Title	Tensile Properties of Sea Ice Grown in a Confined System
Author(s)	Dykins, J.E.
Citation	Physics of Snow and Ice : proceedings, 1(1), 523-537
Issue Date	1967
Doc URL	http://hdl.handle.net/2115/20322
Type	bulletin (article)
Note	International Conference on Low Temperature Science. I. Conference on Physics of Snow and Ice, II. Conference on Cryobiology. (August, 14-19, 1966, Sapporo, Japan)
File Information	1_p523-537.pdf

Tensile Properties of Sea Ice Grown in a Confined System

J. E. Dykins

U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, U.S.A.

Abstract

The salinity, density, and petrographic structure of sea ice grown in a confined system can be closely identified with the characteristics of sea ice formed in a natural environment. This observation was made for ice 44 cm thick. The tensile strength was found to be more dependent on the orientation of the grain and subgrain structure than it was on temperature. The ice had a mean horizontal tensile strength of 41 psi (2.9 kg/cm^2) at −4°C (unpublished data), of 67 psi (4.7 kg/cm^2) at both −10 and −20°C and of 78 psi (5.5 kg/cm^2) at −27°C. The mean vertical tensile strength was 128 psi (9.0 kg/cm^2) at −4°C (unpublished data), 152 psi (10.7 kg/cm^2) at −10°C, 163 psi (11.5 kg/cm^2) at −20°C, and 208 psi (14.6 kg/cm^2) at −27°C. The grain (crystal) size had little effect on the strength, however, the orientation of the grain and subgrain (dendrite) structure in relation to the stress orientation had an appreciable effect. The horizontal tensile strength of the laboratory-grown ice compares reasonably well with the flexural strength reported for natural sea ice. No comparison was made for the vertical strength.

I. Introduction

Though the properties of ice have long been of principal interest to physicists and geologists in their study of earth sciences, an expanding need to know has recently extended to the engineer and field operator who utilize this material in their routine work. To adequately develop the capability of predicting the structural integrity of a given ice system, there is an apparent need for a better characterization of some of the mechanical properties of the material. The pure tensile strength is one property not presently well defined. Part of our current polar research is devoted to establishing the strength envelope for the tensile property; characterizing for one boundary the tensile strength of normal sea ice and for the other boundary the tensile strength of fresh ice.

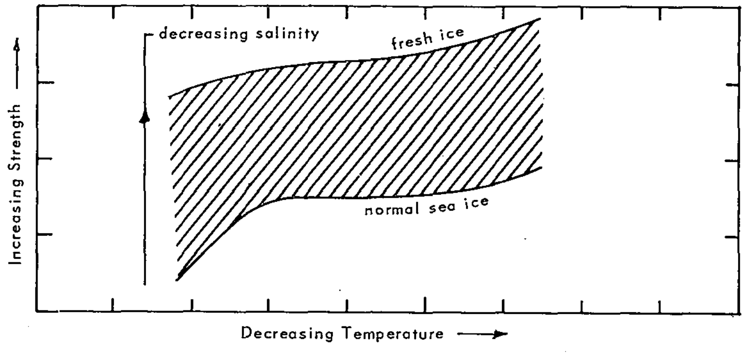

Fig. 1. Envelope of tensile strength as function of temperature and salinity

Once these boundaries have been established, it will be easy to define and any additional work within the envelope that may be necessary, Fig. 1.

This paper (abstracted from NCEL Technical Report R-415, dated January 1966) covers a study of artificially produced polycrystalline saline ice frozen from natural seawater. The principal experiment objectives were to identify the characteristics of the ice and determine the tensile strength and to study creep phenomena (not included in this paper). The tensile strength was observed for both parallel and perpendicular orientation of the ice specimens in respect to the normal vertical growth of the crystals. Tensile-strength data was obtained at ice temperatures of −4°C (not yet published), −10°C (14°F), −20°C (−4°F), and −27°C (−16.6°F).

II. Experimental Procedure

The chamber used for the experimental work maintained the test temperature within ±4°F, with continuously moving air caused by the refrigeration fans. Air velocities measured 2 feet above the surface of the freezing tank, approximately 6 feet above the floor, ranged from 75 to 340 fpm (0.85 to 3.8 mph). The surface exposure of the freezing tank was 64 by 101 inches. The tank walls and floor were insulated to produce unidirectional ice growth from the surface, duplicating natural conditions. The thermal activity through the water column, ice layer, and air immediately above the ice was automatically recorded at hourly intervals. The thermocouples for this purpose were at 3-inch spacing.

When the ice growth approached 22 inches (56 cm), the freezing cycle was interrupted, and the chamber temperature was adjusted to the test schedule. The ice block was divided into quadrants designated for extraction of either horizontal or vertical specimens. Obtaining horizontal specimens required sawing the quarter block free and elevating it from the main block.

Test temperatures. Selection of the test temperatures was based on determining the strength of the ice in relation to the eutectic temperature of the two major salts in normal seawater; these being sodium sulfate salt ($Na_2SO_4 \cdot 10H_2O$) with a eutectic point of −8.2°C, and the major salt, sodium chloride ($NaCl \cdot 2H_2O$), with a eutectic point of −23.3°C. The test temperatures were −4, −10, −20 and −27°C.

Salinity and density. Salinity of the ice blocks and the test specimens was determined by measuring the specific conductance of the melted sample. Density of the ice was determined by two methods. Because of the irregular shape of the broken tensile specimens, volume was determined by fluid displacement. For samples taken specifically for density, the volume was determined both by fluid displacement and measured-dimension. All specimens were weighed on an optical precision balance scale having an accuracy of ±0.03 g.

Tensile specimens. Sampling of the ice for tensile specimens for each of the test temperatures was programmed to provide a random method for selecting the time for extracting the specimen and the area of the block from which it was to be extracted. The sample population for each group of data generally represents ice from more than one tank, Fig. 2.

