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Publisher's version / Version de l'éditeur:

Atmosphere-Ocean, 22, 2, pp. 193-206, 1984

National Research Council Canada
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Reprinted from
Atmosphere–Ocean
Vol. 22, No. 2, 1984
p. 193 - 206

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A Note on Brine Layer Spacing of First-Year Sea Ice

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[Original manuscript received 20 July 1983; in revised form 28 February 1984]

ABSTRACT *Brine layer spacing has been measured in a core sample taken 19 January 1978 from Eclipse Sound, Baffin Island, Canada. Observations on snow and ice conditions and a record of air temperatures for the entire growth season allowed correlation of the brine layer spacing with the growth rate of the sea ice. Growth rate is related to climatology, and the vertical brine layer spacing profile in the ice provides a record of previous weather conditions. It is suggested that the spacing is inversely proportional to the growth rate, and could also be dependent on crystallographic orientation. The spacing decreased rapidly with depth near the bottom of the core sample, and this is not compatible with a general relation between spacing and growth rate. Before a definitive statement can be made, cores from a variety of locations, grown in a range of meteorological conditions, will have to be studied.*

RÉSUMÉ *L'espacement des couches de saumure a été mesuré dans une carotte prélevée le 19 janvier 1978 au détroit Eclipse, île de Baffin, Canada. Des observations sur les conditions de la neige et de la glace et un registre des températures de l'air pour toute la saison de croissance ont permis d'établir une corrélation entre l'espacement des couches de saumure et le taux de croissance de la glace de mer. Le taux de croissance est relié à la climatologie et le profil vertical de l'espacement des couches de saumure dans la glace fournit un registre des conditions atmosphériques précédentes. Il a été suggeré que l'espacement est inversement proportionnel au taux de croissance et l'espacement pourrait également dépendre de l'orientation des axes cristallins. L'espacement décroît rapidement en profondeur lorsqu'on arrive dans la partie inférieure de la carotte, ce qui est incompatible avec une relation générale entre l'espacement et le taux de croissance. Avant de tirer toute conclusion définitive, il faudra étudier un ensemble d'échantillons formés sous diverses conditions climatiques et provenant d'endroits différents.*

1 Introduction

Brine layer spacing, the distance between adjacent planes or layers containing brine pockets, is one of the most important parameters in describing the structure of sea ice. It has often been called the plate width or plate spacing. Laboratory experiments have shown that this spacing increases with a decrease in growth rate, although growth rates in the experiments are larger than those usually encountered in the field (Assur and Weeks, 1963; Rohatgi and Adams, 1967a, b; Lofgren and Weeks, 1969). In natural sea ice Tabata and Ono (1962), Weeks and Hamilton (1962) and Paige (1966) found a progressive increase in the brine layer spacing with increasing depth. These observations are considered to be compatible with laboratory experiments because the growth rate would generally decrease with depth. Gow and Weeks (1977), however, reported that the spacing fluctuated with depth, and even decreased towards the bottom of the ice-sheet. It was difficult to explain the fluctuations in spacing because of the lack of data on the growth history of the ice.

A substantial volume of data on weather, snow and ice characteristics was collected at Eclipse Sound (72.7°N, 78.0°W) near Pond Inlet on Baffin Island, Canada, during the winter of 1977–78. To take advantage of these ice growth data the brine layer spacing of a core sample obtained in the sound was analysed. This paper describes the observations on the spacing and the analyses of the dependence of spacing on growth conditions.

2 Physical setting and general observations

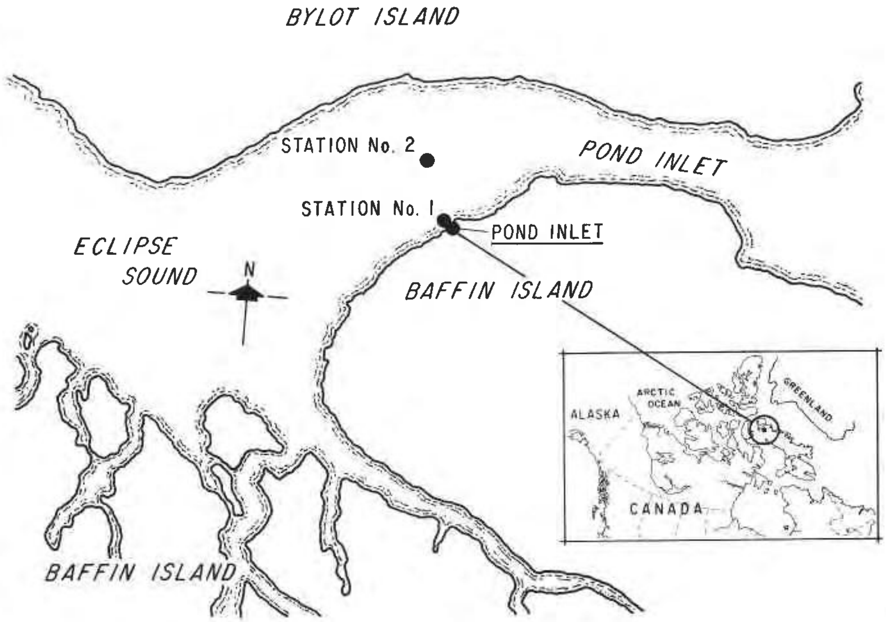
Two stations were established on the ice-sheet at Eclipse Sound (Fig. 1a), aligned approximately 342° north from the main camp (Arctic Research Establishment) located adjacent to the shore. Station 1 was close to the main camp (0.5 km from the southern shore) while Station 2 was almost at the centre of the Sound (7.7 km from the southern shore). The depths of water at Stations 1 and 2, respectively, were about 150 and 660 m. The shoreline of the Sound is oriented about 60° east of north at the stations.

