STRUCTURE, SALINITY AND DENSITY OF MULTI-YEAR SEA ICE PRESSURE RIDGES

J.A. Richter-Menge and G.F.N. Cox

U.S. Army Cold Regions Research and Engineering Laboratory

Hanover, New Hampshire

Introduction

Multi-year pressure ridges present the most significant hazard to arctic offshore structures and vessels. It is therefore surprising that we know so little about their internal physical characteristics. Only recently has a program been initiated to systematically examine the structure and mechanical properties of ice samples taken from multi-year ridges (1,2). Results from this study indicate that the physical properties of a multi-year ridge ice sample have a significant effect on the compressive behavior of the sample.

When a pressure ridge is first formed it consists of angular, broken blocks of ice. Initially, the blocks are weakly joined together. During the course of the winter, the ridge begins to consolidate. In the summer, both the top and bottom of the ridge become ablated and rounded in appearance. Meltwater permeates the ridge, flowing into void areas. If the ridge survives the summer melt and is present the following winter it is called a multi-year ridge. At this point the ridge is massive with little or no voids and has a characteristic low salinity. On the surface of the ridge, individual blocks of ice are no longer discernable. Instead, the ridge is rounded with an irregular pattern of height variations. A split ridge will reveal that the internal structure of the ridge still maintains its blocky nature. This history of formation can result in large in the mean compressive strength value between different ridges (5). The main factor contributing to variations in the strength value from test to test was associated with the extreme local variability of ice structure within a ridge. This large variation in ice structure was also observed in the continuous core.

Additional multi-year ridge ice was obtained during our second field program. This ice was used for tests in the second phase of the multi-year ridge ice study. During this field program four multi-year pressure ridges were sampled. A second vertically oriented continuous core was taken to augment the structure data obtained in the first phase.

The ice data presented in this paper includes salinity, density and structure information from both the Phase I and Phase II continuous multi-year ridge cores and the 220 samples tested in the Phase I program. Salinity and density information from the Phase II test samples are also given. The structural characteristics of the Phase II samples are not yet included in this report because we have not completed the structural classification of the samples.

Sample Analysis

The structural characteristics of the continuous cores and the Phase I test samples were evaluated by preparing ice thin sections according to the techniques described in Weeks and Gow (6). The test samples were sectioned after testing. Horizontal thin sections were prepared from the top, middle and bottom of the tested samples. The remainder of the sample was sectioned vertically in two cuts, one perpendicular to the other. If a sample was destroyed during the tests, end pieces taken immediately adjacent to were taken. After testing, the sample was again placed in front of the light and photographed in the same positions. The two sets of photographs were compared to distinguish between original and test-created ice fabrics.

After post-test backlight photographs had been taken and thin sectioning was completed, the sample was melted and the average salinity was determined with a conductivity bridge. We had also determined the sample density at -20°C before conducting the test.

Before thin sectioning the continuous multi-year pressure ridge cores, each core was indexed with a vertical line along its entire length. The cores were then cut into 10 cm lengths. At each 10 cm mark, a horizontal thin section was prepared. Between these sections two vertical thin sections were made, one parallel to the index line and the other perpendicular to the line. Photographs were taken of the ice thin sections under cross-polarized light. A continuous structural profile was then prepared for each core by splicing the photographs of one series of vertical ice thin sections. These structural profiles are presented along with a detailed description of the ice structure in the mechanical properties of multi-year sea ice project reports (1,2).

Salinity measurements for each 10 cm section of the continuous cores were also taken after the thin sectioning was completed.

Results and Discussion

Schematic profiles of the continuous Phase I and II multi-year pressure ridge cores are presented in Figures 1 and 2, respectively. These profiles summarize the structure and salinity characteristics of the cores. Well-defined columnar zones in the cores, indicated by the letter

C, include a measurement of the angle between the elongated crystal axes and the vertical direction (σ:z). We also note whether the crystal c-axes in the columnar ice were directionally aligned or unaligned.