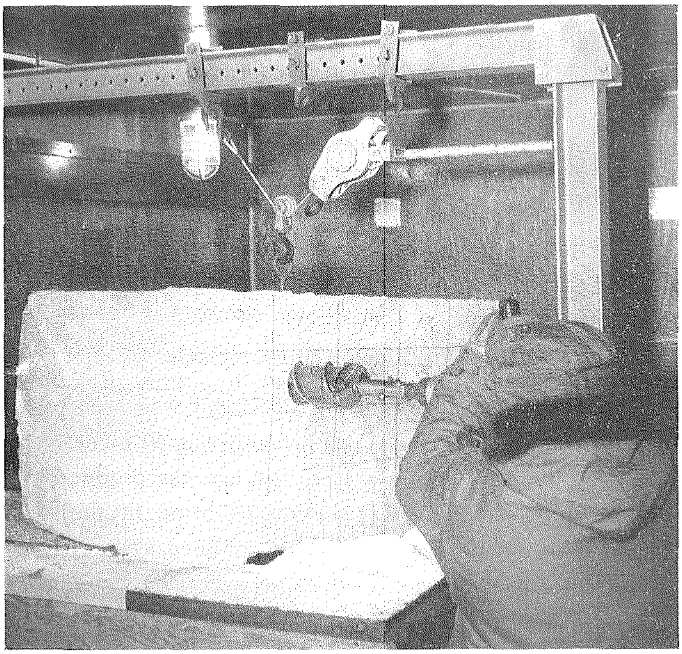

Fig. 2. Extracting horizontal specimen with 3-inch coring tool

Following a temperature change, the ice block temperature was permitted to become nearly stable before specimens were extracted. Further temperature stabilization of the specimen was provided by an overnight soak, generally ranging from 16 to 24 hours.

Tensile specimens were machined on a regular metal lath for the bellshaped ends needed for gripping the specimen for the axially-applied load. This work was done in a chilled room adjoining the chamber where the testing was performed. The temperature of this room approximated the test temperatures of -4 and -10°C but for the two lower test temperatures of -20 and -27°C it generally ran 8 to 10 degrees warmer. After machining the specimen, which generally took under 10 minutes, it was returned to the test chamber where it temperature-stabilized for 3 to 4 hours before testing, Fig. 3.

A gage-section area of 2 square inches was adopted after excessive breakage of the specimen in the test head was found when using a gage-section of 3 square inches. The majority of the specimens had gage lengths of 1 to $2^1/_2$ times the gage diameter,

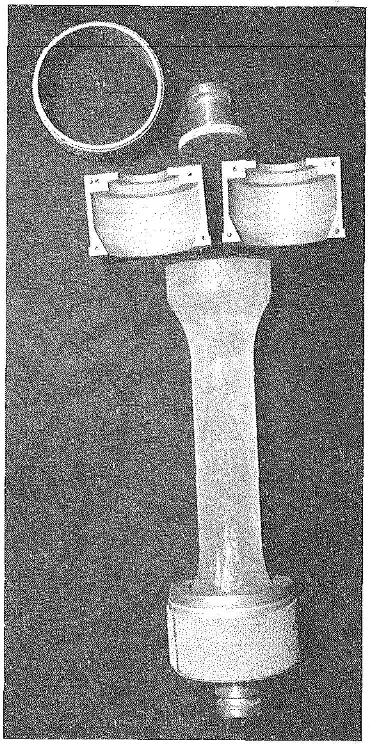

Fig. 3. Tensile specimen and gripping heads

however, no discernible strength difference was found in a small group of specimens tested with shorter gage lengths.

All tensile specimens were tested on a universal 0- to 10 000-pound testing machine. The load frame of the machine was inside the chamber so that the specimen would not have to be removed to a new temperature environment. Axial alignment of the test load was maintained by a standard universal knuckle in the linkage. The load rate used was 0.5 in./min, and it was found necessary to pre-load the specimen to approximately 10 psi (0.7 kg/cm^2) and hold for a few seconds to remove all slack in the system before applying the test load.

III. Ice-Block Characteristics

Natural sea water with a mean salinity of 32.54 ppt was used for the four tanks of ice produced for the experiment. The tank fill depth was 40 inches. Since the freezing tank was not equipped for circulating water, the ice was produced from water of increasing salinity caused by the natural rejection of brine in the accretive process of forming the ice. This is defined as a closed or confined system. Before freezing the ice at −29°C (−20°F), the water was chilled to an average temperature of 0.5°C.

