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Test Report

TR-1993-06

NORTHUMBERLAND STRAIT ICE PROPERTIES MEASUREMENTS

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Canada

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SUMMARY:

Ice properties measurements were carried out in Northumberland Strait in February-March 1993. The characteristics of rubble piles, floes and ridges are described and the data is presented.

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NORTHUMBERLAND STRAIT ICE PROPERTIES MEASUREMENTS

§1.0 INTRODUCTION

For the proposed fixed link across Northumberland Strait, between Prince Edward Island and New Brunswick, ice behaviour around the structure is an important feature in the design. Many studies have been devoted to prediction of ice forces and ice motion, but there are still substantial cost and safety benefits to be gained from more accurate estimates and well defined probabilities.

Over the period of fixed link studies, expertise in ice engineering has grown rapidly. Theoretical and physical modelling techniques can provide reliable information about the action of ice around a structure of a particular shape. However, both theoretical and physical models require accurate information about the mechanical properties of the ice reaching the structure. The scope and reliability of available data on ice in the Northumberland Strait [6] has not increased to meet the new demand.

The Department of Public Works requested that NRC undertake a field program of ice mechanical properties measurements in the Northumberland Strait, to obtain data for modelling ice around structures. The investigation was carried out by a team composed of two people from NRC and one from C-CORE. The team was on the ice in the strait from February 25 to March 4, 1993. Section §2 of this report describes the method of investigation. Section §3 describes the ice formations observed in the strait, §4 explains the ice properties measurements, and §5 presents the results from the field program. In §6, the significance of these results for the proposed fixed link crossing is discussed.

§2 METHOD OF INVESTIGATION

The team surveyed the Northumberland Strait by helicopter on two different days, making observations of type and distribution of ice features. In conjunction with these surveys, the team carried out two systematic helicopter transects: one on a line from Seacow Head, N46°18.80' W63°48.60', to Cape Jourimain, N46°09.30' W63°48.30'; the second in Summerside harbour, from N46°20.60' W63°50.30', to N46°20.88' W63°49.13'; landing and measuring ice properties at regular intervals. The surveys showed that three principle ice formations were present in the strait: rubble piles, level ice or floes, and ridges.

The largest features were rubble piles, located in the active shear zone between landfast ice and the moving ice in the channel, or in an old shear zone enclosed in landfast ice. Individual rubble piles on both sides of the strait were selected for detailed measurement. The examples selected were among the largest piles. One was visited by helicopter and the remainder were accessible from shore. A substantial portion of the field program was allocated to determine the properties of the rubble ice formations.

The characteristics of level ice, floes, and ridges did not change significantly with location in the strait. They were measured during the transects, and as they were encountered during excursions from shore to rubble piles. In addition, one shore based excursion was dedicated to mechanical measurement of the flexural strength of beams taken from landfast level ice adjacent to the shear zone.

§3 ICE FORMATIONS

§3.1 Rubble piles

The rubble piles are long, narrow features formed in the active zone between landfast ice and the moving ice in the channel. The most rapid mass accumulation occurs during compression, when the drifting ice is pushing normal to the fast ice edge. The level ice buckles in compression, or fails in bending as one piece rafts onto another. The ice pieces are large, three to five times the ice thickness, and hence the porosity, the ratio of air or water volume to total occupied volume, of the rubble is high (Photos 1, 2). The keel extends downward rapidly, because of the high porosity and the high ice freeboard ratio. If the rubble comes in contact with the bottom, either at the formation site or in a shallow area as the pile drifts, then there is a high probability that the rubble will ground and stabilize.

Once the rubble pile has snagged on the bottom, further accumulation increases the sail height and compacts the keel. Compaction decreases the porosity and increases the hydrostatic stress in the keel material, leading to an increase in its resistance to shear [1]. Hence the longer a rubble pile persists, the more firmly it becomes anchored to the bottom. Area residents report that rubble piles form and persist on the same shoals year after year.

Although rubble pile growth is due principally to compression, shear activity in the ice produces distinctive rubble formations. As drifting ice pushes past a grounded rubble feature, it grinds away the offshore flange, leaving an almost vertical face on the sail-keel beam (Photos 3, 4). On this face, the ice porosity is almost zero, because ground up ice has been forced between the larger blocks like mortar. If low temperatures follow a shear event, this compacted, drained face will consolidate quickly.