About one-third of the Phase I core (Fig. 1) consists of columnar ice, most of which is near the bottom of the core. The columnar ice at the bottom may be the result of new growth. The upper portion of the core consists largely of granular ice, mixed granular and columnar ice, and pulverized, brecciated ice. In the Phase II core nearly 50% of the ice is columnar and the zones of columnar ice are distributed more evenly throughout the core. The remainder of the core is a combination of granular ice and mixed granular and columnar crystals. The mixed ice is predominantely brecciated. While the amount of columnar ice varies between the cores it is interesting to note that the elongated crystal axes of the columnar ice zones in both cores are oriented at an angle of 15° or less with the vertical. There is only one exception. At 350 cm in the Phase II core one section of columnar ice has a σ:z angle of 35°. These low angle measurements may indicate that most of the ice blocks within the ridge lie in a near horizontal position.

Similar observations can be made when considering the columnar ice samples tested in Phase I of the multi-year ridge ice program. Table 1 gives the number of columnar samples tested in each ridge and Figure 3 presents a frequency histogram of the number of columnar samples in a given orientation. As we would expect, the amount of columnar ice varies from ridge to ridge. This variation may be due to differences in the mode of formation of the ridges. As described in Kovacs and Mellor (9), a first-year ridge formed by compression contains large, unconsolidated blocks of sheet ice. The ice in a ridge formed by shearing, on the other hand, is highly fragmented and very compacted. So we would expect to see a higher percent of columnar ice samples in multi-year pressure ridge initially formed by compression than one formed in shear.

Many of the ridges do contain a significant amount of anisotropic columnar ice. In a total of 220 test samples, 56 or 26% of the samples were made up of columnar ice. Figure 3 further indicates that a majority of these columnar samples had elongated crystal axes that were near vertical. The average angle between the elongated axes and the vertical for all columnar samples was 11° and no sample had an angle greater than 35°.

These observations indicate that many multi-year pressure ridges contain a significant amount of columnar ice and that a majority of this columnar ice is oriented with its elongated crystal axes near vertical. It appears that blocks of first-year sea ice, incorporated into the ridge during its formation, lie in a near-horizontal position with little or no tilt. If this is true, care must be taken applying mechanical property test data from multi-year pressure ridges for the design of offshore structures. The results of the test program on multi-year ridge ice and those of Peyton show that columnar ice samples loaded perpendicular to the elongated crystal axes ($\sigma:z=90°$) have a significantly lower strength value than columnar samples loaded parallel to this axis ($\sigma:z=0°$). Consequently, the mean compressive strength value obtained from a series of tests on vertically oriented ridge samples may be higher than the mean value obtained from horizontal samples. Using the ice strength data from vertically oriented ridge samples may be conservative in horizontal ridge loading problems.

We also studied the salinity profiles of the continuous cores and the salinity and density of the Phase I test samples. Combined with this information are the salinity and density data from the Phase II test samples. The salanity profiles for the Phase I and Phase II continuous cores are presented in Figures 1 and 2 alongside the structural profiles. The salinity profile of the Phase I core shows a characteristically low salinity in the upper portion of the ridge caused by flushing of the brine during the melt season (10). In general, the salanity increases with an increase in depth except for an area of mixed, brecciated ice between 300 and 450 cm which has a low salinity. The Phase II continuous core shows the same increase in salinity with depth with the exception of an uncharacteristically high salinity area near the top of the ridge. Neither core shows any systematic variation of salinity with respect to ice structure type.