The ice-sheet thickness was determined by measuring the length of the cores taken periodically at both stations. The measurements were initiated at Station 1 on 4 November 1977 and continued to July 1978, with an interval of about a week between observations. At Station 2 the observations were started late, i.e. 19 January 1978, and the frequency was less, about every two weeks. The thickness and density of the snow cover was measured at both stations at the time of each regular observation. At the main camp, soon after recovery, the cores were sectioned into 25-mm segments and the salinity of each section was measured by a calibrated commercially-available refractometer designed for this purpose. The daily maximum and minimum air temperatures were recorded at the main camp throughout the season.

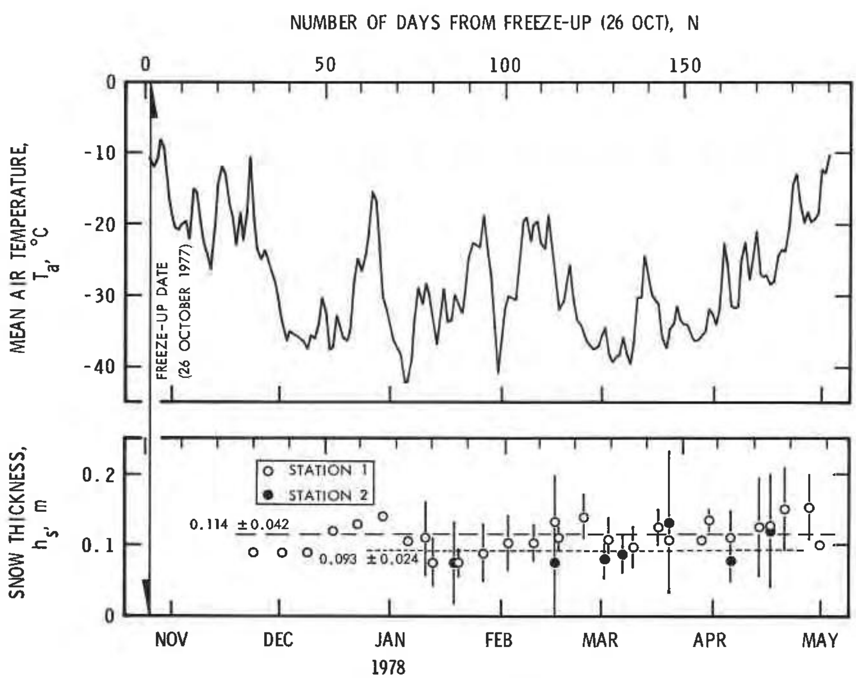
The variations in the daily mean air temperature (the average of the maximum and minimum daily air temperatures) and snow cover thickness are plotted in Fig. 1b from freeze-up to close to the end of the growing season of sea ice (Sinha and Nakawo, 1981). There was a tendency for the snow to be thicker at Station 1 than at Station 2. The average seasonal snow density was 350 ± 40 kg m^{-3} at Station 1 and 380 ± 20 kg m^{-3} at Station 2. The average bulk salinity of the ice cores was almost constant, i.e. about 6‰ for most of the season.

3 Growth history of the ice-sheet

Sinha and Nakawo (1981) presented a simple model for estimating the temperature gradient, growth rate and thickness of first-year sea ice in the High Arctic. According to their model the thickness of the ice, h_i, at a given time, t, in terms of degree-days of



a



b

Fig. 1a Location of observation sites.
b Variation of daily mean air temperature and snow thickness, winter of 1977–78, Eclipse Sound. The bars on the snow thickness values are standard deviations over 4–8 separate readings.