Once the rubble pile is established, landfast ice may extend to enclose it. Because of tides, cracks separate the grounded rubble from the adjacent floating ice, on both the inshore and offshore side. Occasionally, cracks appear in the rubble perpendicular to the long axis. These may also be due to tides, moving floating portions of the rubble relative to the grounded portions. If the area is still active, the ice on the offshore side may be buckled, submerged, or absent. (Photos 5, 6)

§3.2 Level ice and floes

The level ice in large floes drifting in the channel is similar in structure and composition to the landfast level ice in bays on both sides of the strait, and hence these two ice formations are grouped together. The simple level ice structure is columnar first year sea ice of moderate salinity. Thicknesses of 0.45 m to 0.55 m were typical throughout the area at the time of the study, with fast ice slightly thicker, on the average, than drifting ice. Most of the level ice observed from the helicopter was a composite of simple structures, evidence of the dynamics of the ice conditions in the area.

A large percentage of the level ice is formed by the rafting and bonding of two or more simple ice sheets (Photo 7). Surface variations show that larger floes may also be formed by lateral adhesion of adjacent floes of similar thickness. This is probably more common earlier in the season, as the seams in these composites were usually packed with old snow (Photo 8).

Since there is frequently open water in the Northumberland Strait, new ice is forming throughout the growth season. However, when the floe movements bring this new ice in contact with older, thicker ice, the new ice is broken up, forming a fresh ridge on the margin of the older floes. Hence, except for nilas, most of the ice in the strait was large floes such as those sampled, bordered and surrounded by fresh ridges and rubble (Photo 9).

§3.3 Ridges

For the purposes of this study, ridges are floating ice formations. They are formed in both compression and shear, as are rubble piles, but since ridges are not grounded, they do not become as large. Sail height depends principally on the thickness of the parent ice sheet, and hence the ridges formed earlier in the season tend to be smaller. Because of the activity of the ice in the strait, ridging is extensive (Photo 10). Older ridges appear as surface features within large floes. Newer ridges surround the margin of floes, and isolated fragments of ridges float freely in open water.

§4 ICE PROPERTIES MEASUREMENTS

§4.1 Ice Thickness

All ice thicknesses reported here are actual measured thicknesses in holes augured through the ice.

§4.2 Temperature and salinity profile

A 9.68 cm diameter vertical ice core was taken for each profile. In level ice, the core extended through the full ice thickness. In rubble piles, the core extended through the consolidated layer, but the slush and soft ice below was not retrievable. The internal temperature of the core was measured immediately upon retrieval, at 10 cm intervals. Slices of core were then cut, and stored in airtight bags.

The core samples were melted and warmed to room temperature. The conductivity of the melted samples was measured using a YSI Model 32 Conductance Meter, with a rated precision of ± 0.2 % at 20 m-mhos. The YSI was calibrated using a laboratory prepared salinity samples. The calibration yielded the following formula to convert the conductivity reading from the YSI to salinity:

$$S = 0.588\,x + 0.00443\,x^2 - 0.0128 \qquad (1)$$

where S is salinity in parts per thousand (‰)
x is the conductivity in m-mhos

In fact, the accuracy of the salinity measurements was limited not by the instrumentation, but by brine drainage and contamination (by snow or seawater) at the time of sampling. Contamination may induce errors up to ±5%, or approximately ±0.3 ‰ in salinity. Brine drainage makes the salinity readings uncertain for the warm submerged ice cored from deep in a rubble pile. Drainage was visible as a whitening of the ice as soon as the core was pulled. Thus, for example, the recorded salinity of 2.7 at 200 cm depth in the sail of Rubble #4 is lower than the in-situ salinity.

The team retrieved and sampled 14 cores during the study, each associated with one of the ice features documented. Appendix A contains a table and a chart of temperature and salinity versus depth for each core. The tables in Appendix A also show brine volume v_b at each level, calculated using the formula from [2]

$$v_b = 0.93 \times S\left[-4.732 - 22.45\,T - 0.6397\,T^2 - 0.0107\,T^3\right] \quad (2)$$

Each table shows the average salinity, temperature, and brine volume for that feature.

§4.3 Freeboard

Freeboard, or height of ice above the waterline, was measured along with ice thickness at auger holes. The ice freeboard ratio r_i is defined, for ice thickness h_i and freeboard h_f, by

$$r_i = \rho_w (h_i - h_f) / h_i \quad (3)$$

where ρ_w is a the local water density in Mg/m^3. In the data sheets, freeboard ratio is calculated using the value of 1.025 for ρ_w.