The observations from the continuous multi-year cores are consistent with the salinity measurements of the Phase I and Phase II test specimens. The average salinities of the ice samples are given in Table 2. The Phase I data summarizes all the samples tested from the ten multi-year ridges. The ice samples from Ridges A, B, and C were used in the Phase II test program. The salinity measurements from these three ridges are combined in the last column of the table. The average density measurements for all the tested ridge samples are also included in Table 2. The density of each sample was determined at -20°C. The salinity and density data are grouped according to whether the samples were obtained from the ridge sails (above level ice) or the ridge keels (below level ice). In all cases, the samples from the ridge sails had a lower salinity than the samples from the ridge keels. The ice in the sails also had a lower density which can be attributed to the higher porosity and lower salinity of the ridge sails. These results agree well with observations made by Kovacs (11). Comparison of the Phase I and Phase II ice samples indicates that the Phase II samples had a lower average density than the Phase I ice. Notes taken during the Phase II field work point out that the ice contained many air bubbles. The average salinity of the tests samples from both phases were similar.

Conclusions

The salinity and density variation within a multi-year pressure ridge appears to be consistent from ridge to ridge. The average salinity and density in the ridge sail are lower than the average salinity and density in the ridge keel.

The internal structure of a multi-year pressure ridge is much more diverse. The relative amounts of columnar and granular ice and their distribution within a ridge varies and may be dependent on the original mode of formation. Some ridges contain large blocks of columnar ice incorporated into the ridge during compression of adjacent ice sheets. Other ridges, formed primarily by the shearing of one sheet against the other, are made up of a highly fragmented or brecciated ice. It appears that, in a compression ridge, the columnar blocks have a preferred orientation. Low angle measurements between the vertical and the elongated crystal axes in columnar ridge ice indicate that most of the blocks lie in a near horizontal position with little or no tilt. Since many multi-year pressure ridges do contain a significant amount of columnar ice this has an impact on the interpretation of mechanical property test data from ridge samples. The horizontally oriented, columnar ice blocks will provide ice samples that exhibit anisotropic behavior under loading. If a columnar sample taken from an internal columnar block is loaded vertically its compressive strength may be 2-3 times higher than if the sample is loaded horizontally. Therefore, depending on the number of columnar ice blocks in a ridge, the mean compressive strength value obtained from a series of tests on vertically oriented ridge samples may be higher than the mean value obtained from horizontal samples.

The presence of the preferentially oriented columnar ice blocks may also affect the large scale mechanical properties of the multi-year pressure ridge. If the ridge is primarily composed of highly fragmented columnar ice and granular ice we would expect the ridge to behave isotropically. If, however, the ridge contains a significant number of large columnar blocks of ice oriented with the elongated crystal axes near vertical we might expect anisotropic behavior.

References

1. Cox, G.F.N., J.A. Richter-Menge, W.F. Weeks, M. Mellor and H. Bosworth. "Mechanical properties of multi-year sea ice, Phase I: Test results." U.S. Army Cold Regions Research and Engineering Laboratory Report 84-9.

2. Cox, G.F.N., J.A. Richter-Menge, W.F. Weeks, M. Mellor, H.W. Bosworth, G. Durell and N. Perron. "Mechanical properties of multi-year sea ice, Phase II: Test results." U.S. Army Cold Regions Research and Engineering Laboratory, in press.

3. Peyton, H.R. "Sea ice strength." Geophysical Institute, University of Alaska, Report UAG-182, 1966.

4. Wang, Y.S. "Crystallographic studies and strength tests of field ice in the Alaskan Beaufort Sea." Proceedings, Fifth International Conference on Port and Ocean Engineering under Arctic Conditions, Trondheim, Norway, vol. 1, pp. 651-665, 1979.

5. Weeks, W.F. "Variation of ice strength within and between multi-year pressure ridges in the Beaufort Sea," Proceedings, Third International Offshore Mechancis and Arctic Engineering Symposium. New Orleans, vol. 3, pp. 134-139, 1984.

6. Weeks, W.F. and A.J. Gow. "Preferred crystal orientations in the fast ice along the margins of the Arctic Oceans." Journal of Geophysical Research, vol. 83, no. C10, pp. 5105-5121, 1978.

7. Richter, J.A. and G.F.N. Cox. "A preliminary examination of the effect of structure on the compressive strength of ice samples from multi-year pressure ridges." Proceedings, Third International Offshore Mechanics and Arctic Engineering Symposium. New Orleans, vol. 3, pp. 140-144, 1984.

