R 494

Technical Report

CRYSTALLOGRAPHIC STUDIES OF SEA ICE IN MCMURDO SOUND, ANTARCTICA

November 1966

NAVAL FACILITIES ENGINEERING COMMAND

U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

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CRYSTALLOGRAPHIC STUDIES OF SEA ICE IN MCMURDO SOUND, ANTARCTICA

Technical Report R-494

Y-F015-11-01-026

by

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ABSTRACT

The sea ice in McMurdo Sound is used extensively for aircraft operations, travel, and docking areas. The safety and efficiency of utilizing the sea ice depends upon many factors affecting its physical properties throughout the season.

Sea ice is a crystalline solid with physical properties that are highly temperature dependent between $-1.8^{\circ}C$ and $-10^{\circ}C$. This dependence becomes less with decreasing temperatures. A study of various crystal parameters and structure is essential for a better understanding of their relationship with strength properties. Horizontal banding in the ice sheet was studied to determine the effect of temperature fluctuations on band frequency. Various crystal parameters such as subcrystal platelet width, crystal length-to-width ratios, and crystal size were measured from photographs of thin sections.

Subcrystal platelet width increased with depth from about 0.5 mm at the surface to about 1 mm at 2.8 meters. The length - width ratio of single crystals increased from 2 to 1 near the surface to more than 5 to 1 at depths greater than 2 meters. The number of crystals per unit area decreased with depth. Strained ice from a pressure ridge showed preferred c-axis orientation and wavy extinction similar to that observed in strained quartz. There is apparently no correlation between strength and crystal structure in a mature isothermal ice sheet.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

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INTRODUCTION

The sea ice in McMurdo Sound south of McMurdo Station, Antarctica, is used extensively for aircraft operations, travel, freight hauling, and docking areas for cargo handling. The safety and efficiency of utilizing the sea ice depends upon a knowledge of the many factors affecting its physical properties throughout the season.

The most important factors influencing the physical properties of the ice are grouped into two broad classes: extrinsic and intrinsic. The extrinsic factors include solar radiation, tides and currents, water temperature, and snow cover. Intrinsic factors include crystal structure, thickness, salinity, brine drainage, and ice temperature.

The relationship between crystal structure and strength is well known for many crystalline solids. Sea ice is a crystalline solid with physical properties that are highly temperature dependent, especially between -1.8° and $-30^{\circ}C$. The crystal parameters and strength properties of sea ice vary widely and are related to temperature and the growth history of the ice. A detailed study of the crystal structure and other internal features is essential for a better understanding of their relationship with strength properties.

This report presents the results of sea ice crystal studies on that part of McMurdo Sound that forms an embayment south and west of Hut Point Peninsula, Ross Island, Antarctica. The studies were conducted between October 1965 and February 1966 on sea ice 8 to 11 months old. Temperature, salinity, stratigraphy, platelet width, and other crystal parameters were measured at selected locations where different environmental factors may have affected the stratigraphy and crystallography. Ring-tensile strength tests were performed after the ice sheet became nearly isothermal in an attempt to correlate strength with the above properties.

DESCRIPTION OF SEA ICE

Sea ice is different from freshwater ice in many respects — as for example, in salinity, crystallography, freezing temperature, density, features caused by brine drainage, and heterogeneity of physical properties. Sea ice is difficult to describe because it is composed of pure ice crystals, salt crystals, bubbles, and brine cavities of various sizes and shapes, all apparently distributed at random. Sea ice crystals are actually bundles of small, pure ice platelets separated by layers of brine and brine drainage cavities. Ice crystallizes in the hexagonal form, and individual subcrystal platelets are usually disc-shaped normal to the principal, or crystallographic, c-axis. Platelet width, and usually crystal width also, is measured parallel to the direction of the c-axis.

Seawater with a salinity of 30 to 35 parts per thousand begins to freeze at about −1.8°C; the ice sheet then grows at a rate that is primarily dependent upon the air temperature. As the ice sheet grows, brine cavities form that are elliptical or circular in plan view and elongate vertically. The temperature and salinity of the ice determines the brine content, and together with density, the air content (Anderson, 1958, p. 148).

STUDY AREA

Location

McMurdo Sound is located at the western extremity of the Ross Ice Shelf and is part of the Ross Sea that is bounded on the east by Ross Island, the west by the mountains of Victoria Land, and the south by the Ross Ice Shelf. McMurdo Station and Scott Base are located on Ross Island near the tip of Hut Point Peninsula (Figure 1). The camp occupied by personnel of the U. S. Naval Civil Engineering Laboratory (NCEL) is on the Ross Ice Shelf 2 miles southeast of Scott Base. The study area was located on the embayment south of Hut Point Peninsula.

Climate

The climate of the McMurdo Sound area is characterized by low temperatures, extreme temperature fluctuations, frequent high winds, and drifting snow. Mean annual temperatures for the years 1956 to 1961 vary from −18.5°C (−1.3°F) to 17.1°C (1.8°F), with a mean for the 6 years of −17.8°C (-0.1°F). The coldest temperatures occur in July and August, and vary from −40°C (−40°F) to −50°C (−59°F). Maximum temperatures occur in December and January, and can be as high as 5.5°C (42°F) (Climatology of McMurdo Sound, 1961).

The freezing index is the number of degree days during a freezing season and is one of the best methods of expressing the duration and intensity of cold. The degree days for any one day equals the difference between the average daily air temperature and 0°C (32°F) (Linell, 1953, p. 19). The mean air freezing index at McMurdo Station is approximately 13,300 degree days. At Point Barrow, Alaska, the freezing index is 8,500 degree days (Péwé and Paige, 1963, p. 366). Other factors, such as hours of sunshine and solar radiation, are also important in defining the climate of a region and are summarized for McMurdo Sound by Paige and Lee (1965).

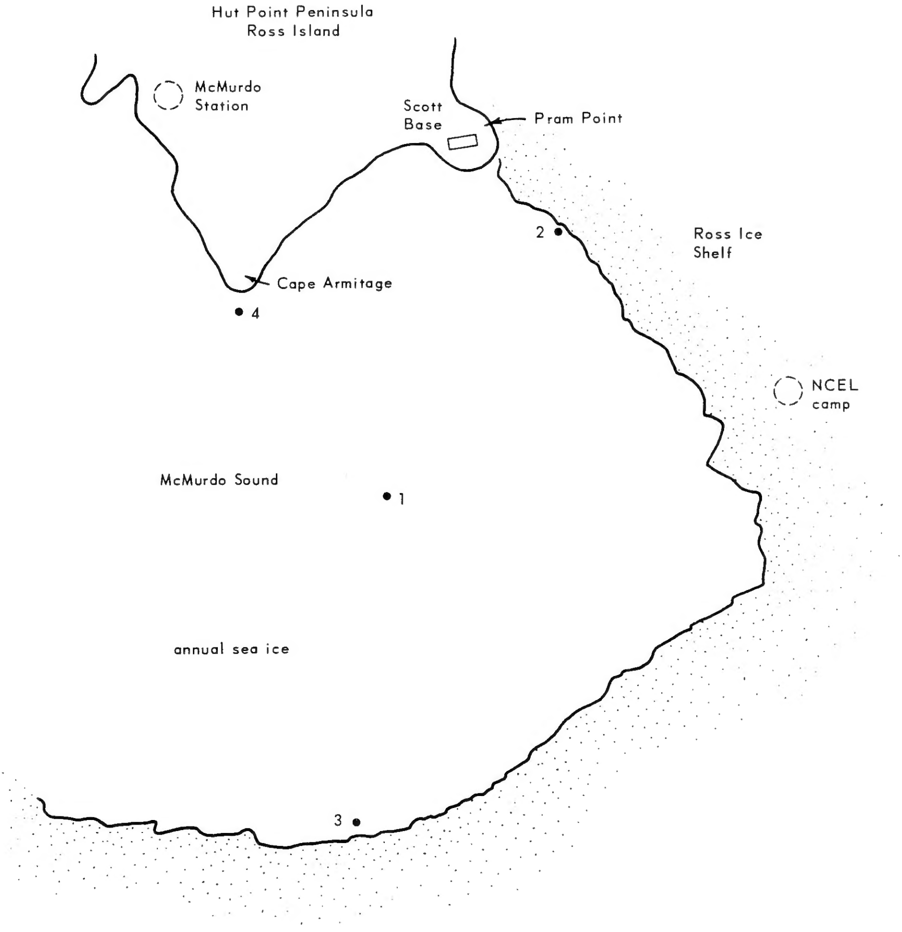


Figure 1. Location of sample sites for sea ice crystal studies. Block samples collected only from station 1.

Sea Ice

The embayment south of Hut Point Peninsula is covered by ice for at least 10 months each year. The maximum breakout commonly occurs in late January or in February, and the sea is usually frozen over again by late March (Heine, 1963, p. 399). During the winter months from March to November the ice sheet grows at a fairly steady rate. In late November the growth rate decreases, and usually by mid-December the ice reaches its maximum thickness of 8 to 11 feet. Surface melting is negligible, but in late December the ice begins to deteriorate internally and starts to thin because of bottom melting.

The thickness and growth rate of the sea ice vary with time and location and are also affected by circulation, depth of water, exposure to wind, and snow cover. Figure 2 shows the maximum ice thickness at four different localities during the austral summer of 1965-66. Figure 3 shows the growth rate from the end of May 1965 to breakout early in February 1966. Data on the initial stages of ice growth in the fall of 1965 are not available; however, data from previous years (Tate, 1963) show that the growth rate is rapid: about 3.2 centimeters per day from the end of March to about the middle of April. A decrease in growth rate during mid-August and the final decrease starting at the end of September are reflected by systematic changes in crystal parameters, as discussed later in this report.