For flat, snow-free ice, the bulk density ρ_i is equal to r_i in equation (3). Level, cold sea ice has a freeboard ratio of 0.91. Nonuniform floating ice features creep towards local buoyant equilibrium. Thus in ice free of internal stresses, thicker parts of a floe have higher freeboard, preserving the ice freeboard ratio r_i in equation (3).

Several circumstances affect the ice freeboard-ratio. Relatively warm sea ice, with high water content, has freeboard ratios of 0.93 to 0.94 [7]. Snow on the ice at or near the measurement location increases r_i, while grounded ice has decreased r_i. Newly deformed ice may not be in buoyant equilibrium. Finally, forces exerted by adjacent floes disturb the buoyancy equilibrium. Thus the freeboard ratio gives information on the buoyant condition of the ice.

§4.4 Beam flexural strength

A direct measure of the flexural strength of the ice is a three-point beam test. Near Mt. Carmel, PEI, at N46°23.40', W64°03.80', the team cut full thickness blocks from level, landfast ice about 800 m from shore. The team then cut the large blocks into uniform beams approximately 1.2 X 0.1 X 0.1, using chain saws with a chain saw mill.

Orientation and depth in the landfast ice were marked on each beam. The beams were tested as soon as they were prepared.

Figure 1 shows the test setup.The test configuration was three point bending, measuring load and deflection. Beams were tested with the top, or uppermost, surface of the ice in tension. Flexural strength was calculated from the maximum load, and bending modulus from the slope of the linear portion of the load-deflection curve, using the classical beam expressions

$$\sigma = \frac{3\,P\,L}{2\,b\,h^2} \qquad E = \frac{k\,\nabla P\,L^3}{4\,b\,h^3\,\nabla y} \tag{4}$$

where σ is the flexural strength, E is bending modulus, P is the load, L, b and h are beam length, width and thickness, y is beam deflection, and k is a geometric factor which depends on the offset of the deflection measurement from the point of load application. These data are presented in Table 1.

§4.5 Floe size

The dimensions of small floes were measured with surveyor's tape, and are accurate to within 1 m. Large floe dimensions were determined using the helicopter Loran system. The relative position accuracy of the Loran in the Northumberland Strait is about ± 20 m.

§4.6 Rubble sail dimensions

Direct measurement with a surveyor's tape is the simplest method of determining rubble sail height, width and length, but it is often not possible because of the roughness of the ice or the size of the feature. Photographs contain detailed information on size and shape. Scale in the photographs is provided by objects (people) of known dimensions, and by features, such as the distance between two paint marks on the sail, which were measured by tape. A surveyor's transit was used occasionally to verify sail height with respect to water level.

§4.7 Rubble profile

The team determined the orientation of the ridge axis, and a line perpendicular to the axis using a compass. They augured holes in the ice on the line perpendicular to the axis at measured distances from the peak in the sail. Ice surface height, depth of consolidated ice, keel depth, and water depth were measured with respect to the water surface.

Time constraints, and the requirement to sample multiple rubble features, limited the number of holes which could be sunk for each feature. Additional data was obtained from the sites of temperature-salinity cores, and from the surface observations described in §4.6.

§4.8 Water temperature and salinity

Salinity in the water column below the ice was measured with a YSI Model 33 portable salinometer. The conductivity cell was post-calibrated by comparison with a calibrated Autosal Model 8400. The salinity of diluted seawater samples was measured with both units, and a correction factor developed to bring the YSI values in line with the Autosal salinities. After correction, the YSI salinities correspond to the Autosal salinities to within ± 0.25 ppt. The temperature sensor in the YSI salinometer was not calibrated. Appendix B contains a table and a chart of temperature and salinity versus depth for each profile. The profiles show that the water under moving ice was mixed throughout the water column. Under the landfast ice, the near-surface layers were slightly brackish, due to freshwater runoff or melting ice.

§4.9 Ice drift

During the helicopter transect from Seacow Head to Cape Jourimain, the team noted Loran position and time at each landing and takeoff. The data sheets for Floes #3 to 7 contain these values, and the calculated drift velocity and direction. Although the Loran precision may permit an accuracy of 5% in these results, the actual ice drift velocities may vary by an order of magnitude with time of day, weather, and position in the strait.