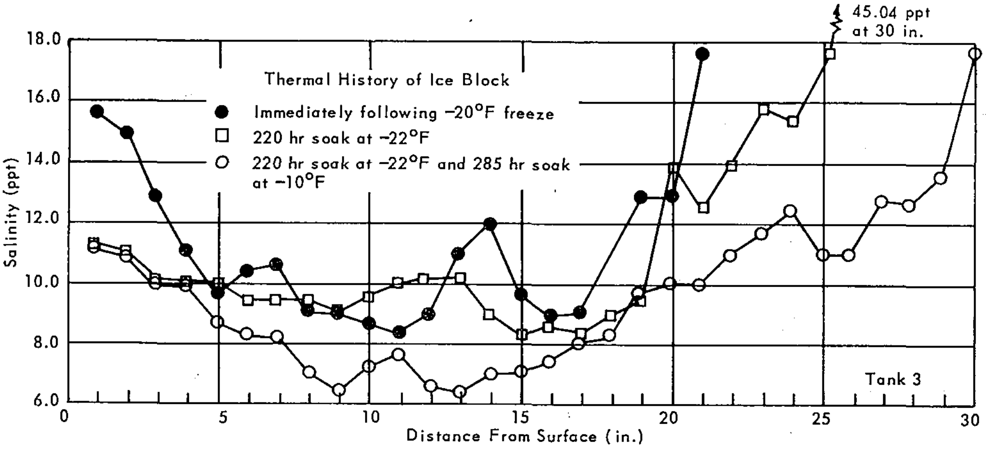

Fig. 4. Vertical salinity profile

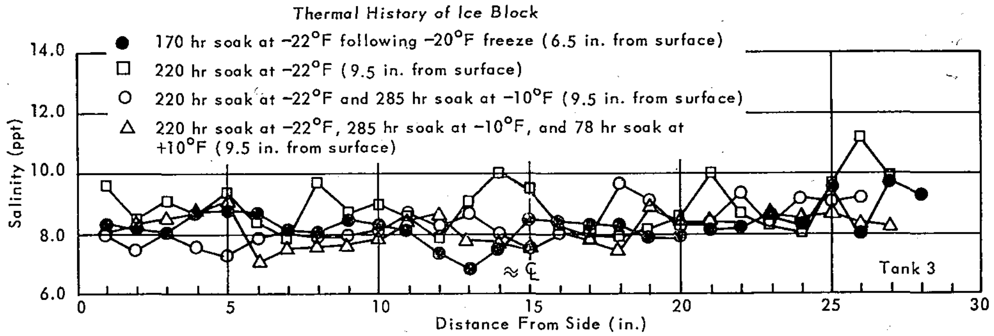

Fig. 5. Horizontal salinity profile

Salinity. Prior to sampling each tank of ice for strength specimens, salinity profiles were taken. Most of the profiles constitute salinity specimens taken at 1-inch increments. Vertical and horizontal profiles are shown in Figs. 4 and 5. The thermal history of the ice block is included with the profile, covering the period preceding the profile. It is noted that the vertical profiles indicate a similar general trend found in a newly-formed natural sea-ice sheet; *i.e.*, high salinity in the surface strata, decreased salinity in the mid-belt, and again high salinity in the lower strata. The mid-belt salinity of the blocks, which centers about a mean of 8 to 9 ppt, is fairly typical of salinities found in young natural sea ice (Weeks and Lee, 1962). The surface salinities of the tank ice are also in the general range found for young sea ice. No literature has been found to compare the bottom layer with a comparable thickness of natural sea ice.

The horizontal salinity profiles show a fairly uniform distribution through the blocks. In each case, the horizontal profile correlates reasonably well with the intersection of the vertical profile for depth and thermal history. As in the vertical profiles, thermal history had little apparent effect on the salinity profile.

Density. The vertical and horizontal profiles taken before strength sampling show the ice block to have a reasonably uniform density, centering around 0.920 to 0.925 g/cm^3, Figs. 6 and 7. The density value for the ice blocks agrees reasonably well with the mean densities of the tensile specimen groups taken from the blocks, except for the somewhat lower values found for the tensile specimens at the -4 and -10°C temperatures which implies that some loss of brine occurred during the preparation of the specimen for testing. While no measurable drainage of brine was observed during storage of the

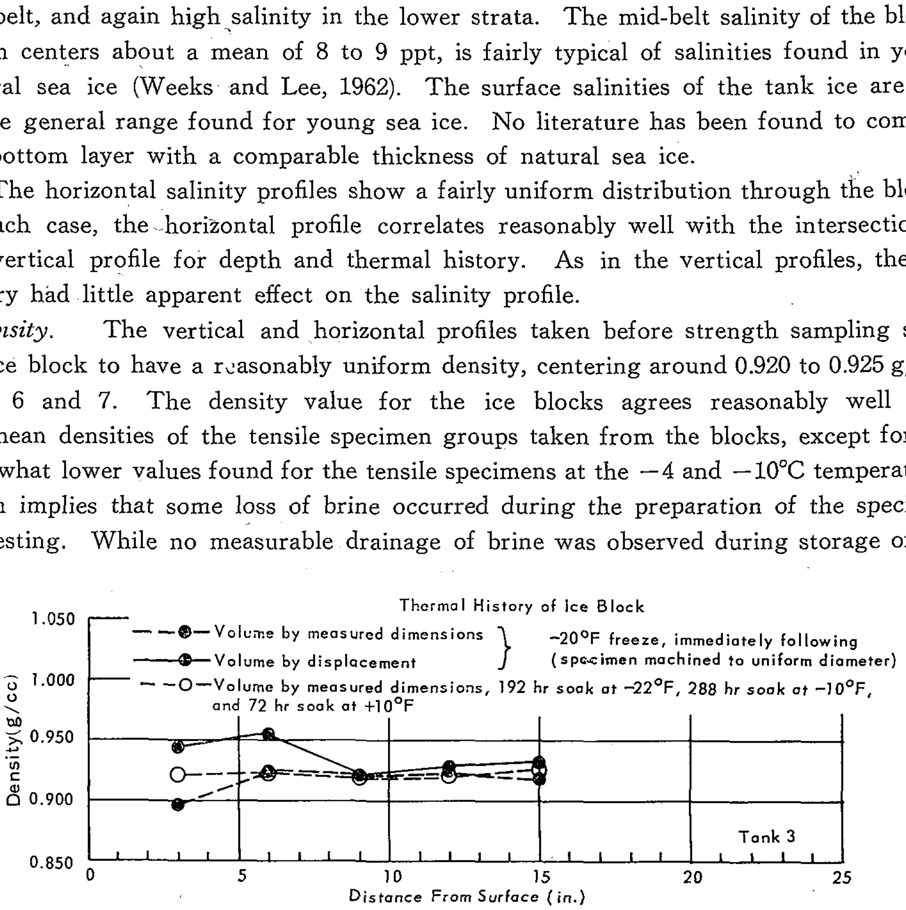

Fig. 6. Vertical density profile

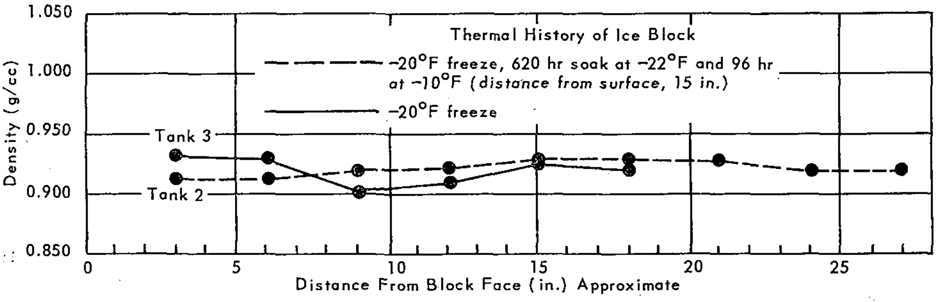

Fig. 7. Horizontal density profile

sample in the tray, centrifugally displaced brine was occassionally observed during the machining process at these two temperatures.

Petrographic structure. To determine the petrographic structure, horizontal thin sections, approximately 0.12 mm thick, were examined and photographed between cross polaroids for grain structure and under the microscope to observe the inclusions. The enlarged photograph (Fig. 8) shows a thin section of ice with a well-defined grain (crystal) and subgrain (dendrite) structure. Laminar composition of the grain is typical of saline ice. These lamina (dendrite) are plates of fresh ice separated by inclusions containing the foreign impurities rejected by the freezing process, indicated in the photograph. The impurities are principally concentrations of brine held at an equilibrium temperature with the ice. The brine dilutes and reconcentrates at the expense of the dendrite as the ice temperature passes through the various eutectic points for those salts in solution. The width of the dendrite, center-to-center spacing, for this photographed section varies from about 0.3 to 0.6 mm.