Sample Sites and Study Methods

The four sample sites for the sea ice crystal studies were located, as shown on Figure 1, within the embayment south of Hut Point Peninsula. Samples were collected from three sites where the ice sheet was thought to have had different growth histories significant enough to be reflected by different crystallographic features. The fourth site was used for thickness measurements only.

Core samples were collected with a standard coring auger and stored in a cold room at −12°C to −9°C. Thin sections were made from the cores and from blocks cut from the upper part of the ice sheet at station 1. Several blocks illustrating growth features at the bottom of the ice sheet were collected from broken and overturned ice behind the icebreaker USS Glacier in the area opposite McMurdo Station.

Large-scale features easily seen in a sea ice sheet, such as banding and large brine drainage channels, were studied to determine their origin and relation to the history of the ice. Data concerning the nature of ice growth, crystal size and orientation, and the morphology of the bottom surface of a thick, growing ice sheet are rare because direct measurements are difficult to obtain. During Deep Freeze 66, direct observations and estimates of crystal size and relative relief at the bottom were made from an under-ice observation chamber installed by the U. S. Antarctic Research Program.

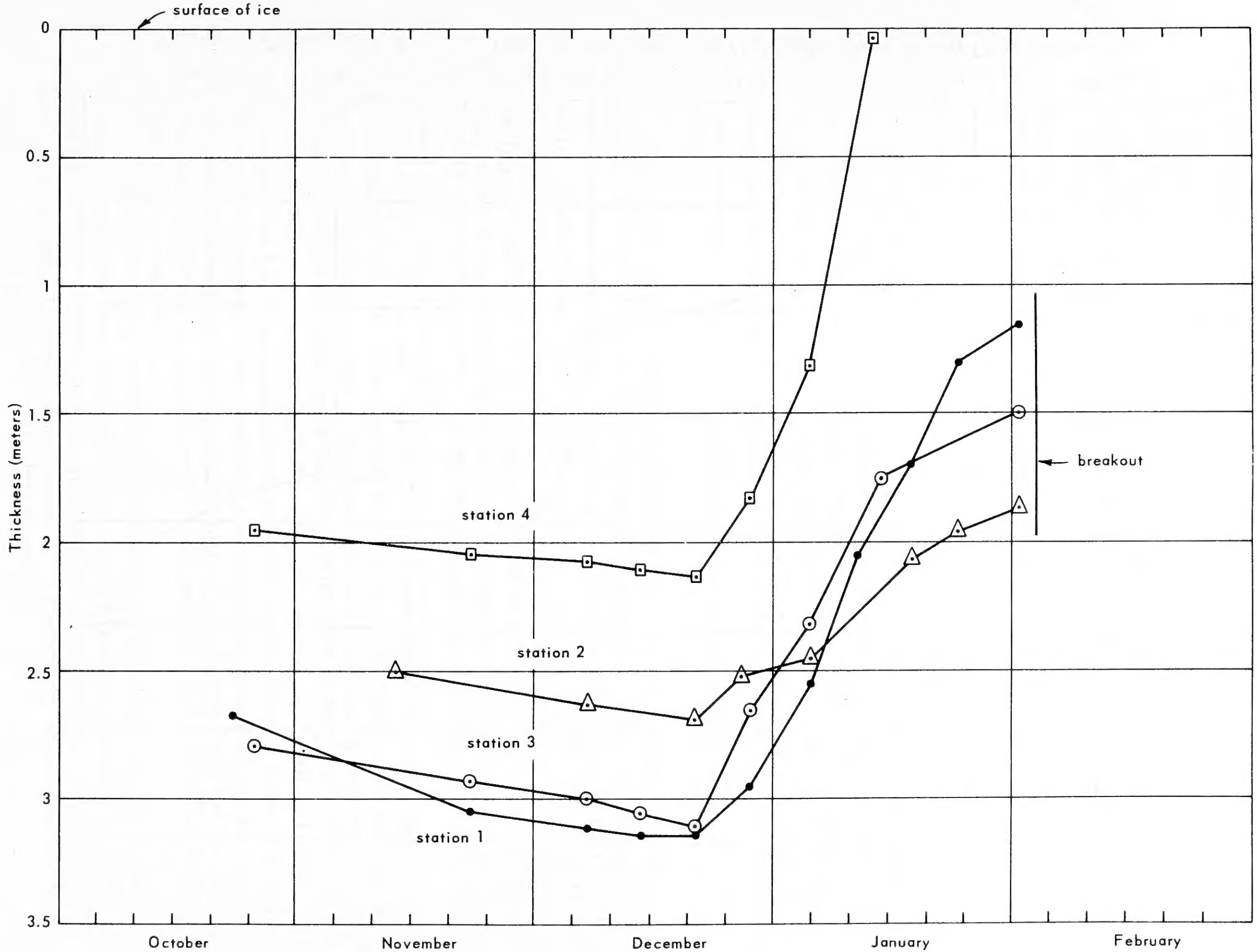


Figure 2. Growth and thickness of annual sea ice at stations 1, 2, 3, and 4 during Deep Freeze 66.

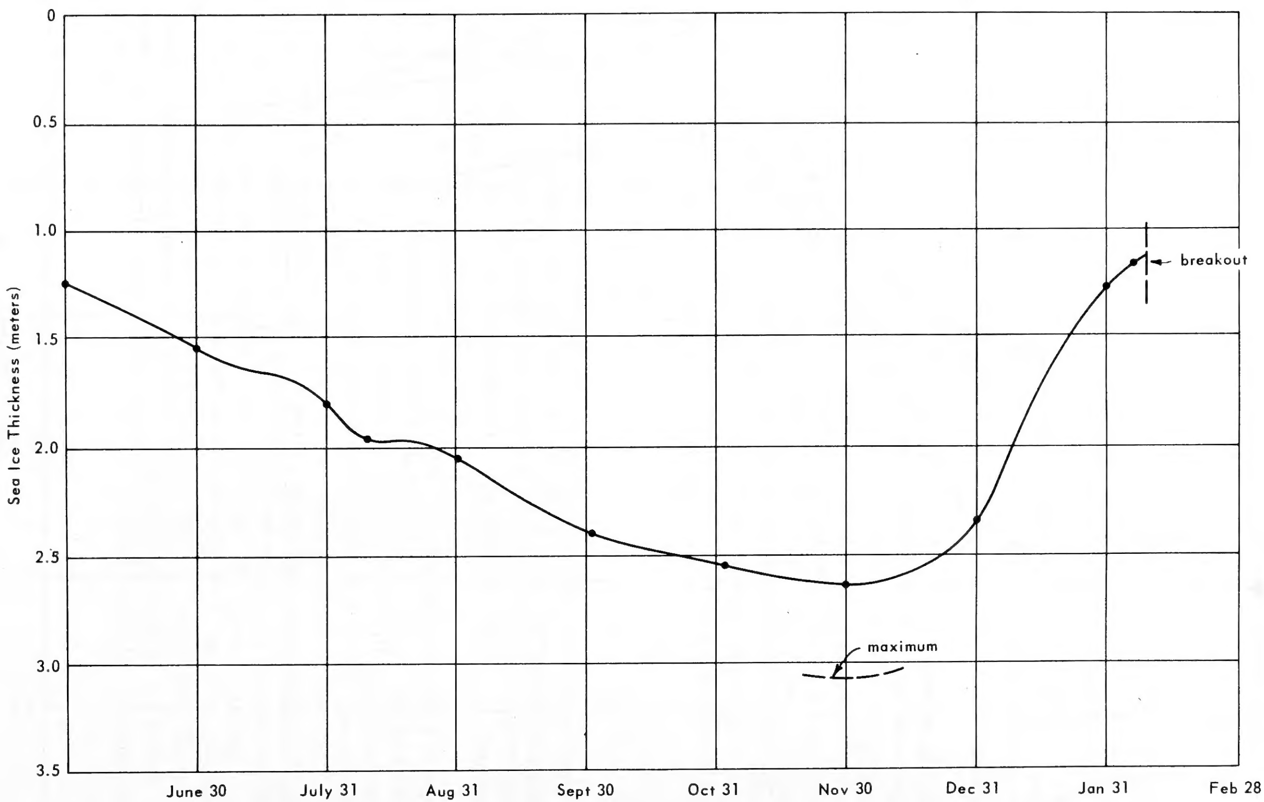


Figure 3. Growth and thinning of the annual sea ice in McMurdo Sound during Deep Freeze 66.

Small-scale details and measurements of various crystal parameters were obtained from thin sections of sea ice that were photographed under plain and crossed polarized light to bring out different features. Most of the crystal measurements were made from enlargements of the photographs. Ring-tensile strength data collected after the ice sheet had become nearly isothermal were plotted and compared with temperature, salinity, platelet width, and other crystal parameters in an attempt to correlate these properties with the strength data.

LARGE-SCALE FEATURES

The most obvious features visible in a vertical section of an ice sheet are horizontal banding (stratification), brine drainage channels and cavities, and bubble zones. Under natural conditions these features are usually seen only in pressure areas, where the ice may be uplifted, broken, or tilted in such a way as to expose a vertical section. The easiest way to study these features is to extract complete 7.62-cm-diameter cores and photograph sections of the core against a dark background.