§5 RESULTS

§5.1 Rubble piles

Tables 2 to 7, with accompanying charts, show the measurements on six individual rubble piles. The first line of the table gives the date and time of the observations, and an identifying comment. The second line gives geographic coordinates and drift. The third line locates the feature with respect to the shore and ice shear line, and gives water depth at the time of observation. This water depth changes due to tides. The fourth line gives lateral dimensions for the main body of the pile, excluding secondary and neighboring piles. The next two lines give maximum and median height/depth for the sail/keel, and a brief description of the composition. The temperatures and salinities are the averages for the consolidated portions of cores. The profile shows surface elevation, depth of consolidated portion, keel depth, and water depth for a typical cross section of the rubble, with the positive x axis pointing offshore.

From the measurements, and from casual observations of many rubble piles, the picture which emerges for a typical large rubble pile is the following. The pile is aligned with the direction of ice motion along the strait. The sail is composed of large, well bonded blocks, and sail height is greater for rubble piles nearer the shear line. In rubble piles in an active shear zone, the offshore face of the sail is packed with crushed ice. The keel is composed of blocks and slush, with low porosity, and extends to the bottom. The profile is skewed so that the mass centre of the keel is inshore of the mass centre of the sail. The spine of the rubble is a beam of consolidated ice. Cores in Rubble #4 had void free portions 1.7 m and 2.1 m long. Given the slope of the sail, the width of the spine would be approximately half the width of the sail. Transverse tide cracks and voids occasionally interrupt the length of the spine. Hence, typical spine dimensions are 2 m deep x 15 m wide x 35 m long. Extreme values of these dimensions are three times each of the above, but they occur independently.

Freeboard ratios at some distance from the sail peak are normal (0.91 - 0.93) for unstressed ice. In Rubble #3, r_i values in the inshore portion of the sail are 0.96 - 0.99, indicating the ice is being submerged, while at the peak, the sail is supported by the grounded keel (r_i = 0.67). Similarly, the range of values of r_i for Rubble #4 and Rubble #6 indicate areas of activity and grounding.

Near Richibucto Beach and near West Point, rubble piles were not linear, but covered areas up to 100 X 100 m. These features were not measured from the ground, but it is likely they were similar in structure to those described here in more detail.

Although the rubble keel is unconsolidated, it provides an effective anchor. The vertical shear face on Rubble #5 had a surface area of approximately 50 m^2 (Photo 4). The keel anchored the rubble pile in position as the channel ice ground and slid along this face to form it. A nominal average shear and sliding stress of 20 kPa exerted over this surface would transmit to a global load of 1 MN through the rubble pile to the anchor.

Strength tests were not performed in rubble piles. The strength relative to the level ice flexural strength (which was measured) may be inferred by comparing temperatures, salinities, and brine volumes. The averages for these values are not significantly different for rubble and level ice, but the distributions are different. The rubble keel is relatively warm, and has relatively high salinity; the sail is exposed to colder air temperatures and part of the brine has drained. The calculated brine volumes indicate that the strength of the keel ice is approximately 30% less, and the strength of the sail ice is approximately 30% more, than that of the level ice [3].

The ice sheet adjacent to the rubble pile is thickened by rafting and by spreading of the keel. The main body of the rubble pile is separated from the adjacent sheet by tide cracks, both inshore and offshore. These tide cracks are also activity sites, showing flooding, buckling, and shearing.

§5.2 Level ice and floes

Tables 8 to 15 show level ice measurements at eight different locations. The first line of the table gives the date and time of the observations, and an identifying comment. The next two lines give geographic coordinates and drift for moving floes, or location with respect to the shore and ice shear line for landfast features. The fourth line gives lateral dimensions for distinct floes. Measured ice thicknesses and freeboards are listed, and freeboard ratio is calculated according to equation (3). Ridge sail heights are given where they were measured. The temperatures and salinities are the averages for the cores indicated, and for the surface water.

From the measurements, the picture which emerges for typical level ice is the following. Ice thickness is about 0.55 m, with a range of 0.42 m to 0.89 m. Thinner ice is new, and likely to be broken up by older floes; thicker ice due to rafting is present in many floes. The freeboard ratios are high: 0.94 occurred frequently in snow-free ice, and 0.91 was the lowest recorded in level ice. Freeboard ratios higher than 0.94, such as in Summerside harbour (Floe #8) are due to the substantial snow cover in the vicinity.

Melting and refreezing of the snowcover produced a hard top layer, detectable by auguring, on the surface of some floes. This layer shows up as low salinity at 0 to 10 cm, as for Floe #7.

The temperature-salinity profiles also confirm the rafted and bonded structure of the ice. The rafting is revealed in the double mode salinity profile. The bonding is confirmed by the linear temperature profile, as for Floe #4 (rafted). If the rafting has occurred late in the development, then adjacent portions of composite floes may have thicknesses in the ratio two to one, as was the case for Floe #2 and Floe #4.