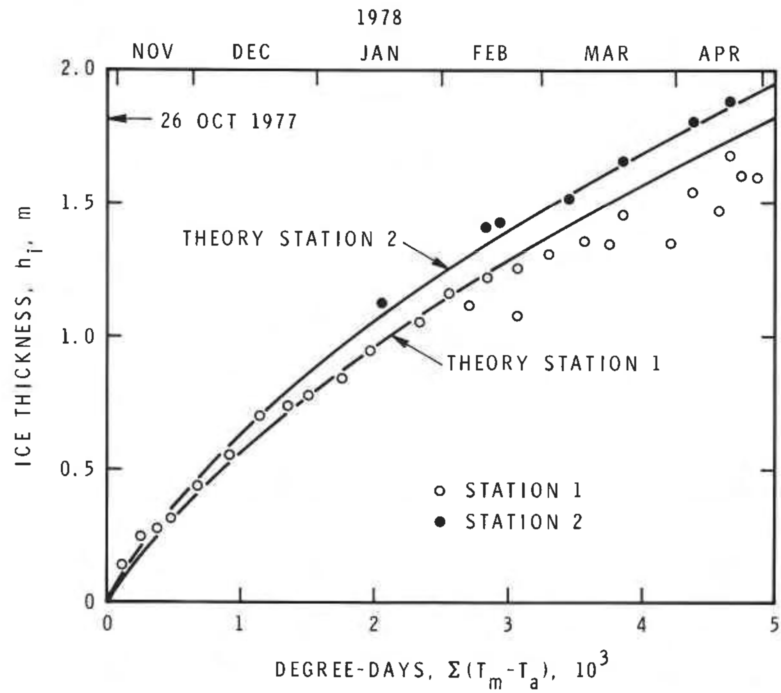


Fig. 2 Growth of ice in Eclipse Sound, winter of 1977–78. Solid lines are calculations based on Eq. (1) with the snow and ice characteristics given in Table 1.

freezing, is given by

$$\int_0^t (T_m - T_a)dt = \frac{L\rho}{2k_i} h_i^2 + \frac{L\rho h_s}{k_s} h_i \tag{1}$$

where k_i and k_s are the thermal conductivities of ice and snow, respectively; L is the latent heat of fusion; ρ is the density of sea ice; h_i and h_s are the thicknesses of ice and snow, respectively; T_m is the freezing point of sea ice; T_a is the ambient air temperature; and t is the time. A comparison of the theory with actual measurements is given in Fig. 2 for Station 1 for the 1977–78 and 1978–79 seasons and for Station 2 for the 1977–78 season (never published because the number of measurements was limited). The calculations are based on (1), the daily mean air temperatures and the snow conditions shown in Fig. 1b, and the physical properties of ice and snow given in Table 1.

4 Sampling for analyses

Two core samples, spaced 1 m apart, were recovered from the ice-sheet at Station 2 in the late afternoon of 19 January 1978 when the air temperature was −32°C. North was marked on the upper core surface before recovery. The geographical orientation was determined from markers in the ice-sheet installed earlier during survey work. When horizontal breaks occurred during coring, the orientation of the lower core

TABLE 1. Physical properties of snow and ice

Average salinity of water in the test area in Eclipse Sound = 32‰	
T_m	= −1.8°C for sea water with salinity of 32‰
ρ	= 900 ± 10 kg m^{-3} (density of sea ice at Eclipse Sound, measured at DBR/NRCC)
L	= 293 J g^{-1} (Anderson, 1960; Schwerdtfeger, 1963; Ono, 1968)
k_i	= 2.1 W m^{-1} °C^{-1} for sea ice of about 6‰ salinity (Schwerdtfeger, 1963; Ono, 1968)
h_s	= 0.114 ± 0.042 m (average snow thickness at Station 1)
	= 0.093 ± 0.024 m (average snow thickness at Station 2)
Snow density	= 350 ± 40 kg m^{-3} (average value at Station 1)
	= 380 ± 20 kg m^{-3} (average value at Station 2)
k_s	= 0.25 W m^{-1} °C^{-1} for snow density of 350 to 380 kg m^{-3} at −20 to −30°C (Pitman and Zuckerman, 1967; Mellor, 1977)

segments was estimated by matching the irregularities in the breaks. The core diameter was 75 mm and the lengths 1.130 and 1.134 m, the thicknesses of the ice-sheet at that time.

Soon after their recovery from the ice-sheet the cores were taken to the main camp where the salinity profile was established by measuring the salinity of each 0.1-m segment of the shorter core. The longer core was packed in dry ice and shipped to Ottawa for detailed analyses of the structure, including measurement of the brine layer spacing.