Banding

Horizontal bands of alternating blue and white ice are a prominent feature in uplifted or tilted blocks of sea ice, especially when the ice has been exposed for several days and the bands are emphasized by sublimation. Banding, or stratification, in arctic sea ice has been briefly discussed by Schwarzacher (1959) and Smith (1964). Bennington (1963) presents an excellent discussion of banding in arctic sea ice and states (pp. 681-682) that bands are caused by one of the following processes: (1) an accumulation of crystals with vertical c-axis orientation, (2) high-porosity zones consisting of brine pockets along staggered intersections of platelets, and (3) the expansion of trapped brine pockets.

Banding in the sea ice of McMurdo Sound was seen at all levels, but occurred most frequently and with closer spacing in the upper half of the ice sheet. The frequency of the bands (number of bands per foot) and the spacing between them varied from place to place and apparently reflected differences in the growth history of the ice. The bands varied in width from 1 to several centimeters and all had diffuse boundaries. The ice between bands was generally clear, although zones of a slightly milky ice were common. Long, vertical, small-diameter brine drainage channels were common throughout the ice sheet but increased in size and number towards the bottom. The bands were easily seen in cores or blocks but were almost indistinguishable in thin section.

Banding in the sea ice of McMurdo Sound consists of high-porosity zones formed by horizontal rows of minute, closely spaced, elongated bubbles and brine drainage cavities. They are apparently caused by the downward drainage of high-density brine formed during platelet growth under supercooled conditions at the ice-water interface. According to Bennington (1963) the growing platelets separate brine with a progressively increasing concentration and density. This unstable brine layer then cascades to a lower level and leaves a greater proportion of brine pockets (p. 683). In discussing a possible driving mechanism for brine drainage, Bennington (1966) also states that temperature fluctuations create internal pressure changes that result in brine expulsion from the zone of growing platelets. Each temperature-related episode of brine expulsion would, therefore, form a band and, in turn, record the temperature fluctuation. Dykins (1966, p. 19) describes banding that occurred while freezing seawater in a laboratory tank and states that it may have been caused by varying the temperature in the freezing chamber.

That the development of banding is related to temperature effects during the growth of the ice is strikingly evident in the different band frequency seen in the cores from stations 1, 2, and 4. At station 1 (Figure 4), where the ice grew over the deep, open water of McMurdo Sound, there were 19 bands in the upper 60 cm (2 feet). At station 2 (Figure 5), where the ice grew in a protected zone of deep, quiet water between the ice shelf and a stranded iceberg, there were eight bands in the upper 60 cm. At station 4 (Figure 6), where an early snow cover 91 cm thick dampened the effect of temperature fluctuations, there were only five bands in the upper 60 cm.

A temperature decrease promotes the growth of platelets and the attendant expulsion of brine. As the temperature of the ice becomes colder during the early stages of ice growth, pure ice platelets are able to grow from seawater of increasing brine concentration. Zones of clear ice between bands probably represent periods of steady growth when convection, tidal currents, or other circulation allowed platelets to grow from seawater of normal salinity.

In McMurdo Sound the decrease in frequency and the increased spacing between bands from the top of the ice sheet downward results from the dampening of temperature fluctuations by the thickening ice sheet. From the 1.2-meter depth (4 feet) to the bottom of the ice sheet, banding is either rare or absent. Thus, it appears that banding accurately records the temperature fluctuations of an ice sheet during its growth.

Brine Drainage

During the early growth stages of sea ice, brine is expelled by the growing platelets of pure ice and becomes trapped as layers and as vertical elongated cells at interplatelet boundaries. It is this localization of brine cells and cavities that so clearly defines the subcrystal structure of sea ice. Figure 7 is a horizontal thin section of sea ice that shows brine cells and layers outlining the platelets of pure ice. While the ice sheet grows during the coldest part of the winter, most brine features are small and closely spaced except for occasional large vertical drainage channels. As the ice sheet warms during the summer, the size and shape of brine drainage features change considerably.

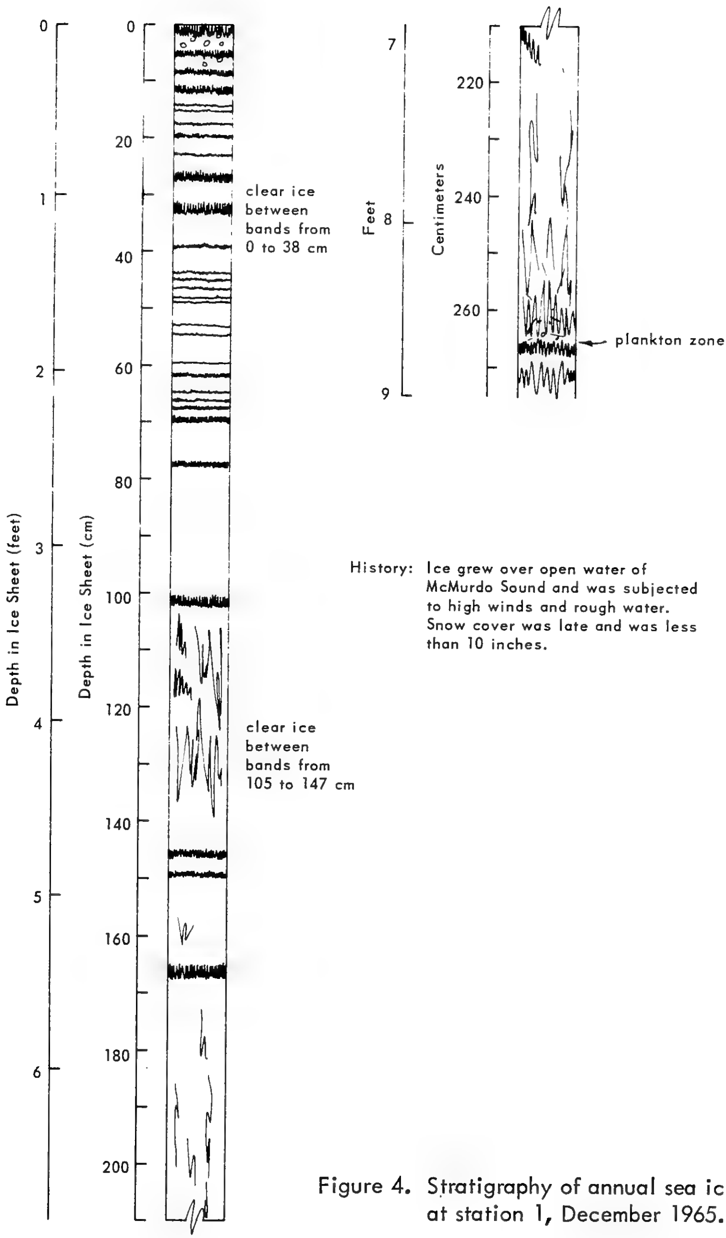


Figure 4. Stratigraphy of annual sea ice at station 1, December 1965.

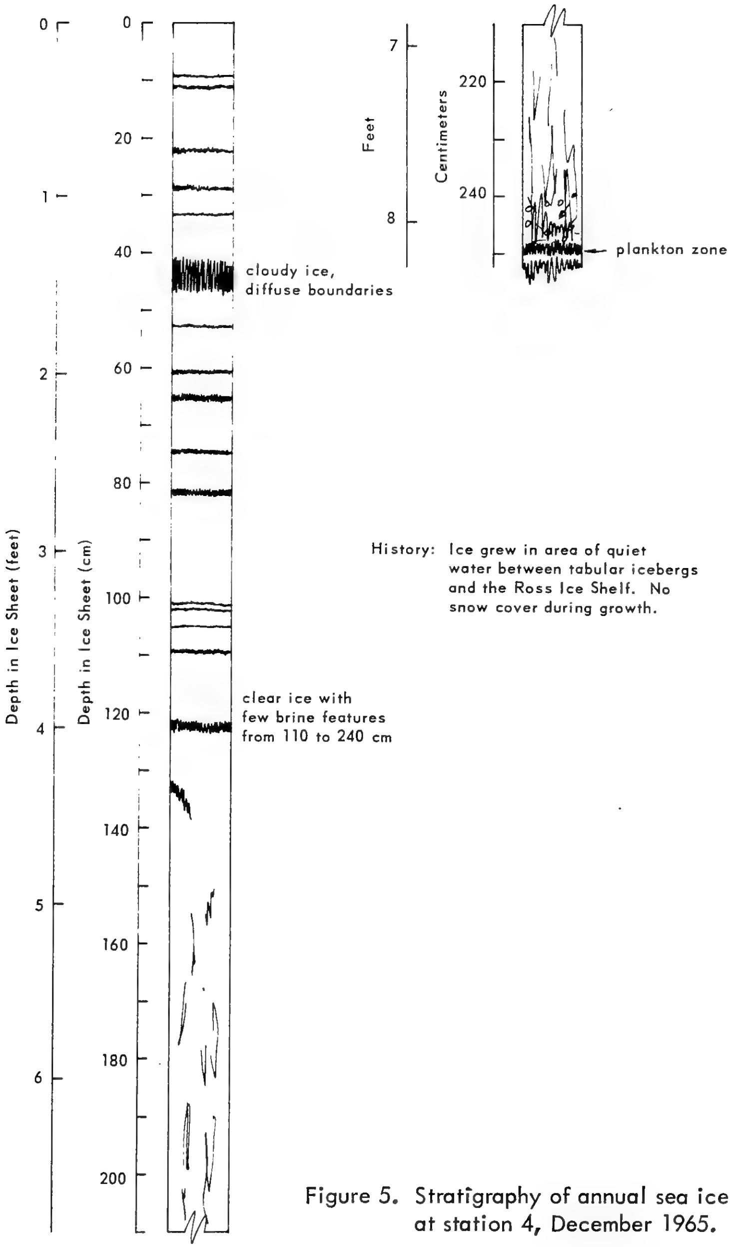


Figure 5. Stratigraphy of annual sea ice at station 4, December 1965.