8. Langway, C.C. "Ice fabrics and the universal stage." SIPRE Technical Report 62, 1958.

9. Kovacs, A. and M. Mellor. "Sea ice morphology and ice as a geological agent in the southern Beaufort Sea," The Coast and Shelf of the Beaufort Sea, Proceedings of the Arctic Institute of North America Symposium on Beaufort Sea Coast and Shelf Research, 1974.

10. Cox, G.F.N. and W.F. Weeks. "Salinity variations in sea ice." Journal of Glaciology, vol. 13, no. 67, pp. 109-120, 1974.

11. Kovacs, A. "Characteristics of multi-year pressure ridges," Proceedings, Seventh International Conference on Port and Ocean Engineering under Arctic Conditions, Helsinki, Finland, vol. 3, pp. 173-182, 1983.

Figure Captions

Figure 1. Salilnity and schematic structural profile for the Phase I continuous multi-year pressure ridge core. G = granular ice, C = columnar ice, M = mixed granular and columnar ice.

Figure 2. Salinity and schematic structural profile for the Phase II continuous multi-year pressure ridge core.

Figure 3. Frequency historgram of the number of Phase I columnar ice samples in a given orientation.

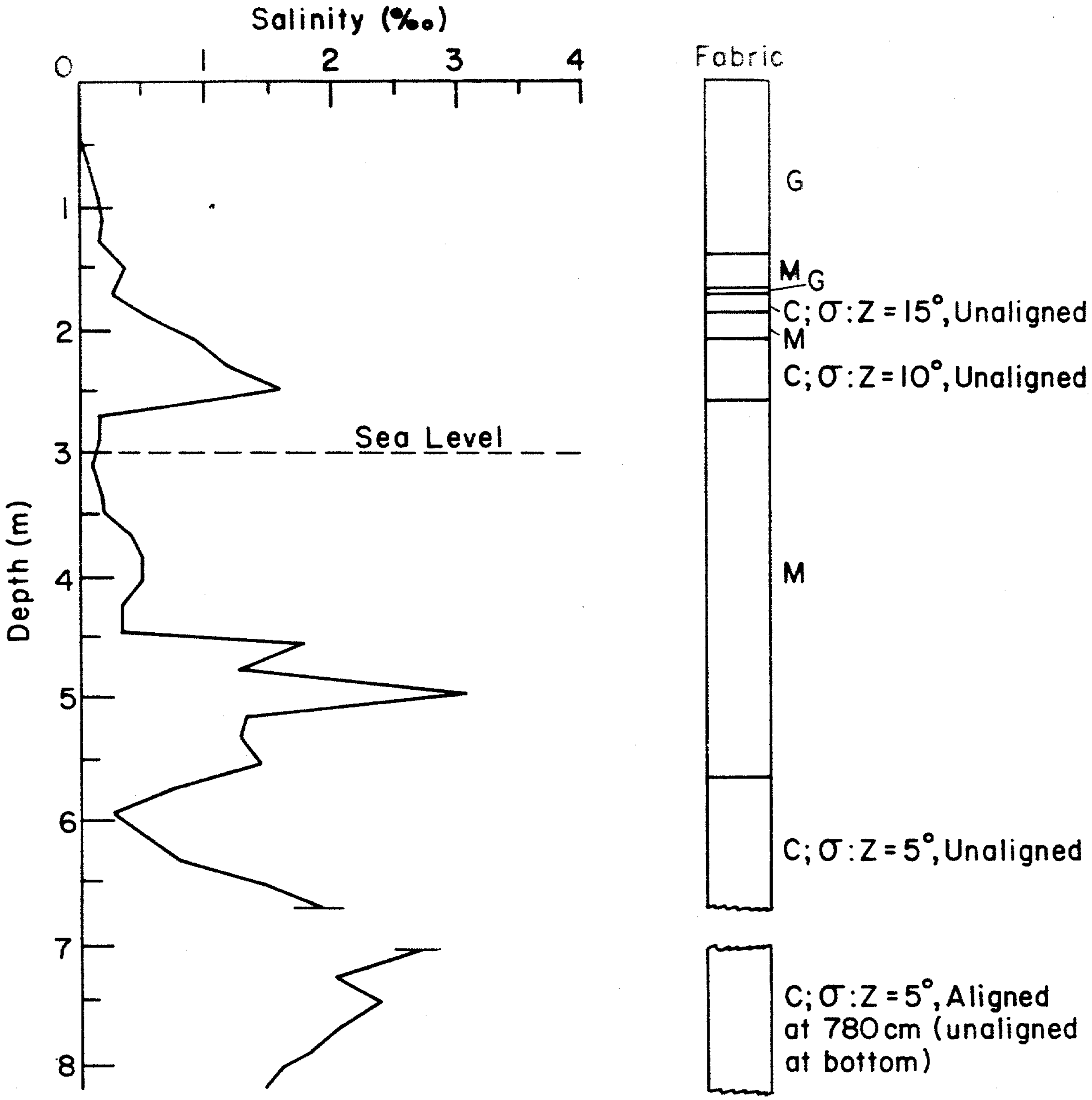
Salinity (‰)
0
1
2
3
4
Depth (m)
0
1
2
3
4
5
6
7
8
Sea Level
Fabric
G
M
G
C; σ:Z = 15°, Unaligned
M
C; σ:Z = 10°, Unaligned
M
C; σ:Z = 5°, Unaligned
C; σ:Z = 5°, Aligned at 780 cm (unaligned at bottom)