The rafted ice portions of floes were clearly visible from the air as lighter, blue-green ice. These portions comprised approximately 50% of the ice area.

The flexural strength of small beams taken from level ice, Table 1, did not show a consistent variation with depth. The average flexural strength was 418 kPa. The ice property of practical importance, however, is the flexural strength of the entire ice cover. A full thickness beam of proportions corresponding to the beams tested would be 6.0 x 0.5 x 0.5 m. The large beam strength would be lower, consistent with the common observation that strength decreases as stressed area, or volume, increases.

A recent study on the effect of of beam size on flexural strength [8] performed tests on sea ice beams over four orders of magnitude in beam volume. Strength varied as (beam volume)$^{-1/12}$. A subsequent study [7] confirmed this relationship for small beam samples and full thickness beams in the sizes considered here. Hence we estimate the corresponding strength for full thickness beams from the smaller beam strengths using

$$\sigma_2 = \sigma_1 \left(\frac{V_1}{V_2}\right)^{1/12} \qquad (5)$$

where σ_2 is the full thickness beam strength, σ_1 is the measured strength, 418 kPa, V_1 is the measured beam volume, 0.012 m^3, and V_2 is the large beam volume, 1.5 m^3. Thus with volume scaling, the flexural strength of the entire ice cover is approximately 280 kPa.

Figure 2 shows the flow velocities measured during the February 27 transect, on a 1:100,000 scale sketch map. The velocity vectors are drawn to the indicated scale, and the tail of the vector is on the position of the floe at the midpoint of the measurement interval. Time of day for the midpoint of each interval is indicated. The velocity swings from NE to NW. There is insufficient data to verify whether this variation is diurnal, geographical, or meteorological. However there is a correlation with the tide. The DFO tide tables for 1993 show that the current for a falling tide in Abegweit Passage is East to West, and on February 27, the high tide turned at 1315 AST. This is close to the time at which the ice velocities were observed to reverse direction.

Floe sizes measured directly in this study ranged from 300 m diameter to 2000 m diameter. From the helicopter surveys, the team estimated that 60% of the surface area was covered by floes in this size range. However more reliable statistics on floe size as a function of location and time of year could be obtained from sets of aerial photographs of the strait [4, 5] such as those in archives at the Ice Centre of Atmospheric Environment Services, Ottawa.

§5.3 Ridges

In an informal survey carried out from the helicopter, the study team counted 13 large (1.2 to 1.6 m sail), 13 medium (0.8 to 1.2 m sail), and 29 small (0 to 0.8 m sail) ridges over a straight line distance of 7.5 km, indicating a flat size distribution.

Table 16, with the accompanying profile, shows the detailed measurements on a large ridge drifting near Cape Tormentine, N.B. The table entries are the same as for the tables of rubble data. Other ridge measurements appear with the floe data, in Tables 8 to 15.

Ridge sail heights ranged from 0 to 2.0 m, with mean peak dimensions for a sail of 1.5 m high x 5 m wide x 20 m long. Block sizes up to 0.5 x 2.0 x 2.5 m were observed in sails with high porosity, and while in sails with low porosity blocks dimensions were about 0.2 m. The structural variations indicate a combination of compressive and shear stress states during ridge formation, consistent with the degree of ice activity in the strait.

§6 DISCUSSION

The results of the study provide a clear picture of ice properties in the vicinity of the proposed fixed link crossing of Northumberland Strait. From this picture it is possible to describe potential interactions between ice and the bridge.

During breakup, the rubble piles will become floating ice features, separated from the adjacent ice sheets. The unconsolidated keel will disintegrate once the overburden is removed, and the large blocks of the sail will break off as it rolls into the water. In mechanical interactions with bridge piers, the residual features may be considered as beams with the dimensions of the consolidated spine.

Apart from their mechanical resistance, the rubble piles merit consideration for their existence, size, and prevalence. A rubble formation becomes grounded frequently.

Once grounded, these features are stable and strong, withstanding the considerable shear forces tending to dislodge them. Grounded rubble may form in shallow water near the bridge piers, and in compression zones caused by the deceleration of the ice pack upstream of the piers.

In the case of level ice, the distributions of floe thickness, size, and mass are required for evaluation of ice force risk. The collection of the statistics necessary to determine such distributions was beyond the scope of the current study. However the study did reveal some important features of these distributions.