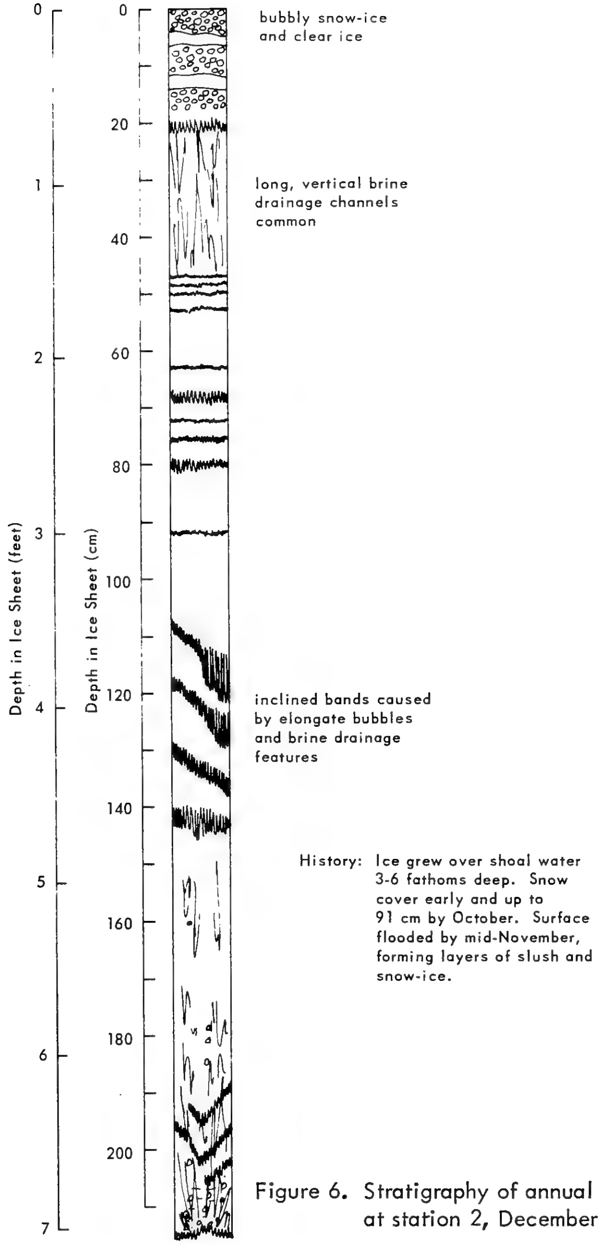


Figure 6. Stratigraphy of annual sea ice at station 2, December 1965.

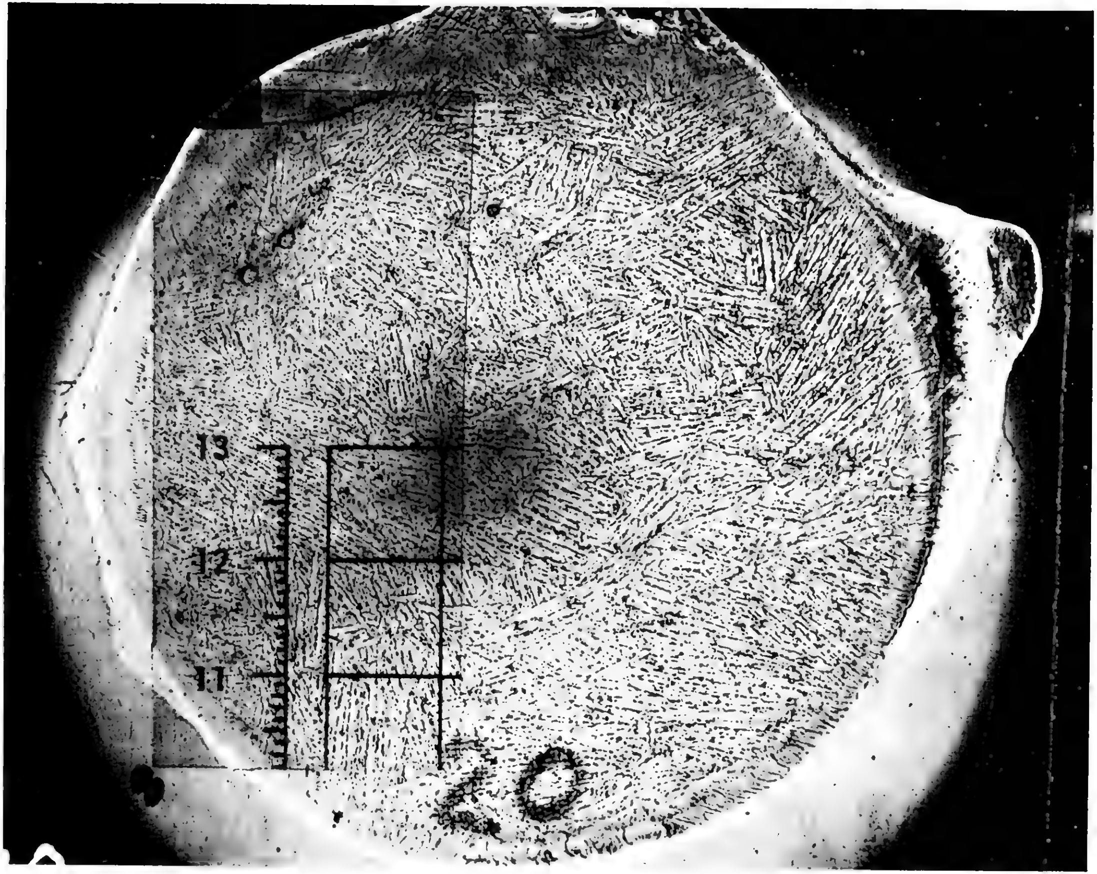


Figure 7. Thin section of sea ice from a depth of 50 cm showing crystal structure, platelets, and brine features. Grid is 1 cm.

By late December high ambient temperatures and strong solar radiation in the McMurdo area caused the ice sheet to become nearly isothermal and to approach the melting point of sea ice. Brine drainage was accelerated as the cells enlarged and coalesced (Figure 8) and formed long columnar brine drainage channels normal to the surface of the ice. Many of the brine drainage channels were open to the sea below and filled with seawater to a level depending upon hydrostatic conditions of the ice sheet. Solar radiation transmits considerable energy to the ice sheet, especially if the ice has no protective layer of snow. Because of this, a zone of unusually weak ice occurred between the 30- and 91-cm depth, where brine cavities became numerous and large.

Bottom Growth

The bottom of a growing sea ice sheet is unlike that of freshwater ice and is characterized by an irregular surface with numerous disconnected ice platelets protruding downward into the seawater. This layer has been termed the "skeleton layer" by Assur (in Butkovich, 1956, p. 1) and results from the separation of pure ice platelets freezing from seawater, as explained by Weeks (1958, p. 97).

The small amount of available information regarding the thickness of the skeleton layer comes from various sea ice studies in the arctic and subarctic. The skeleton layer has been observed in arctic sea ice to be 2.4 to 2.8 cm (Weeks and Anderson, 1958, p. 644), 1 to 2 cm (Schwarzacher, 1959), and up to 2 cm (Bennington, 1963, p. 685).

Direct observation revealed that the bottom surface of the growing ice sheet in McMurdo Sound had a skeleton layer 10 to 15 cm thick, with a maximum of 30 cm in isolated locations. Individual sheet-like platelets that protruded downward 10 to 15 cm beyond the bottom of the ice sheet were common. The bottom surface was undulating and extremely irregular, with a possible relative relief of at least 60 cm (2 feet). It must be emphasized that the above observations were made when the ice was more than 1.8 meters thick and about 10 months old.

The idealized concept of platelet-crystal growth at the bottom of a sea ice sheet shows the platelets growing vertically downward with their c-axes truly horizontal (Assur and Weeks, 1964, p. 4), (Stehle, 1965, p. 3), and (Peyton, 1963, p. 109). Weeks and Anderson (1958, p. 643) describe the skeleton layer as consisting of unconnected vertical ice plates. Two photographs by Bennington (1963, pp. 679, 682) of vertical thin sections from the bottom of thick ice clearly show that c-axis horizontal crystals predominate.

The c-axis orientation of platelet-crystal growth at the bottom of thick sea in McMurdo Sound was random, with only a slight majority of platelets growing vertically downward. Figure 9 shows a slab cut vertically from the bottom of 2.44-meter-thick sea ice. The slab was about 25 cm wide, 25 cm long, and 1 cm thick. The dendritic platelet growth with the c-axes inclined at a wide variety of angles is quite evident. Figure 10 is a vertical thin section at a depth of 246 to 254 cm, where the ice was 2.7 meters thick. Crystals with the c-axis inclined far from the horizontal predominate in this section. Figure 11 is a horizontal thin section from within 5 cm of the bottom of ice 2.87 meters thick. Again, the variety of c-axis angles is obvious, as shown by the large, irregular clear areas.