5 Preferred crystal orientations

The core sample had basically columnar-grained structures almost throughout its depth. The top 0.25 m, however, showed a discontinuous pattern in vertical thin sections when examined under cross-polarized light. Below 0.25 m a continuous pattern of columnar structure was observed that extended to the bottom of the sample.

Fifteen horizontal thin sections at various depths were prepared from the core, using the technique described by Sinha (1977). The orientation of the crystallographic optic axis was measured for the crystals in each thin section by the standard method with a universal stage. Figure 3 shows the distribution of orientations at three levels, plotted on a Schmidt equal-area net through the lower hemisphere. It may be seen that the optic axes of the crystals are almost all in the horizontal plane; the plunges are small. Moreover, they seem to concentrate approximately in the NE–SW direction. Neglecting the slight deviation in plunge from the horizontal, i.e. assuming that the optic axes are in the horizontal plane, the mean and standard deviations of the orientations of the optic axes were calculated. The mean orientation is shown by a two-headed arrow and the standard deviation by the "bow tie" in each fabric diagram in Fig. 3. (This representation was used by Weeks and Gow, 1978, 1980.) Similar patterns were found for the thin sections at the other levels.

Figure 4 shows the depth dependence of the variation of the mean azimuth angle, and the standard deviation. The mean was about 40° (measured clockwise from north) in the shallow sections and decreased to about 20° near the 0.8-m level, but it increased to about 40° towards the bottom. The preferred orientation near the bottom, 50 to 60° from north, agrees particularly well with the orientation of the shorelines, i.e. 60° from north. It is probable that the direction of the water current under the ice is

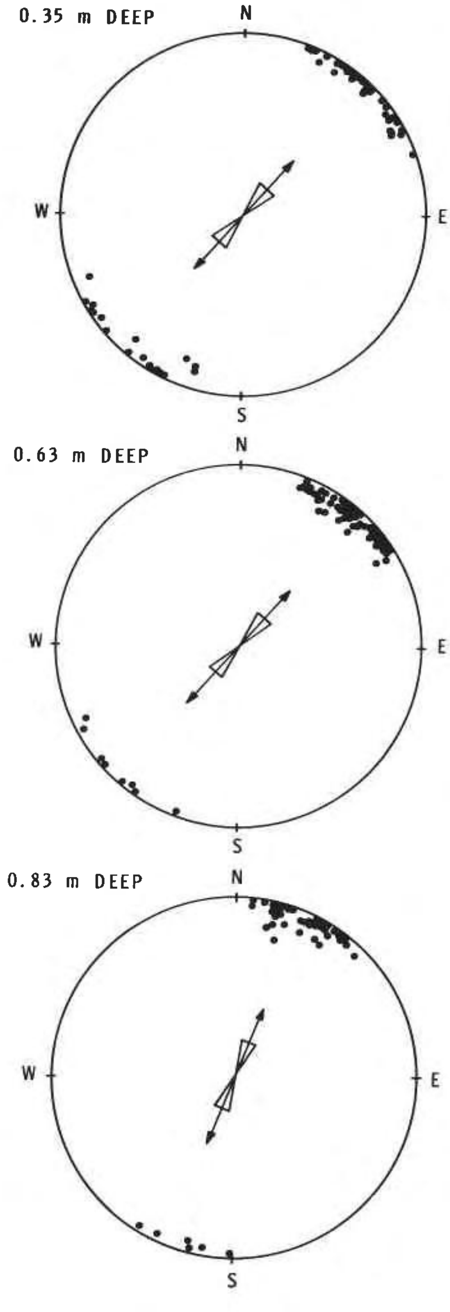


Fig. 3 The crystal optic axis orientations obtained at three different depths. The two-headed arrow indicates the mean and the "bow tie" indicates a standard deviation.

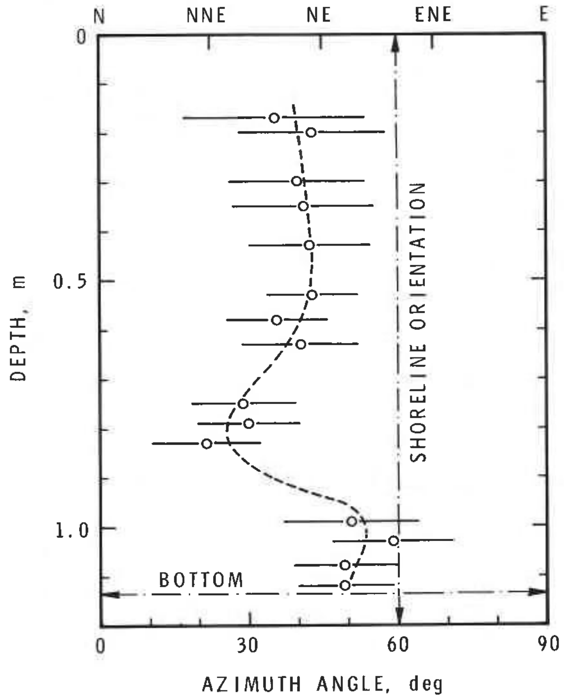


Fig. 4 The variation of the average azimuth angle of optic axis orientation. The bar shows the standard deviation.

parallel to the shoreline at the station in Eclipse Sound. These observations agree with previous observations (Weeks and Gow, 1978, 1980).