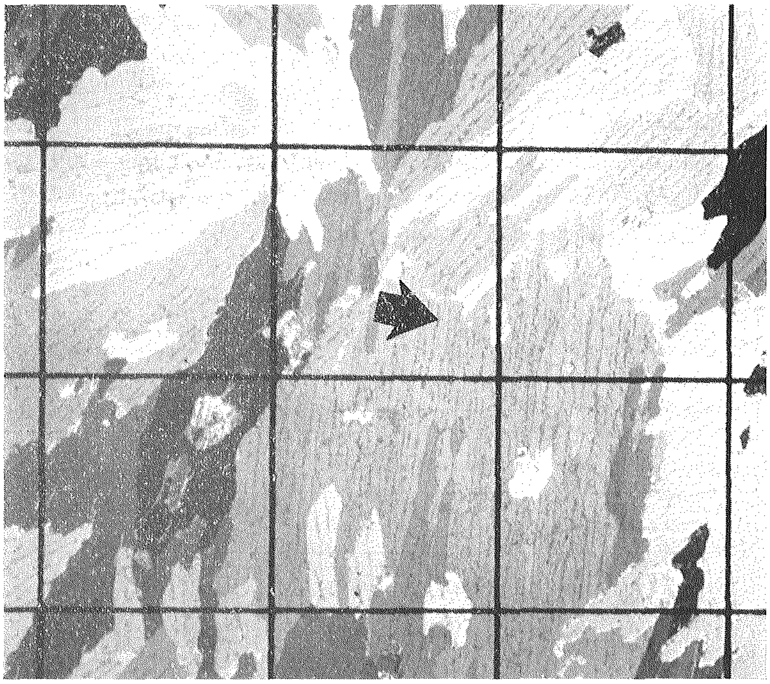

Fig. 8. Horizontal thin section enlarged to show grain and subgrain structure. The grid is 1 cm on a side

A review of the petrographic structure reported from investigations of young sea ice (Bennington, 1963; Weeks and Hamilton, 1962; Anderson, 1960) shows that the laboratory-grown ice was essentially typical of naturally-formed sea ice. Probably the most notable departure was the absence of a slush-ice zone at the surface, which no doubt, is the result of freezing under conditions of still water and the absence of snow.

The greatest divergency found in the petrographic structure with depth was the increase in grain size (Fig. 9). The grain size increased through the 41-cm stratum

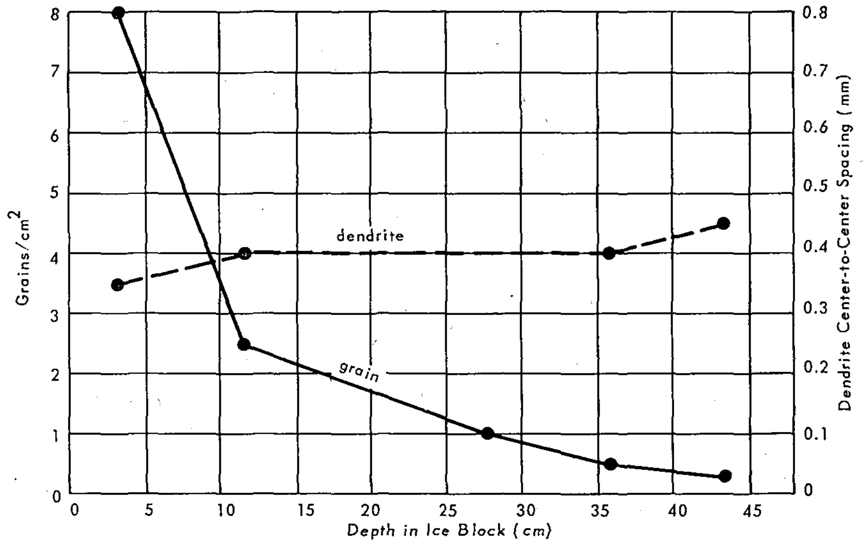

Fig. 9. Increase in grain (crystal) size and dendrite, center-to-center spacing, with depth

by a factor of almost 25. The increase in dendrite width, center-to-center spacing, for this stratum was not appreciable, varying from an approximate mean for the upper strata of 0.3 to 0.4 mm and 0.4 to 0.5 mm for the lower strata.

IV. Tensile-Strength Analysis

The tensile strength was investigated for dependency of strength on temperature, grain (crystal) orientation and subgrain (dendrite) structure, brine volume, and density. The tests were conducted to determine the strength with the stress field applied across the dendrites (specimen extracted from horizontal plane of the ice block), and with the stress field applied along the longitudinal axis of the dendrite (specimen extracted from vertical plane). The direction of applied stress on the horizontal specimens represents the relationship of bending stress to grain orientation in surface loading of an ice sheet.

The tensile data are summarized in Table 1. The table gives the mean tensile strength, a summary of statistical analysis, data dispersion, mean density, and mean salinity for each sample in relation to orientation and temperature. The statistical analysis is based on normal distribution; however, most of the data groups only approximate the normal and are actually skewed to the right. Analysis by normal distribution was selected after finding no other transformation technique that would improve the fit. It is believed that the standard deviation by normal distribution with the 95% confidence limit reasonably represents the dispersion about the mean strength.

In Fig. 10 it is seen that the mean tensile strength representing horizontal orientation is 41 psi (2.9 kg/cm^2) for −4°C, 67 psi (4.7 kg/cm^2) for both −10 and −20°C, and 78 psi (5.5 kg/cm^2) for −27°C. The mean tensile strength for vertical orientation is 128 psi (9.0 kg/cm^2) for −4°C, 152 psi (10.7 kg/cm^2) for −10°C, 163 psi (11.5 kg/cm^2) for −20°C, 208 psi (14.6 kg/cm^2) for −27°C.