When the sea ice stopped growing and bottom melting began, the skeleton layer was quickly destroyed and, as melting progressed upward, crystals with horizontal c-axis orientations predominated. This suggests that during the early stages of ice growth in McMurdo Sound, the skeleton layer is thin with mostly horizontal c-axis crystal growth, as reported for arctic sea ice. The unusually thick skeleton layer with its variety of c-axis orientations may not begin to form until late in the winter, when the growth rate becomes extremely slow (about 10 cm for November) and the ice is usually more than 2.4 meters thick. The bottom surface of the melting ice sheet became smooth and attained a reversed sun-cupped appearance similar to the surface of an ablating snowfield.

STRUCTURAL PARAMETERS

Structure, as used herein, defines the relationship of sea ice crystals to each other as well as their size, shape, subcrystal features, and c-axis orientation. In a horizontal section, the structure consists of an intensely interlocking mosaic of elongate, sharply angular crystals. Brine layers and cavities occur both at crystal and subcrystal boundaries and vary in size and shape depending upon the age and temperature of the ice. In a vertical section, individual crystals appear as long, lenticular, spindle-shaped grains with their long axis normal to the surface of the ice sheet. Brine features are also commonly elongate in a vertical section, as compared to round or elliptical in a horizontal section. C-axis orientation is predominantly random in the horizontal plane except in the upper few centimeters and at the bottom of a growing ice sheet.

Gross crystal parameters, such as length, length-width ratio, relative size in terms of crystals per unit area, and subcrystal platelet width, were plotted against depth in the McMurdo ice sheet. All measurements were made in the horizontal plane from photographs of thin sections and are somewhat subjective. Each point plotted is an average of 8 to 12 measurements. Most of the measurements are restricted to a 7.62-cm-diameter core specimen and do not truly represent crystal dimensions at the bottom of the thick, growing ice sheet. For example, actual crystal lengths were as much as 15 cm (horizontally) and some crystals were so large that only a small fraction of the crystal occupied 1 cm^2.

Figure 8. Vertical thin section of sea ice from a depth of 147 to 155 cm showing brine drainage features. Grid is 1 cm.

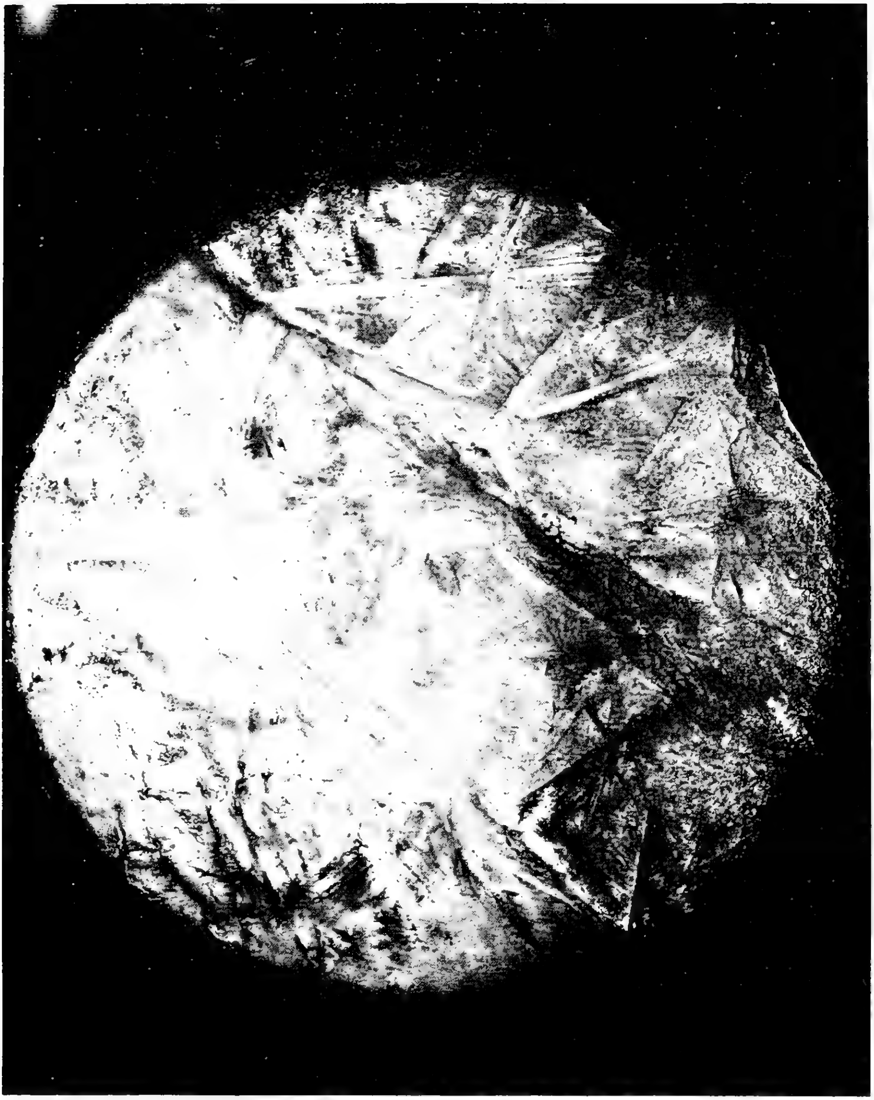


Figure 9. Vertical slab from the bottom of sea ice 2.44 meters thick. Slab is 25 cm across.

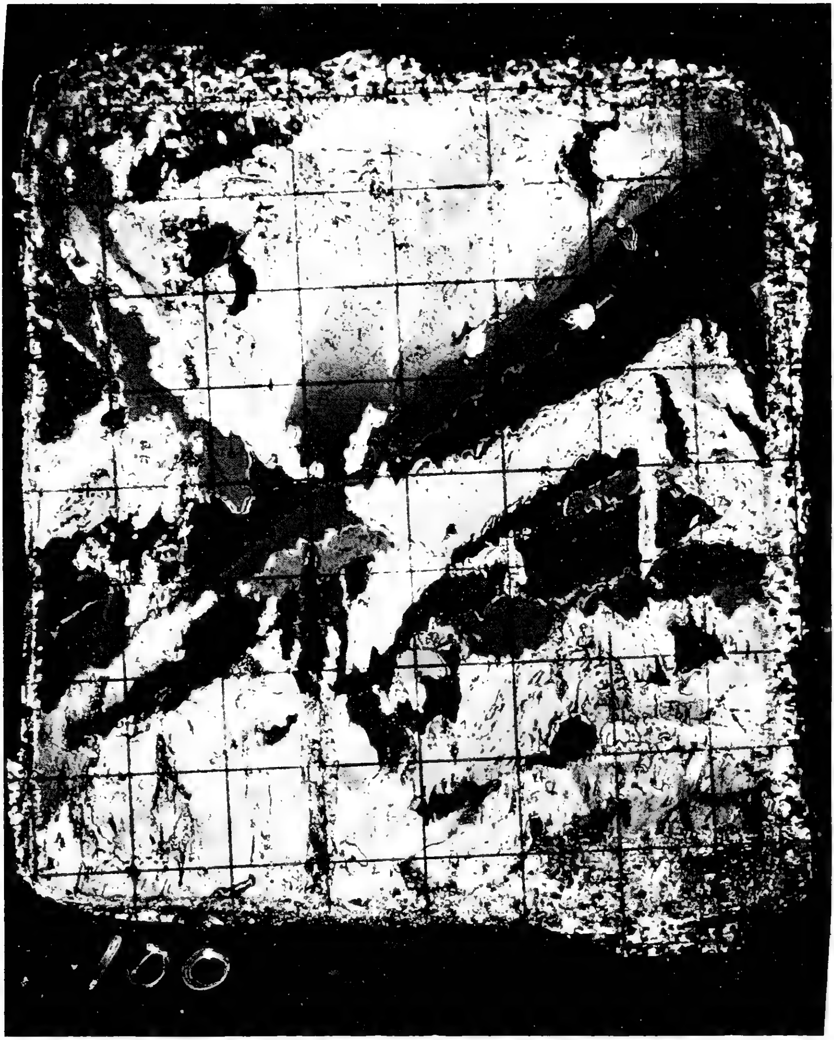


Figure 10. Vertical thin section of sea ice from a depth of 246 to 254 cm, showing platelets with random c-axis orientation. Photographed under crossed polarized light. Grid is 1 cm.