6 Vertical profile of brine layer spacing

It is known that brine pockets are present not only at grain boundaries but also inside grains of sea ice. They tend to be located on planes normal to the optic axis of a crystal. The spacing between adjacent planes or layers containing brine pockets will be called brine layer spacing in this paper.

For a horizontal thin section, the brine layers appear as rows of brine pockets, giving a mosaic pattern (Fig. 5). As the brine layers are essentially vertical, their spacing can be represented by the spacing of the brine rows found in a horizontal section. For thin sections, the spacings were measured in a cold room using a travelling microscope.

The measurements were slightly more difficult in the sections of ice near the surface because the brine rows were not always clearly distinguished owing to the wide spaces between brine pockets. Identification of a row of pockets was, therefore, rather subjective. The rows were clearer and better distinguished in thin sections from layers deeper in the ice.

Figure 6 shows the depth dependence of the average of the brine layer spacings for the single core available for study. The average spacing was about 0.7 mm near the

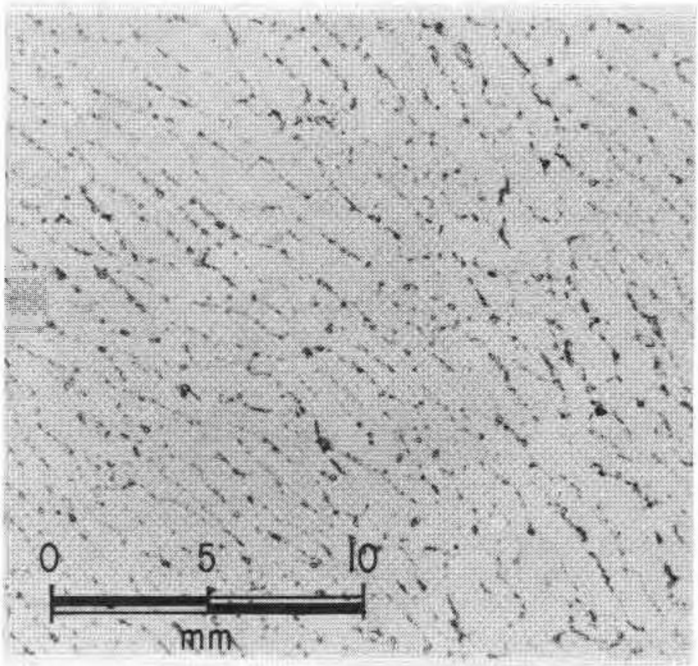


Fig. 5 An example of a horizontal thin section of sea ice. The photograph was taken using transmitted light only.

surface, decreasing to 0.5 mm near 0.4-m depth. At about 0.8-m depth, however, it increased to about 0.9 mm, decreasing again to 0.4 mm towards the bottom. Samples at shallower depths (17, 20, 30 cm) had a significant number of crystals whose optic axes were not in the horizontal plane, and consequently the brine layer spacing could be overestimated. This, however, does not apply to the wide spacings measured at depths from 0.8 to 1.0 m. The variation in the brine layer spacing with depth will be correlated with growth conditions later.

7 Brine layer spacing and crystal orientation

As shown in Fig. 4, the optic axes of the crystals were roughly within ± 15 to 20° of the mean in each thin section. In several sections, however, there were one or two domains in which the crystal orientations were distinctly different by more than 20° from those of the rest of the section, for example, in Fig. 7. The brine layer spacings and crystal orientations in these misoriented domains were measured separately for sections in which the domains were clearly distinguished.