Table 1. Mean tensile strength for horizontal and vertical orientation

Specimen orientation w/surface	Ice temperature (°C)	Number of specimens	Mean tensile strength (psi)	Standard error of Mean (psi)	95% Confidence Limit on mean		Range of observations		Mean density (gm/cm^3)	Mean salinity (ppt)
					Lower (psi)	Upper (psi)	Lower (psi)	Upper (psi)	*	*
Horizontal**	− 4	27	41	2.96	35	47	10	62	0.876 (60)	5.30 (27)
Horizontal	−10	47	67.4	2.92	62	73	30	109	0.910 (42)	7.59 (37)
Horizantal	−20	47	66.9	4.44	58	76	22	148	0.927 (47)	8.47 (45)
Horizontal	−27	47	77.8	4.45	69	87	33	164	0.926 (47)	8.44 (41)
Vertical**	− 4	86	128	4.0	120	136	82	187	0.892 (98)	5.87 (86)
Vertical	−10	42	152.3	5.60	141	164	67	253	0.922 (41)	6.80 (41)
Vertical	−20	62	163.1	5.76	152	175	65	247	0.924 (48)	8.32 (45)
Vertical	−27	21	208.0	12.39	182	234	98	302	0.936 (21)	8.85 (19)

* Numbers in parentheses indicate number of specimens.

** Data not yet published.

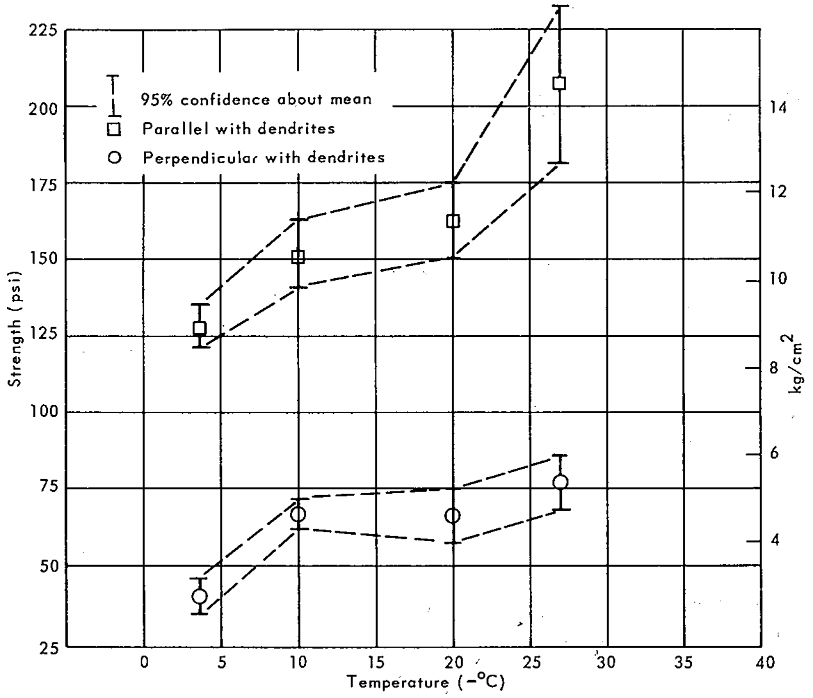

Fig. 10. Mean tensile strength versus temperature

The change in the tensile strength through the temperature range of −4 to −27°C, in general, follows the pattern suggested (Fig. 11) by the phase relations diagram for standard sea ice (Assur, 1958). This temperature range includes the eutectic point of the two major salts in sea water, sodium sulfate ($Na_2SO_4 \cdot 10H_2O$) with a eutectic point of −8.2°C, and sodium chloride ($NaCl \cdot 2H_2O$) with a eutectic point of −23.3°C. An approximation of the ratio of liquid to solid present in the ice for any specific temperature can be interpolated from phase relation diagram. The diagram between

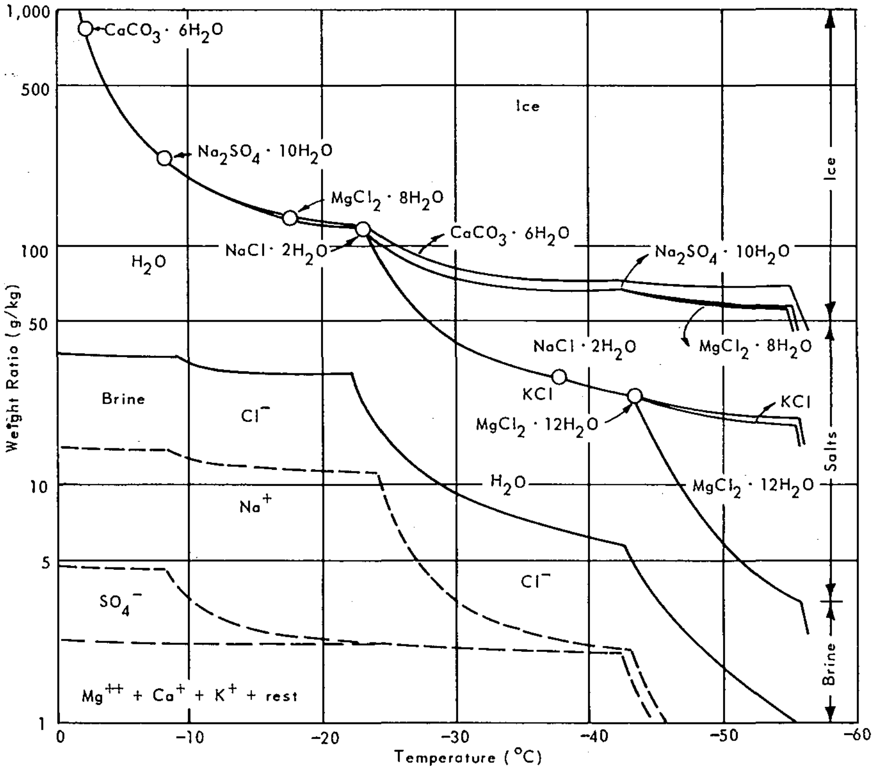

Fig. 11. Phase diagram for sea ice (after Assur)

temperatures −4 and −10°C, which includes the eutectic point of sodium sulfate salt, predicts the occurrence of a sharp decline in the liquid phase present, amounting to about 23%. This was reflected by a 63% increase in the horizontal tensile strength and a 19% increase in the vertical tensile strength. For the temperature range between −10 and −20°C, which does not include a eutectic point of either of the salts and for which the phase diagram predicts a rather small decrease, about 8% in the liquid phase the horizontal tensile strength showed no increase, while the vertical tensile strength showed only a 7% increase. Between the temperature range of −20 and −27°C, which includes the eutectic point of sodium chloride salt, the phase diagram predicts a somewhat higher reduction in the liquid phase than for the −10 to −20°C temperature. This is reflected by a 16% increase in the horizontal tensile strength and a 37% increase in the vertical tensile strength.