FIGURE 1.

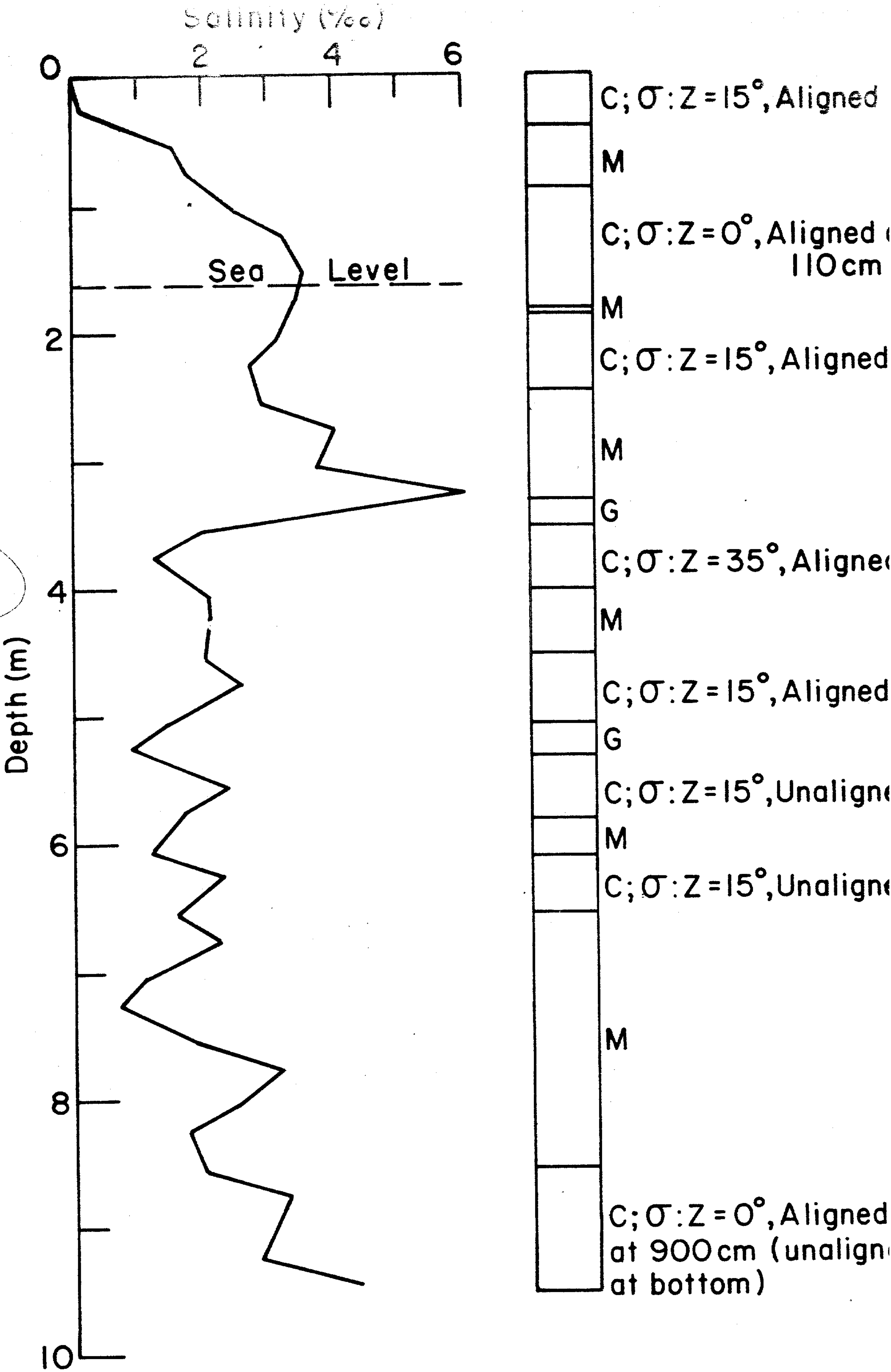
Salinity (‰)
0
2
4
6
Sea Level
0
2
4
6
8
10
Depth (m)
C; σ:Z = 15°, Aligned
M
C; σ:Z = 0°, Aligned
110cm
M
C; σ:Z = 15°, Aligned
M
G
C; σ:Z = 35°, Aligne
M
C; σ:Z = 15°, Aligned
G
C; σ:Z = 15°, Unaligne
M
C; σ:Z = 15°, Unaligne
M
C; σ:Z = 0°, Aligned
at 900cm (unalign
at bottom)

FIGURE 2.