The averages of the spacing and orientation calculated for each area are plotted in Fig. 8. There appears to be a trend for the spacing to increase in azimuth angle at a given depth as long as the angle is below about 50°. As the angle increases farther, the spacing tends to decrease with increasing azimuth, except at 1.08-m depth. The rate of the increase or decrease is different from depth to depth, but as a whole the brine

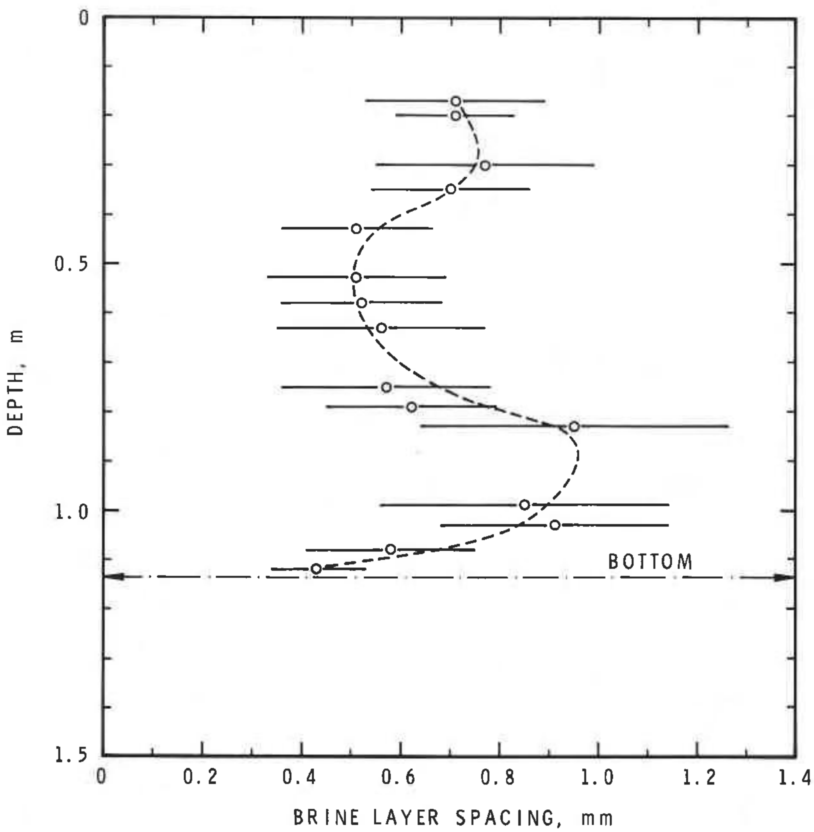


Fig. 6 The variation of the average brine layer spacing with depth. The bar shows the standard deviation.

layer spacing at a given depth seems to have a maximum value for crystals whose optic axes are about 50° clockwise from north. This orientation is close to the average orientation of crystals near the bottom of the core (Fig. 8). As mentioned, this crystallographic orientation was considered to be the one most favoured for ice growth. It seems to suggest, therefore, that at a given depth the brine layer spacing becomes greatest when the optic axes of the crystals are in the favoured direction for ice growth. Many more cores, from a variety of locations and growth histories, must be analysed, however, to confirm this conclusion, since the data in Fig. 8 are for a single core only.

8 Growth rate and brine layer spacing

Equation (1) was adopted for estimating the growth rate of sea ice of a given thickness, h_i. The daily mean temperature shown in Fig. 1 and the physical constants for snow and ice given in Table 1 were again used for the calculation. The calculated growth rate for the Station 2 core plotted against depth is shown by curve "a" in Fig. 9. Curve "b" is the mean growth rate for an interval of ± 50 mm centred on the 25-mm

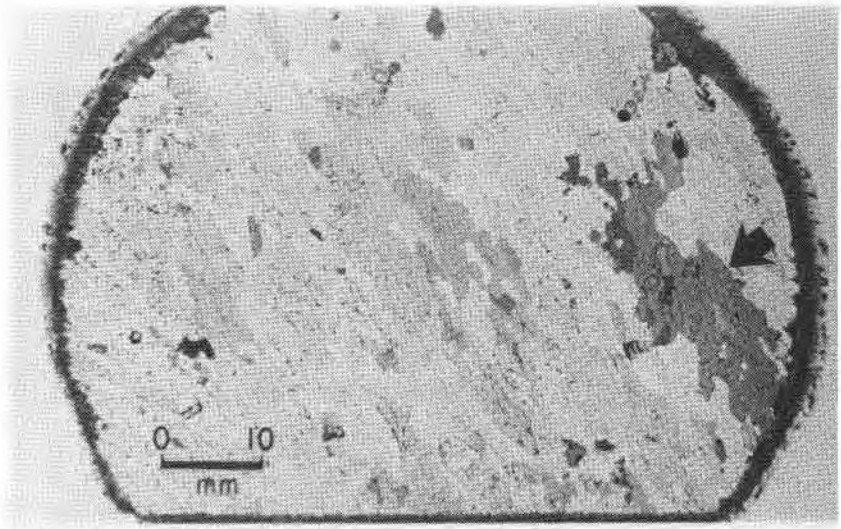


Fig. 7 An example of the misoriented domain (dark area shown by an arrow in the picture). The photograph was taken using cross-polarized light.