A method of relating the effect of salinity on strength is by determining the brine volume present in the ice as a function of salinity and temperature (Assur, 1958). The data in Fig. 12, which is plotted as strength versus the square root of the brine volume, is based on using mean salinity and strength values for the specimen groups at the various test temperatures. The vertical specimens which were stressed parallel with the longitudinal axis of the subgrain (dendrite) show a reasonably good linear relationship together with a fairly strong trend for the strength to behave as an inverse function of the square root of the brine volume. This, however, is much less evident for the

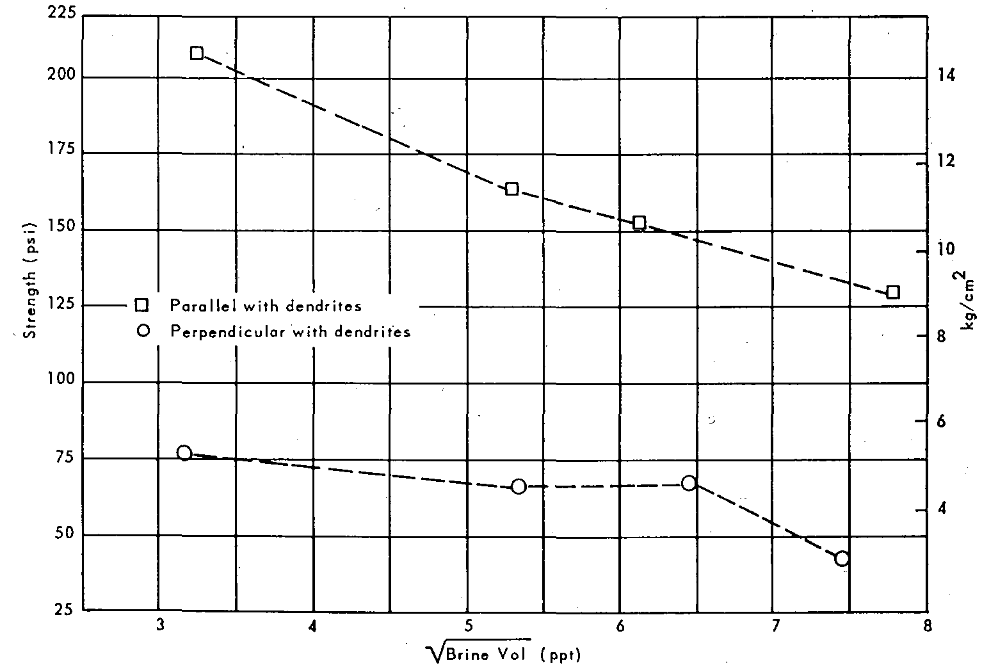

Fig. 12. Mean tensile strength versus brine volume

horizontal specimens which were stressed perpendicular with the longitudinal axis of the subgrain (dendrite).

To examine the tensile strength for a possible correlation with grain (crystal) structure, vertical profiles of the strength of the ice block were plotted, Figs. 13 and 14. These relate the location of the specimen break face to its *in-situ* position by 4-inch

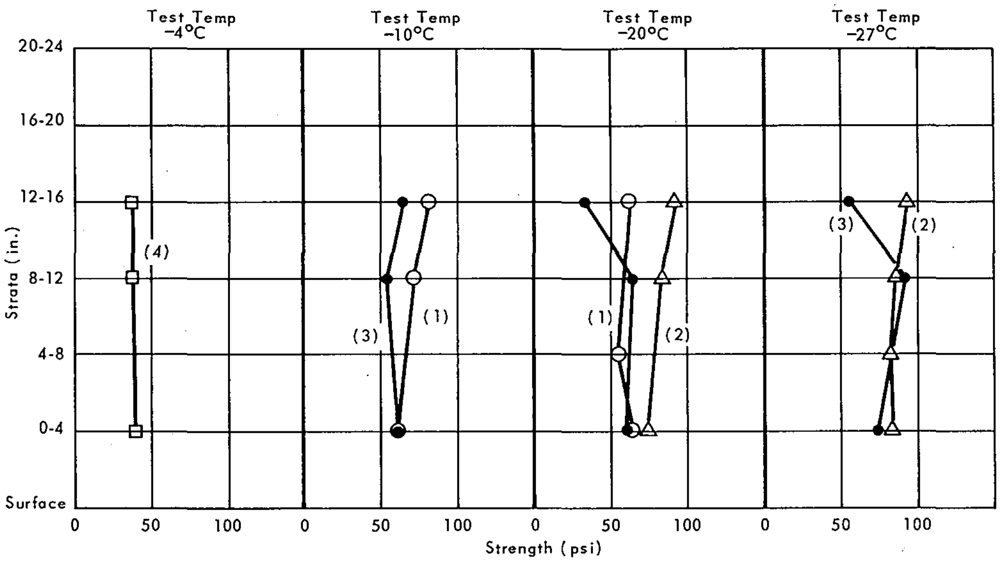

Fig. 13. Horizontal tensile strength versus depth strata. Numbers in parentheses are tank numbers

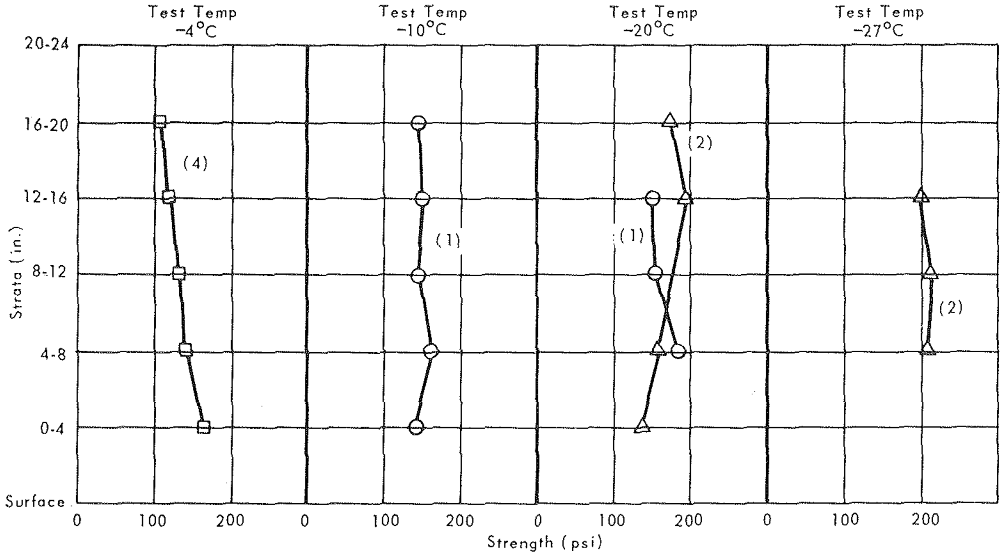

Fig. 14. Vertical tensile strength versus depth strata. Numbers in parentheses are tank numbers