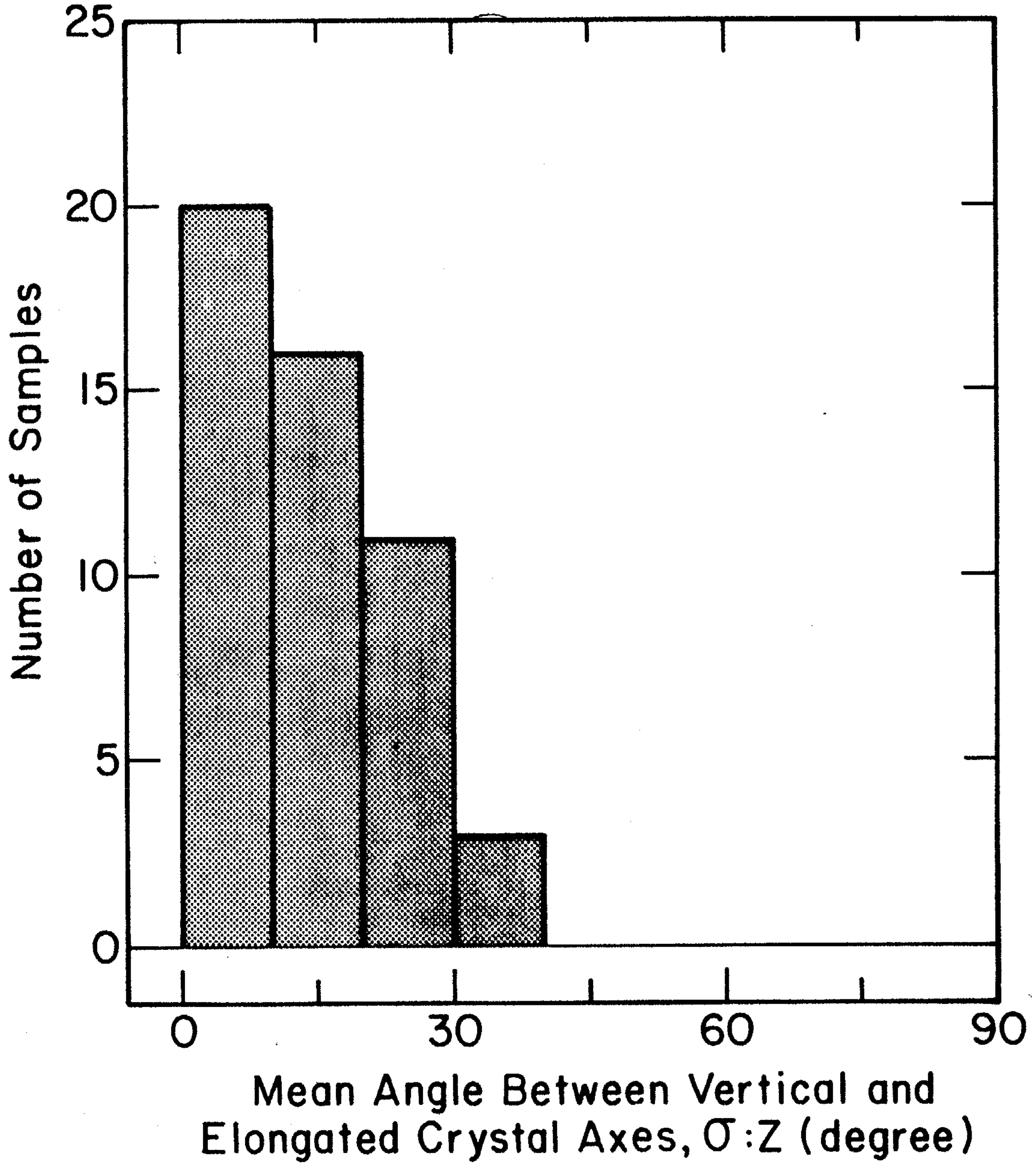
25
20
15
10
5
0
Number of Samples
0
30
60
90
Mean Angle Between Vertical and
Elongated Crystal Axes, σ:Z (degree)

FIGURE 3

Table 1. Columnar ice samples tested in Phase I.

Ridge Number	Total Number of Samples Tested	Columnar Ice Samples	% Columnar Ice Samples
1	23	13	57
2	24	5	21
3	22	3	14
4	22	7	32
5	22	3	14
6	12	0	0
7	23	4	17
8	24	12	50
9	24	1	4
10	24	8	33
Total	220	56	25

Table 2. Average salinity and density (-20°C) of ice samples obtained from all ridges in Phase I and Ridges A, B, and C in Phase II.

Above Level Ice	Phase I (10 ridges samples)	Ridge A	Ridge B	Ridge C	Three Ridges
Salinity (°/oo)	0.71±0.57	0.08±0.14	0.86±0.56	1.68±1.06	0.77±0.91
Density (Mg/m^3)	0.875±0.032	0.807±0.032	0.850±0.038	0.879±0.030	0.841±0.045
Below Level Ice					
Salinity (°/oo)	1.56±0.77	0.89±0.46	1.66±0.91	2.68±1.11	1.89±1.16
Density (Mg/m^3)	0.899±0.018	0.877±0.024	0.888±0.018	0.894±0.018	0.888±0.020
Above and Below Level Ice					
Salinity (°/oo)	1.26±0.82	0.38±0.49	1.29±0.87	2.29±1.19	1.34±1.18
Density (Mg/m^3)	0.891±0.026	0.834±0.046	0.870±0.035	0.888±0.024	0.865±0.042