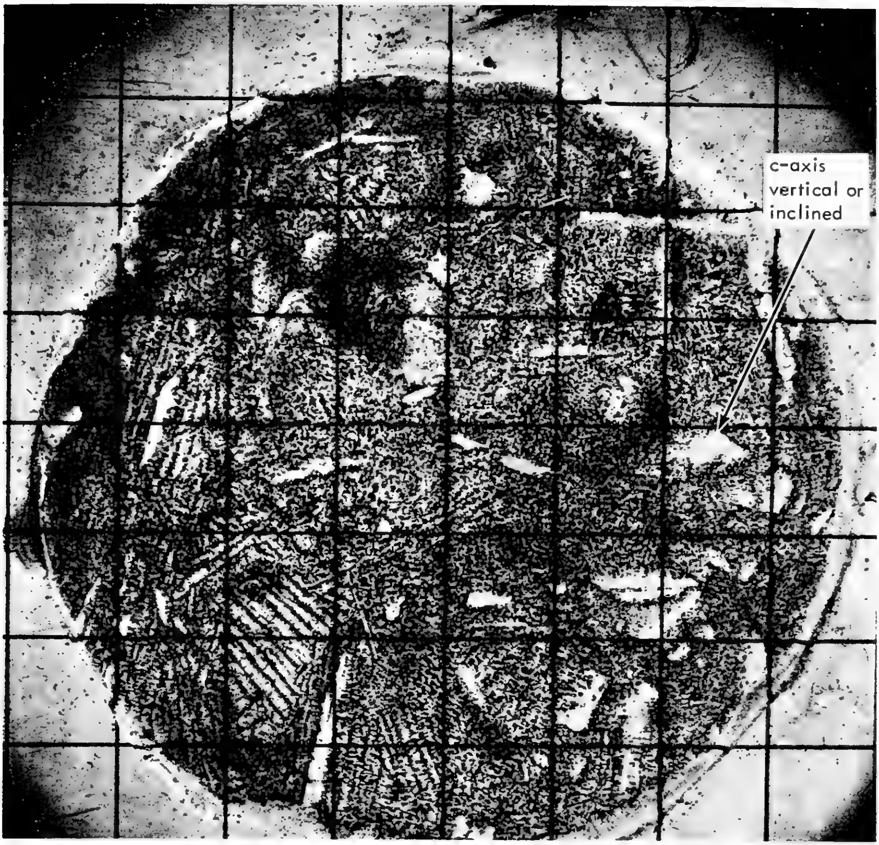


Figure 11. Thin section of sea ice from a depth of 282 cm, showing platelets with a variety of c-axis orientation. Photographed under crossed polarized light. Grid is 1 cm.

Crystal Length Versus Depth

In Figure 12 the crystal length in a horizontal plane is plotted against depth in the ice sheet. Measurements were made from thin section photographs at various depth levels and from two locations. These measurements show a systematic and definite increase of crystal length with depth as related to the growth rate of the ice. This increase probably applies to length both horizontally and vertically, although crystal dimensions in a vertical plane are difficult to obtain and are not presently available.

Crystal Length-to-Width Ratio

The ratio of crystal length to width in a horizontal plane is shown in Figure 13. The true ratio is probably not accurately represented for ice near the bottom because of the restricting effect of the 7.62-cm-diameter specimen. The length was measured normal to the c-axis direction, and the width was measured parallel to the c-axis. It was observed that the length-to-width ratio changed considerably with depth and, for this reason, the data were arbitrarily divided at the 1.2-meter depth and were plotted separately to emphasize this difference. The change in the length - width ratio is not abrupt but is probably gradational downward through the ice sheet.

For the 0- to 120-cm depth, the length - width ratio is approximately two to one, which compares closely with data by Weeks and Hamilton (1962, p. 953) from arctic sea ice 30 cm thick. However, as the ice sheet becomes thicker, the length - width ratio becomes more nearly five to one, as shown in Figure 13. The scatter in both plots was caused by crystals having a width greater than their length. It is also obvious that there is only a slight increase of crystal width versus depth, and that this parameter is of little significance.

Crystals Per Square Centimeter

The number of complete crystals in a measured area on the photograph of a thin section were counted and plotted against depth in Figure 14. More data from closely spaced depth intervals were available from station 1 than from station 3 and show strong fluctuations in number of crystals per unit area in the upper 91 cm of the ice sheet. The large number of crystals per square centimeter at the 40-cm level probably indicates a period of extreme cold, when rapid ice growth formed small crystals. As the ice sheet became thicker, growth rate decreased and crystal size increased accordingly. Such an increase in crystal size with depth is discussed by Weeks and Hamilton (1962, p. 951), who compare it with similar phenomena occurring in metal castings. Dykins (1966, p. 25) shows a strong increase in crystal size with depth in sea ice grown under laboratory conditions. In the reports cited above, it is shown that there is less than 1 crystal per square centimeter in ice no more than

40 cm thick. Observations of McMurdo Sound sea ice show that, although there are many crystals of enormous size near the bottom of a thick ice sheet, there are also many crystals that occupy much less area than 1 cm^2. When crystals of all sizes were considered, the average was found to be about 1 crystal per square centimeter for the bottom meter of the ice sheet.

Platelet Width Versus Depth

An average platelet width of 0.45 mm, with a range varying from 0.2 to 0.8 mm, was determined for arctic sea ice by Weeks (1958, p. 97). Schwarzacher (1959) made about 500 measurements of arctic sea ice to get an average platelet width of 0.902 mm (p. 2359), or about twice that determined by Weeks. Weeks and Hamilton (1962) describe the subcrystal structure in arctic sea ice 30 cm thick and state that one of the apparent variations in structure is the gradual increase in platelet width with increasing depth (p. 954). They further state, however, that the expected variation in platelet width with depth has not yet been demonstrated.

Figure 15 is a plot of platelet width versus depth in the ice sheet. Measurements were made at various depths from thin section photographs of sea ice at stations 1, 2, and 3. Platelet widths were measured in the horizontal plane parallel to the c-axis by counting the number of distinct platelets within a predetermined linear distance and dividing to obtain an average width. Measurements were also made from cores collected on three different dates at station 1, but show no apparent differences in width that can be related to time or temperature changes. The systematic increase in platelet width from about 0.4 mm near the surface to more than 1.0 mm at the bottom is clearly shown in Figure 15.

Stressed Sea Ice

A sea ice specimen oriented in relation to the stress field was collected from the crest of a small pressure ridge near station 2 to study the effect of stress on the crystal structure. The ice in the actively growing pressure ridge was about 2.44 meters (8 feet) thick and had been stressed for at least 8 months by horizontal pressure from the adjacent westward-moving McMurdo Ice Shelf.

A thin section from a depth of 20 cm photographed in crossed polarized light is shown in Figure 16. The large arrows in photograph 16a show the direction of tensile stress. The small lines on the photograph show the strongly preferred direction of c-axis orientation typical of many stressed materials made up of elongate, plate-like, or tabular crystals. Photograph 16b has been rotated 20 degrees under crossed polarized light to show the wavy extinction in the large crystal in the center of the view. Wavy extinction is typical in thin-section photographs of strained minerals such as quartz or olivine, and is a good criterion that the mineral has undergone stress sufficient to cause crystal deformation. The preferred c-axis orientation and the wavy extinction occurring in stressed sea ice indicate that the stress conditions in a sea ice sheet can be deduced by detailed crystal studies.

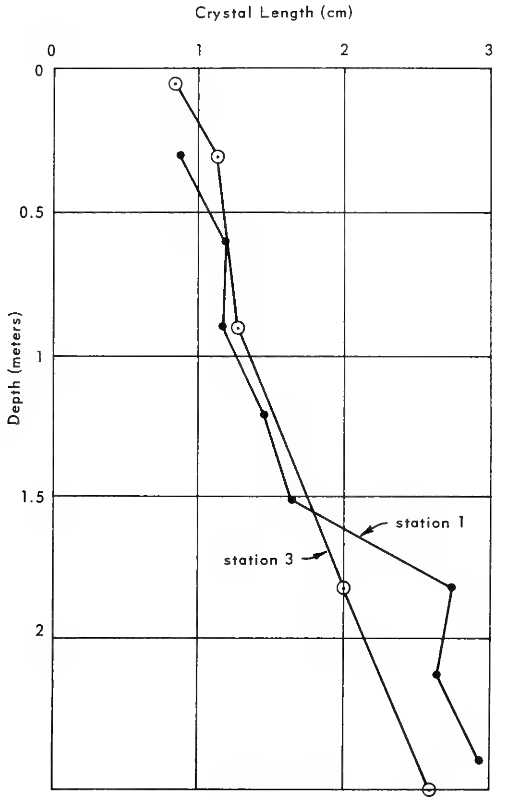
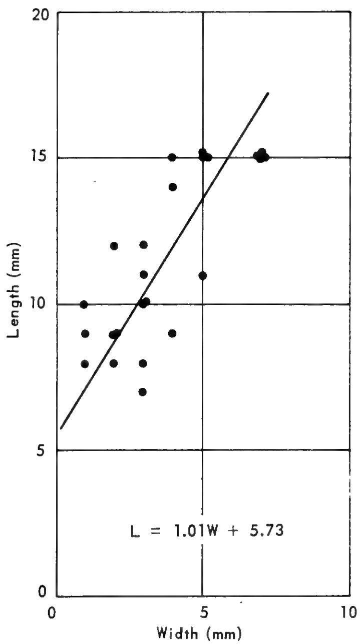
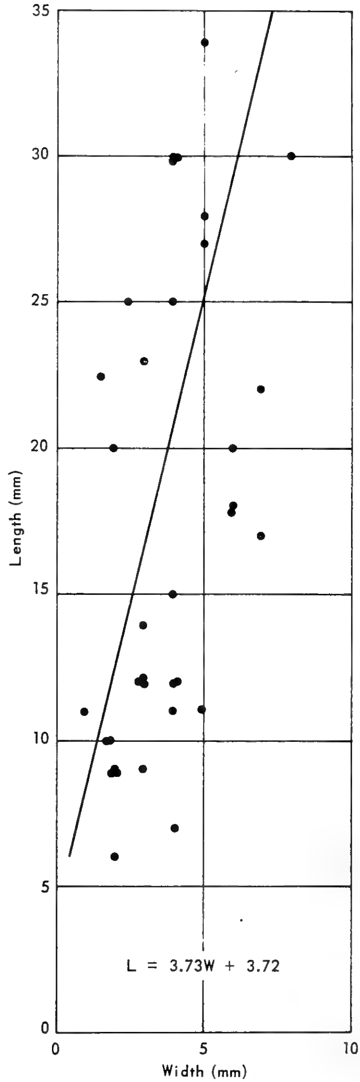


Figure 12. Crystal length versus depth at stations 1 and 3.