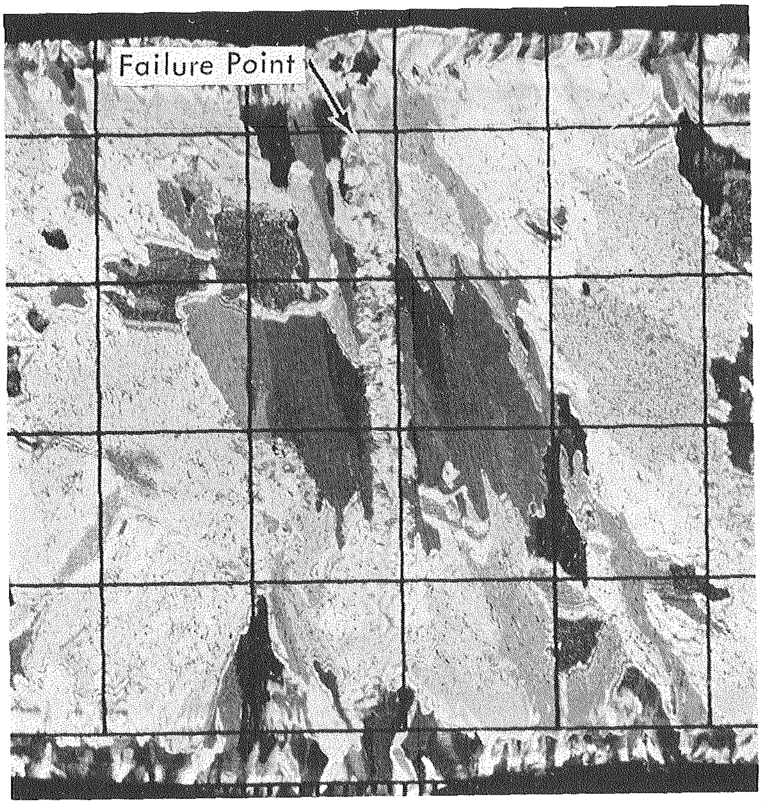

Fig. 15. Low-strength horizontal tensile specimen. Grid is 1 cm on a side. Test temperature, −20°C; salinity, 9.04 ppt; density, 0.928 g/cm³; tensile strength, 35 psi; distance from surface, 12.2 cm (4.8 in)

strata. The values plotted are the mean strength for the strata. Since the profiles indicate a fairly uniform strength throughout the observed strata and we know from previous examination of the petrographic structure that the grain size had increased by a factor of almost 25; it is fairly conclusive that at least the grain size had no major influence on the strength. The orientation of the stress in relation to the longitudinal axis of the grain (crystal), however, does produce a marked difference in the strength of the ice as noted from the vertical and horizontal tensile strengths. The difference in magnitude of the two strengths is fairly constant: 3.1, 2.3, 2.4 and 2.7 for the respective test temperatures of −4, −10, −20 and −27°C.

A notable effect on the horizontal tensile strength is also produced by the orientation of the subgrain (dendrite) structure in respect to the failure plane of the stressed specimen. The two photographed thin sections represent a low and a high strength specimen, Figs.

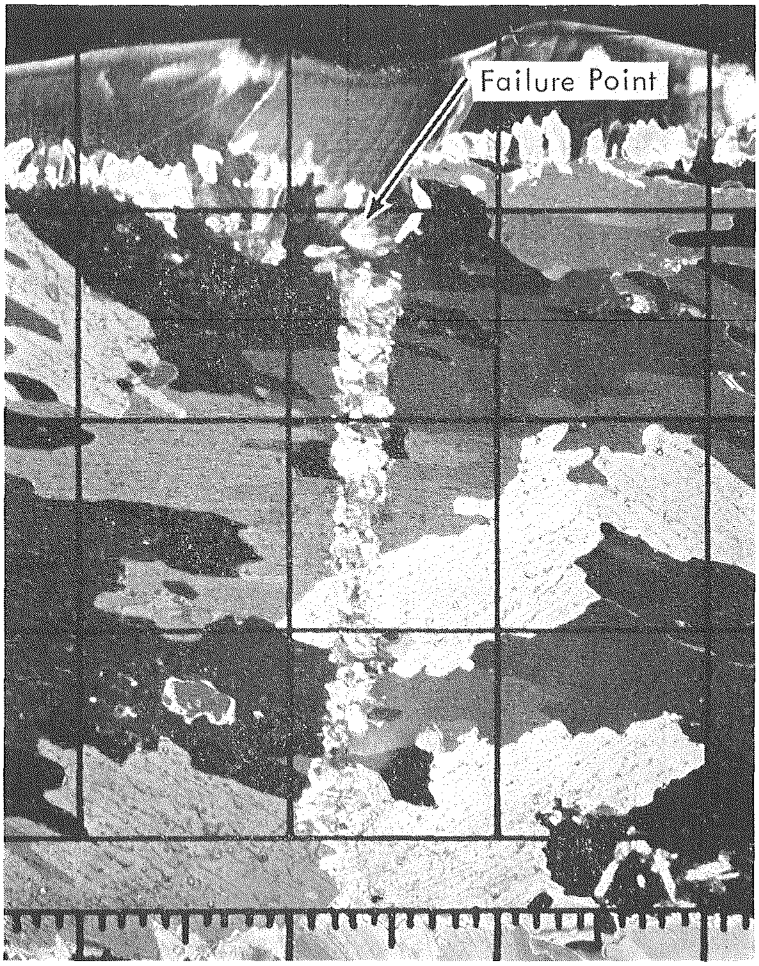

Fig. 16. High-strength horizontal tensile specimen. Grid is 1 cm on a side. Test temperature, −10°C; salinity, 7.36 ppt; density, 0.985 g/cm^3; tensile strength, 96 psi; distance from surface, 39.3 cm (15.7 in)

15 and 16. For the low strength specimen, Fig. 15, the predominant alignment of the subgrains are nearly parallel with the failure plane, while for the high strength specimen, Fig. 16, the subgrain alignment is nearly perpendicular with the failure plane. This produced a strength about $2^1/_2$ times greater even though the high strength specimen was tested at a 10°C higher temperature.