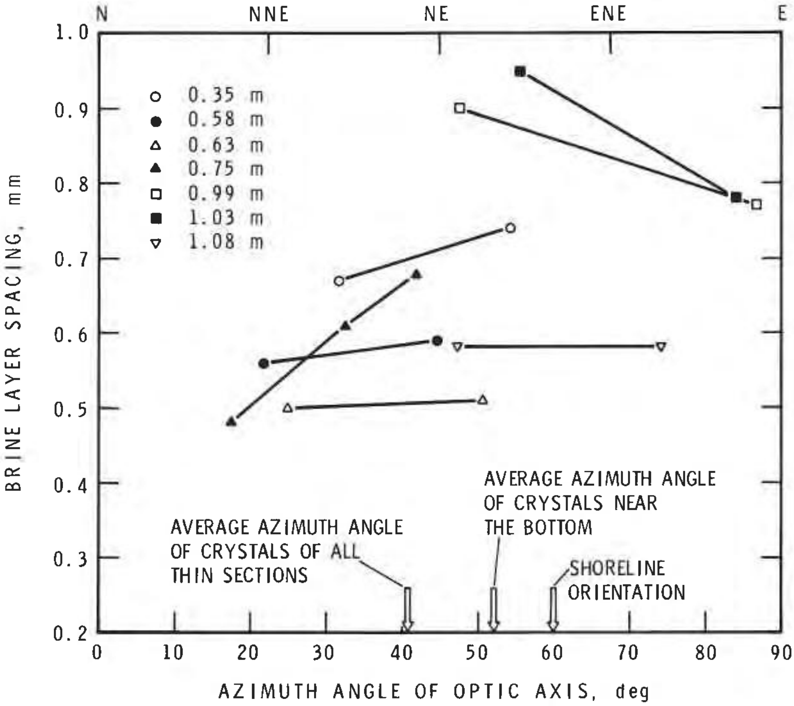


Fig. 8 Dependence of brine layer spacing on crystal orientation.

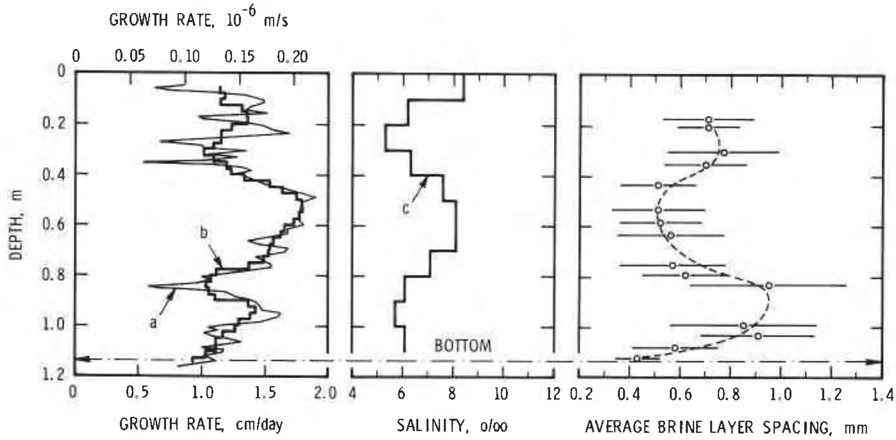


Fig. 9 Profiles of growth rate, salinity and brine layer spacing. Curve "b" represents the mean of calculated growth rate, curve "a", for an interval of ± 50 mm for every 25 mm.

segment of ice for which it is plotted. The mean growth rate would be more realistic because the thermal resistance of the snow-ice system dampens the variations in daily air temperature and hence the growth rate (Nakawo and Sinha, 1981).

There is a variation in growth rate as a function of depth; the three maxima, at about 0.2, 0.5 and 1.0 m, correspond to the cold periods in November, December and January mentioned earlier and shown in Fig. 1. The small growth rate at about 0.8 m corresponds to the warm period in late December between the latter two cold periods.

Curve "c" in Fig. 9 shows the salinity profile of the core adjacent to that used for structural analysis. Although it represents the salinity distribution in one core at Station 2, the shape of this curve, including a low salinity of 5‰ at a depth of about 0.2 m and a high salinity of 8‰ at a depth of about 0.5 m, agrees (within ±0.5‰) with the average salinity profile (average of 25 cores) obtained at Station 1 and discussed in detail in Nakawo and Sinha (1981). The similarity between curve "b" for growth rate and curve "c" for salinity in Fig. 9, indicating an interdependence between the growth rate and salt content, is also in excellent agreement with the results quantitatively analysed and presented in Nakawo and Sinha (1981) for Station 1. This type of relationship has also been observed in the laboratory (Weeks and Lofgren, 1967; Cox and Weeks, 1975).