(a) 0–120–cm depth.



(b) 120–262–cm depth.

Figure 13. Length-to-width ratio of sea ice crystals versus depth in thick sea ice.

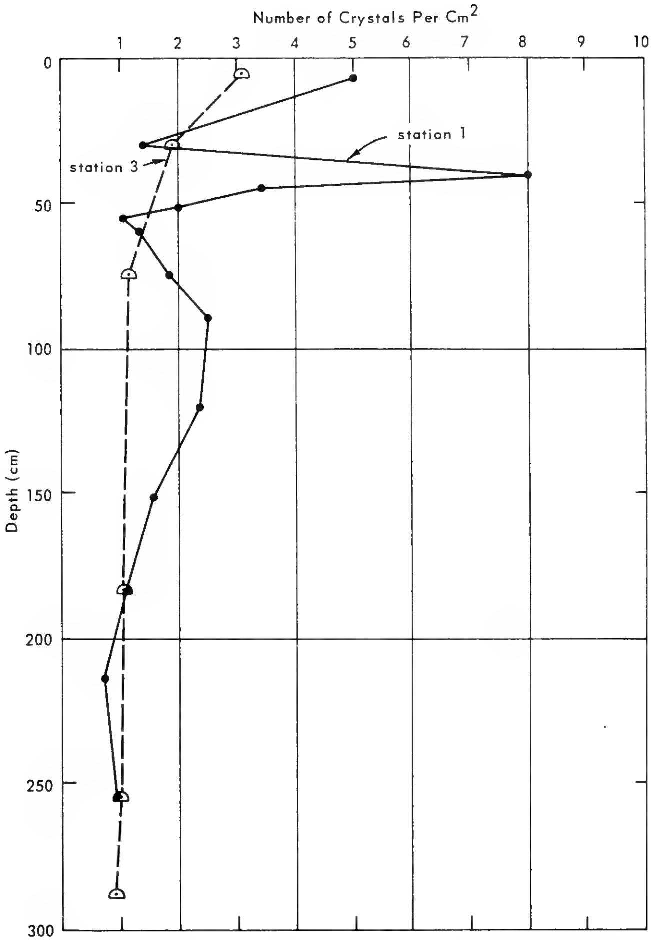


Figure 14. Number of whole crystals per square centimeter versus depth at stations 1 and 3.

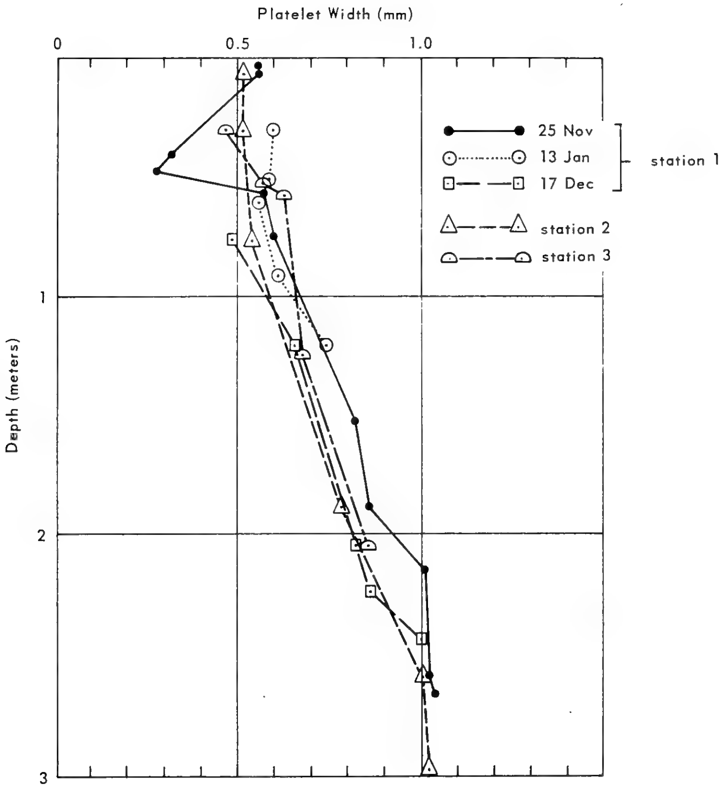


Figure 15. Subcrystal platelet width versus depth at stations 1, 2, and 3.

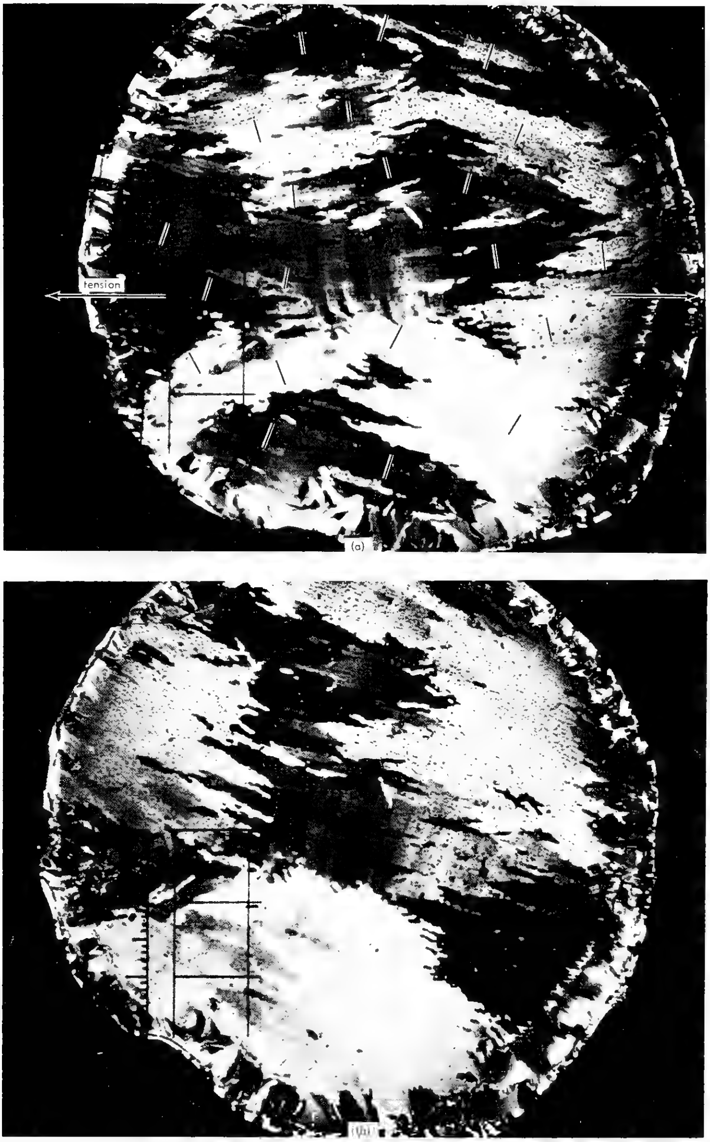


Figure 16. Thin section of stressed sea ice from the crest of a pressure ridge. Photographed under crossed polarized light. The small lines in (a) indicate the direction of the crystallographic c-axis. Grid is 1 cm. (b) has been rotated 20 degrees clockwise in relation to (a).

Structural Parameters Versus Depth and Growth Rate

The variation in structural parameters occurring at different depth levels throughout an ice sheet is related to the growth rate of the ice. This is especially true in the upper levels of a young ice sheet, where temperature fluctuations have a pronounced effect on crystal growth. The sudden increase in crystals per square centimeter at the 40-cm depth in Figure 14 correlates well with the decrease in platelet width at the same depth as shown in Figure 15, and probably indicates a period of extreme cold during the early growth history in McMurdo Sound.

CRYSTAL STRUCTURE VERSUS STRENGTH

The relationship of crystal structure to strength is a well-established property of many crystalline solids. The obvious variation of certain crystal and subcrystal parameters with depth suggests that the strength of ice should also vary with depth. The possible reasons for the vertical variation of strength have been discussed in detail by Assur (1958) and by Anderson and Weeks (1958). Weeks and Assur (1963) state (p. 259) that "the principal structural parameter controlling the distribution of brine in single crystals of sea ice is the plate width....If the plate width changes systematically with the distance below the upper surface of the ice sheet, this variation might conceivably account for a change in vertical strength."

The platelet width determines the primary spacing of brine layers and cylinders. The size, shape, and spacing of brine inclusions vary with temperature, but after their initial formation these inclusions no longer have any relation to crystal structure. If an ice sheet becomes cold, more ice freezes out of the trapped brine and the brine cavities become smaller; as an ice sheet warms up, ice melts and dilutes the brine. The brine cavities and layers then become larger and migrate downward through the ice sheet under the influence of gravity and a temperature gradient. The spacing and geometry of brine drainage features are thought to be the major factors affecting the strength of sea ice (Anderson and Weeks, 1958, p. 632).

