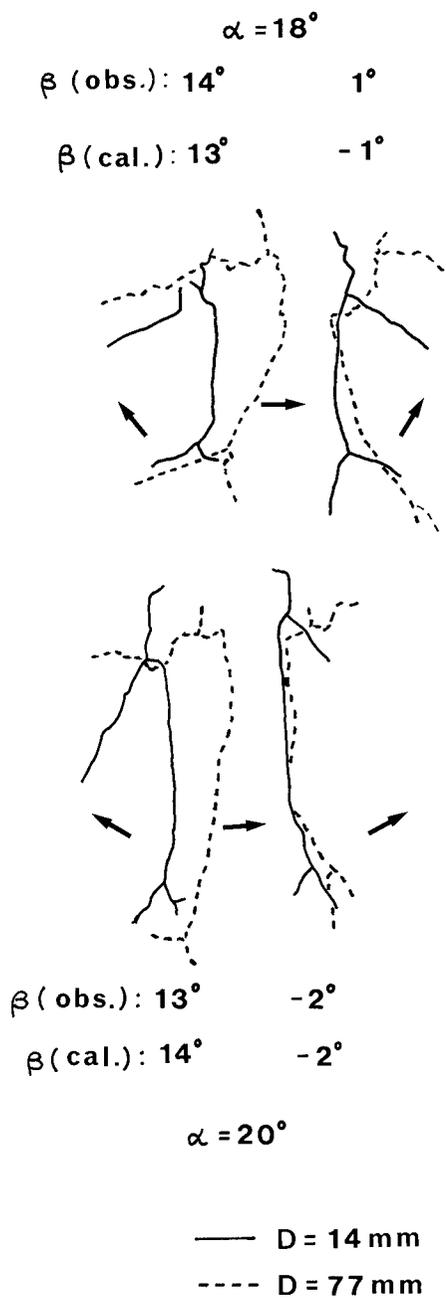


Fig. 23 Profile of grain boundaries of both upper (solid line) and lower layer (dashed line) in Fig. 22. Arrows indicate projection of caxes on the horizontal plane. Inclination angle of c-axes of the middle grains and observed and calculated encroachment angles are presented.

can expose their basal planes at the grain boundary groove, the encroachment angle was expressed by the mean value of the *c*-axis inclination angles of the two grains. That is, the grain boundary proceeded with growth in the direction of the bisector of the opening angle at the groove. On the contrary, when the basal planes of not both the grains can expose at the grain boundary groove (zones III and IV), the encroachment angle was controlled principally by the *c*-axis inclination angle of the preferred grain with the *c*-axis closer to the horizontal plane. There was a particular zone in which a grain with a *c*-axis having a smaller inclination angle to the horizontal plane was wedged out by a grain having a larger angle. This is contrary to the commonly observed feature of sea ice grains in which the preferred grain of sea ice generally has a horizontally directed *c*-axis. Because similar results were obtained in this type of *c*-axis arrangement regardless of the *a*-axis orientations, the *c*-axis was considered the primary factor to determine the preferred growth of sea ice grains.

(2) In the experiments using seeds in which the two *c*-axes of neighboring grains existed on vertical planes intersecting each other at right angles, the most important result was obtained when the present *c*-axis directed horizontally. Although both the *c*-axes of the grains were equally directed horizontally under these conditions, the encroachment angle never showed 0 degree, that is, wedging-out still occurred. The relation between the *c*-axis inclination angle and the encroachment angle was given by a linear function over the inclination angle ranging from -15 to 10 degrees.

(3) Even when platelets of two neighboring grains were in contact with each other at an acute angle unlike right angles, the encroachment angle was in agreement with the value calculated by the equation obtained in the case of right angles. Therefore, the encroachment features in this modified type could be fully explained by the above results. It is possible to describe more general encroachment features of sea ice on the basis of these experimental results.

(4) Conditions of sea ice growth seem to be different from those of pure ice because of the condensed salt layer formed at the advancing solid-liquid interface. Nevertheless, noticeable dependence of neither salinity nor growth rate was recognized within their limits in the present experiments. This finding suggests that preferred growth of sea ice grain is not affected by the condensation of salt and that it is essentially the same as that of pure ice grain. It is interesting that the qualitative results obtained by Ketcham and Hobbs (1967) on the preferred growth of pure ice agreed in part with the present results.

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