The vertical profile of brine layer spacing given in Fig. 6 is also plotted in Fig. 9 for comparison. Note the relation between growth rate and spacing; a large growth rate seems to give a small spacing, and vice versa. This general tendency agrees with previous observations (Weeks and Hamilton, 1962; Assur and Weeks, 1963; Rohatgi and Adams, 1967a, b; Lofgren and Weeks, 1969). The data on the bottom two sections, however, are not compatible with this general trend. The growth rate decreased with depth near the bottom, yet the brine layer spacing also decreased sharply.

Bolling and Tiller (1960) predicted theoretically that the spacing is inversely proportional to the growth rate at very small rates. They also predicted, however, an

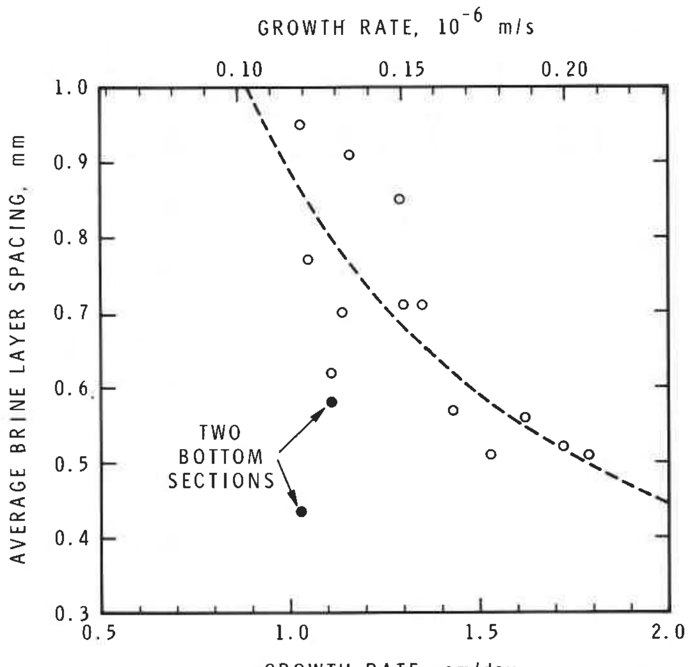


Fig. 10 Plot of average brine layer spacing (open circles) versus the corresponding growth rate of curve "b" of Fig. 9. The solid circles indicate the bottom two sections. The broken line shows a least-squares fit assuming that the spacing is inversely proportional to the growth rate.

inverse proportionality between the spacing and the square root of the rate at large growth rates. This seems to agree with the experimental data for high growth rates reported by Rohatgi and Adams (1967a, b). Lofgren and Weeks (1969) also found that Bolling and Tiller's predictions are compatible with their experimental data, but only for the experiments in which convection is not pronounced at the growing front. Their results with convection showed that, in fact, the spacing increased slightly with decreasing growth rate.

The data obtained at Eclipse Sound (open circles in Fig. 10) showed that the spacing tends to be inversely proportional to growth rate (the broken line in Fig. 10 is a least-squares fit) in accordance with Bolling and Tiller's prediction. As mentioned earlier, however, the spacing also seems to be dependent on crystallographic orientation, which was not taken into account in presenting the results given in Fig. 10. If crystallographic orientation is taken into consideration by assuming that the spacing decreases uniformly as the difference in orientation from the favoured direction increases, the trend given in Fig. 10 tends to flatten.

9 Conclusions

Systematic methods of field observation and laboratory techniques have been established for examining the microstructure of sea ice and its dependence on the growth environment. The average brine layer spacing in the bulk of sea ice depends on growth rate and crystallographic orientation and hence on the orientation of the water current under the ice. This spacing appears to be inversely proportional to the growth rate as a first approximation. A relatively small value of the spacing was observed near the bottom of the core sample that was not compatible with the general relation found between spacing and growth rate. Studies of a wide variety of cores will be required to fully investigate this aspect of the microstructure of sea ice.

Acknowledgements

Field data were collected by Steltner Development and Manufacturing Company Limited under contract with the Polar Continental Shelf Project, Energy, Mines and Resources Canada. Special thanks are extended to Messrs H.A.R. Steltner, S. Koonark, M. Komangapik and S. Koonoo for their efforts in collecting the samples and the scientific data in the harsh climatic conditions of the Arctic; and to Ms D. Komangapik, Ms S. Akoomalik and Ms J. Arnakallak for tabulating the results. The authors are also grateful to D. Wright of the Division of Building Research, National Research Council Canada, for assistance in the cold room.

This paper is a contribution from the Division of Building Research, National Research Council Canada, and is published with the approval of the Director of the Division.

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