Assur (1958) established a correlation between brine volume and ring-tensile strength and showed that as brine volume decreases, ring-tensile strength increases (p. 130). Further, brine volume is shown to decrease with depth in an ice sheet as a result of increasing platelet width (Weeks and Assur, 1963, p. 267). The data of Graystone (1960, pp. 36-39) show a slight increase of strength with depth in sea ice 1.2 to 1.5 meters (4 to 5 feet) thick. However, Weeks and Anderson (1958, p. 643) found no difference in strength when breaking cantilever beams by both push-up and push-down loading of sea ice varying in thickness from 6.3 to 36.8 cm.

Figure 17 shows ring-tensile strength,* temperature, and salinity, versus depth. A comparison of the ring-tensile strength curves with the data shown in Figures 12, 13, 14, and 15 indicates that there is no apparent correlation between the vertical distribution of strength and the various crystal parameters in a mature, isothermal ice sheet. The progressive strength decrease with time occurring in the 0.3- to 0.9-meter depth interval (Figure 17a) results predominantly from solar radiation energy causing accelerated brine drainage and the enlargement of brine layers and cavities. This phenomenon also has no relation to crystal structure. The strength increase at the surface of the 12 January 1966 plot resulted from freshening of the sea ice by almost complete brine drainage.

FINDINGS

1. There is apparently no distinct correlation between crystal structure and ring-tensile strength in the thick, mature isothermal ice sheet in McMurdo Sound.

2. Subcrystal platelet width increased from about 5 mm at the surface to more than 10 mm at a depth of 3 meters, but had no apparent effect on the variation of ring-tensile strength.

3. Crystal length (in a horizontal plane) increased systematically with depth from less than 1 cm near the surface to as much as 15 or 20 cm (as observed) at the bottom of the ice sheet.

4. The crystal length-to-width ratio changed from about 2 to 1 in the upper half of the ice sheet to more than 5 to 1 near the bottom.

5. The spacing and frequency of horizontal bands of cloudy, white ice alternating with zones of clear ice was attributed to temperature fluctuations during early growth of the ice sheet.

6. Wavy extinction in single crystals and a strong preferred c-axis orientation in ice from a pressure ridge indicated that the stress conditions in sea ice can be deduced by detailed crystal studies.

7. The bottom surface of the thick, growing ice sheet was extremely irregular, with a possible relative relief of at least 60 cm (2 feet).

8. Brine drainage features varied in size and shape in relation to temperature and solar radiation intensity. This was especially true in the 0.3- to 0.9-meter depth interval, where a zone of weakness was caused by enlarged and closely spaced brine drainage cavities.

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*The ring-tensile strength test (Butkovich, 1956) was performed by drilling a 1/2-inch-diameter hole coaxially through a 3-inch-diameter core specimen and applying a load normal to the axis at a loading ram rate of 8 in./min.

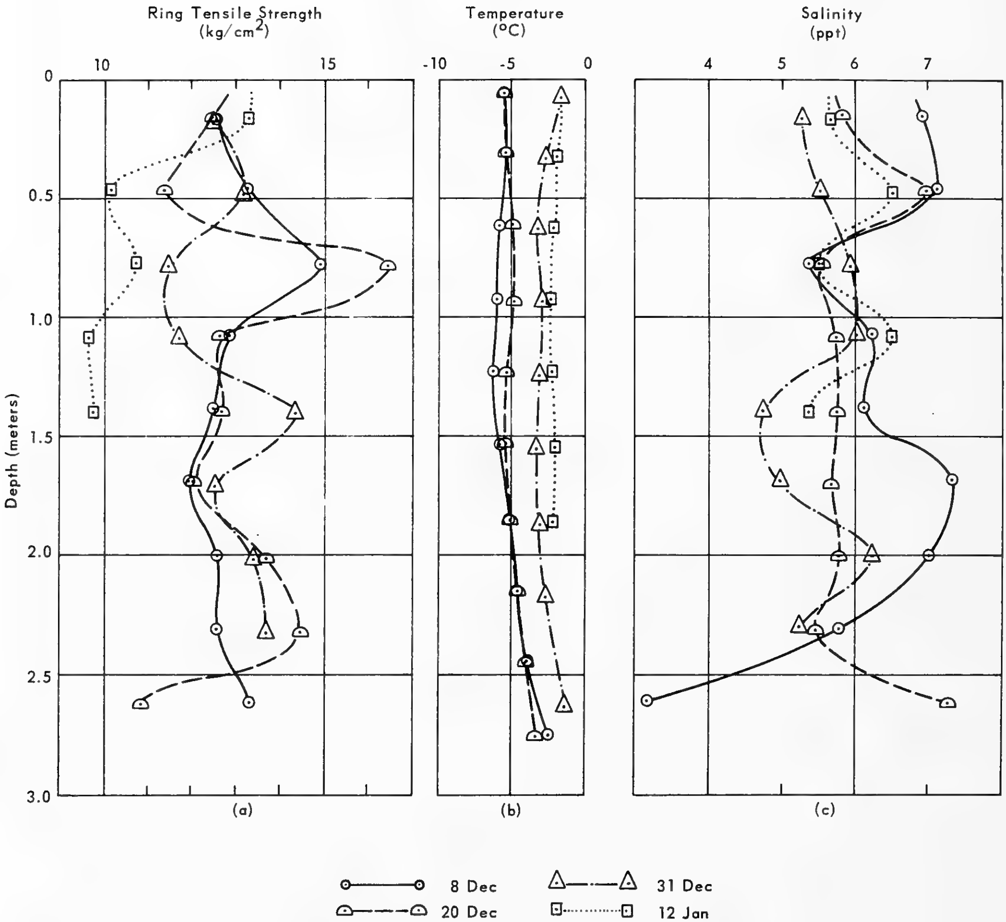

Figure 17. Comparison of ring-tensile strength, temperature, and salinity in a thick, mature isothermal ice sheet.

CONCLUSIONS

1. The vertical variation of ring-tensile strength in a thick isothermal ice sheet does not correlate well with subcrystal platelet width or other crystal parameters. The strength variations observed in McMurdo Sound sea ice were caused by temperature differences and varying stages of internal deterioration.

2. The growth history of the annual sea ice in McMurdo Sound varies with time and location, and is affected by climatic differences, water circulation and depths, exposure to wind, and snow cover. A detailed study of large- and small-scale features such as banding, brine drainage, and crystal structure provides much information concerning growth conditions of ice at particular locations.

3. Stressed sea ice in pressure ridges has distinct optical properties, such as wavy extinction under crossed polarized light and preferred c-axis orientation. This indicates that stress conditions in an ice sheet may be determined by studying the crystal structure and optical properties. However, more data are needed under a wider variety of stress conditions to establish better interpretive criteria.

4. Measurements of various crystal parameters, both horizontally and vertically, are restricted in 7.62-cm-diameter core specimens. Measurements are needed from large blocks of sea ice to further study the relationship between crystal structure and sea ice strength.

ACKNOWLEDGMENTS

Dr. A. J. Gow and Mr. Steven Roth rendered invaluable help in photographing many of the thin sections. Dr. W. F. Weeks and Mr. Justin Dykins have contributed much helpful discussion and many useful suggestions. Mr. C. W. Henderson furnished excellent assistance in the field and laboratory.

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TR-494   35 p. illus   Nov 1966   Unclassified

1. Strength versus crystal structure   2. Antarctic sea ice   I. Y-F015-11-01-026

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Sea ice is a crystalline solid with physical properties that are highly temperature dependent between -1.8°C and -10°C. This dependence becomes less with decreasing temperatures. A study of various crystal parameters and structure is essential for a better understanding of their relationship with strength properties. Horizontal banding in the ice sheet was studied to determine the effect of temperature fluctuations on band frequency. Various crystal parameters such as subcrystal platelet width, crystal length-to-width ratios, and crystal size were measured from photographs of thin sections.

Subcrystal platelet width increased with depth from about 0.5 mm at the surface to about 1 mm at 2.8 meters. The length-width ratio of single crystals increased from 2 to 1 near the surface to more than 5 to 1 at depths greater than 2 meters. The number of crystals per unit area decreased with depth. Strained ice from a pressure ridge showed preferred c-axis orientation and wavy extinction similar to that observed in strained quartz. There is apparently no correlation between strength and crystal structure in a mature isothermal ice sheet.

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1. ORIGINATING ACTIVITY *(Corporate author)* U. S. Naval Civil Engineering Laboratory Port Hueneme, California 93041	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Crystallographic Studies of Sea Ice in McMurdo Sound, Antarctica

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Not final; October 1965 - June 1966

5. AUTHOR(S) *(Last name, first name, initial)*

Paige, R. A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1966	35	23

8a. CONTRACT OR GRANT NO. b. PROJECT NO. Y-F015-11-01-026 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TR-494 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

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13. ABSTRACT

The sea ice in McMurdo Sound is used extensively for aircraft operations, travel, and docking areas. The safety and efficiency of utilizing the sea ice depends upon many factors affecting its physical properties throughout the season.

Sea ice is a crystalline solid with physical properties that are highly temperature dependent between $-1.8^{\circ}C$ and $-10^{\circ}C$. This dependence becomes less with decreasing temperatures. A study of various crystal parameters and structure is essential for a better understanding of their relationship with strength properties. Horizontal banding in the ice sheet was studied to determine the effect of temperature fluctuations on band frequency. Various crystal parameters such as subcrystal platelet width, crystal length-to-width ratios, and crystal size were measured from photographs of thin sections.

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DD FORM 1 JAN 64 1473 0101-807-6800

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Crystallographic studies						
Antarctic sea ice						
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