The author found it very difficult to compare the tensile strength of the laboratory-grown ice with that of natural sea ice because not only is there a meager quantity of literature but much of that found lacked sufficient identification. The reported tensile strength of arctic region, old summer-pack ice (Peyton, 1963) was felt to be sufficiently identifiable for comparing the −10°C horizontal strength. From Peyton's graphed data (Fig. 3, p. 112) it is estimated that he found an average strength for the horizontal orientation at −10°C of about 75 psi (5.3 kg/cm^2). Using this interpolation and comparing the laboratory-grown ice at −10°C with its 67 psi (4.7 kg/cm^2), we find a reasonably good agreement between the strengths. His data, however, contained two parameters that were notably different: (1) the salinity of the pack ice was only 0.14 to 0.24 ppt, while the average salinity of the laboratory specimens was 7.6 ppt; and (2) his load rate is quoted as up to 150 psi per minute (10.6 kg/cm^2/min), while the laboratory specimens were loaded at a value of about 20 psi per second (1.4 kg/cm^2/sec). To overcome the strength dependence on the rate of loading, a minimum of about 7 psi per second (0.5 kg/cm^2/sec) has been recommended for snow and ice (Butkovich, 1958).

Two comparisons are made of the horizontal tensile strength of laboratory ice with the flexure strength of in-place beams of natural sea ice. The first is for cantilever beams made on annual sea ice in the Alaskan and Greenland regions (Brown, 1963).

Interpolating the graphed data by Brown (Figs. 11 and 12, p. 93) for which the strength is plotted as a function of brine volume, the flexure strength ranged from about 28 to 78 psi (2 to 5.5 kg/cm^2) with a square root brine volume range of about 4 to 6 ppt. The horizontal strength of the laboratory ice ranged from 41 to 78 psi (2.9 to 5.5 kg/cm^2) with a square root of brine volume range of 3.2 to 8 ppt.

The second comparison of flexural strength for natural sea ice beams with that of the horizontal tensile strength is with data we obtained for tests conducted at McMurdo, Antarctica during February 1966, shown below:

Beam type	Beam span (ft)	Beam width (in)	Beam depth (in)	Flex. str. (psi)	Ice surface temperature (°C)
Fixed-end	61.20	36	73	36.5	−3
Fixed-end	60.17	35.5	73	38.5	−5
Simple	26.00	36	73	39.2	−3
Simple	26.17	34	73	34.4	−3
Simple	16.08	35.5	72	44.4	−5

Though the data consists of only 5 beams cut from 6-foot-thick ice, it permits making a comparison of the strengths at the warm temperature of −4°C. The average salinity of the ice sheet at this time was 5.47 ppt, while the temperature 3 inches below the surface ranged from −3 to −5°C with the bottom temperature of the ice sheet at about

$-2°C$. In examining the laboratory-grown ice at $-4°C$ for average horizontal tensile strength and salinity we find almost identical values to those of the field data, a 41-psi (2.9 kg/cm^2) strength and a salinity of 5.30 ppt.

V. Summary

The characteristics for the 44 cm of laboratory-grown ice which were observed for salinity, density, and petrographic structure did not show an appreciable difference from reported values for young natural sea ice, even though the closed system of freezing had caused the water to gradually increase from normal sea water salinity to something above 50 ppt.

Neither the grain size nor the center-to-center spacing of the subgrain structure were identified to have much influence on the tensile strength. By contrast, however, the orientation of the grain structure in relation to the stress field had a significant influence, *i.e.*, the vertical tensile strength in general was from 2 to 3 magnitudes greater than the horizontal strength. A significant influence on the horizontal tensile strength was also found to result from the orientation of the subgrain structure in relation to the failure plane of the specimen. When alignment of the subgrains was parallel, *c*-axis perpendicular, with the failure plane, a low tensile strength resulted but as the alignment of the subgrains approached 90 degrees to the failure plane, a high strength value was observed. This observed behavior for the horizontal specimens explains the reasons for much of the scatter found in the horizontal strength data. Although this had a pronounced effect on specimen strength, it would be of lesser consequence in causing strength variation of a large ice mass because of the non-preferred orientation of the subgrain structure, and thus, the random orientation would tend to normalize this effect for a large failure surface. The data indicates that neither the horizontal nor vertical tensile strength is a linear function of the temperature, and further, both strength versus temperature curves have the same shape characteristic.

The favorable comparison of the mean horizontal tensile strength of the laboratory-grown 5- to 9-ppt ice with the flexure strength of large in-place natural ice beams leads to the conclusion that the data obtained from the experiment reasonably characterizes the tensile strength behavior of natural sea ice. We are presently working on the strength curve for fresh ice to characterize the upper limit of the strength envelope that was introduced earlier.

References

1) ANDERSON, D. L. 1960 The physical constants of sea ice. *Research*, **13**, 310–318.
2) ASSUR, A. 1958 Composition of sea ice and its tensile strength. *In* Arctic Sea Ice. *Nat. Acad. Sci.-Nat. Res. Council U.S.A., Publ.* **598**, 106–138.
3) BENNINGTON, K. O. 1963 Some crystal growth features of sea ice. *J. Glaciol.*, **4**, 669–688.
4) BROWN, J. H. 1963 Elasticity and strength of sea ice. *In* Ice and Snow (W. D. KINGERY, *ed.*), M. I. T. Press, Cambridge, Mass., 70–106.
5) BUTKOVICH, T. R. 1958 Recommended standards for small-scale ice strength tests. *SIPRE Tech. Rept.*, **57**, 1–6.

6) PEYTON, H. R. 1963 Some mechanical properties of sea ice. *In* Ice and Snow (W. D. KINGERY, *ed.*), M. I. T. Press, Cambridge, Mass., 107–113.

7) WEEKS, W. F. and HAMILTON, W. L. 1962 Petrographic characteristics of young sea ice, Point Barrow, Alaska. *CRREL Res. Rept.*, **101**, 1–11.

8) WEEKS, W. F. and LEE, O. S. 1962 The salinity distribution in young sea ice. *J. Arctic Inst. North Amer.*, **15**, 93–108