Once thick ice is established, the ice dynamics in the strait converts thin level ice to rubble. The rafting throughout the growth season results in a high percentage of thick ice. For these two reasons, the thickness distribution at the end of February is likely to be skewed towards the higher thicknesses. Furthermore, the ice activity creates portions of open water in which ice growth is more rapid. Thus the total volume of ice in the strait is greater than that which would be produced under steady state growth conditions.

During the study, Ice Centre data for the Gulf of St. Lawrence were compared with on–site observations. The ice chart for 27 February shows ice conditions for the study area to be: 60% cover with thickness 30 to 70 cm, 30% cover with thickness 15 to 30 cm, and 10% cover with thickness 10 to 15 cm, all in floes less than 500 m in diameter. The helicopter survey and measurements for that day indicate that over 10% of the area, ice cover thickness exceeded 70 cm, and 20% of the area was covered by floes greater than 500 m in diameter. The helicopter survey and measurements on 02 March were carried out in a CCG helicopter, with the Coast Guard Ice Observer. The (corrected) ice chart egg for that day shows thickness distributions which coincide with the study team observations, but the floe sizes are smaller than indicated by on-site observations.

The ice charts collate a large amount of information, and interpret it for the purposes of mariners and shippers. The ice charts may not have high resolution in the particular parameters which are important for the design of the fixed link. As mentioned in §5.2, reliable statistics on floe size as a function of location and time of year could be obtained from AES aerial photographs of the strait. It may be possible to derive distributions of ice thickness from carefully planned overflights with the Coast Guard's airborne EM ice thickness sensor.

The freeboard ratios for level ice, at 0.94 to 0.96, are consistently higher than the values normally assumed for sea ice (0.91 to 0.92). The higher freeboard ratios mean that the momentum and inertia of a piece of ice of known dimensions are higher by 2%, and the buoyant forces acting on the ice are lower by by 50%, than those which would be calculated using the normally assumed values. Furthermore, the high freeboard ratios indicate a tendency for ice to rubble downwards, with high keel to sail height ratios.

The largest ridges are normally attached to thicker floes. The length of an unbroken ridge structure is much less than the diameter of a floe, because of irregular floe margins. In mechanical interactions with bridge piers, ridges may be considered as beams which reinforce the ice sheet. Because of the large number of ridges in the strait, and the volume of ice they represent, they may be important for their contribution to rubble formation.

A constraint in the application of the study results to the prediction of ice effects on the proposed fixed link crossing is that the observations were made during one short time period, and do not represent ice conditions at other times and years. The average dimensions of ice features are largest near the end of the ice growth season, the time of this study. The current ice season, with 758 freezing degree days recorded at Charlottown up to 26 February, 1993, has been relatively cold [9]. The average accumulation of freezing degree days up to 26 February for the years 1953-1975, historically recorded at Summerside, is 560 [6]. The ice growth is not determined by temperature histories alone, because of the ice dynamics. However given similar ice activity, in a year with a higher accumulation of freezing degree days there is likely to be larger ice volume in the strait than in a year with fewer freezing degree days. Hence the dimensions of ice features observed during this study are likely to be large compared with those present in warmer years.

§7 SUMMARY AND CONCLUSIONS

The field program carried out in Northumberland Strait, February 25 to March 4 1993, produced the following information about ice properties in the strait near the end of the ice growth season:

- Grounded rubble piles are the largest ice features in the western part of the strait.
- The rubble sail may exceed 7 m height.
- The rubble keel is compacted blocks and slush, and is firmly grounded.
- The consolidated spine of a large rubble pile is approximately 2 x 15 x 35 m.
- The average strength of consolidated rubble is similar to that of the level ice.
- Rubble piles with large shear faces demonstrate the stability of grounded features.

- Grounded rubble is separated from the adjacent ice sheet by tide cracks.
- Drifting floes 300 to 2000 m in diameter cover 60% of the strait area.
- Approximately 50% of level ice is rafted.
- Floating ice has a tendency to rubble downward.
- Level ice strength is approximately 280 kPa.
- The ridges on free drifting floes show a uniform size distribution.
- The mean peak ridge sail dimensions are 1.5 x 5 x 20 m.
- Ice concentrations and floe size distributions should be determined from aerial photos.
- Distributions of ice thickness with location and time of year will have higher mean ice thickness than a meteorological freezing model would predict.

The data set presented here is small, and biased towards large features. We have not addressed some quantitative aspects of the ice description because of the limitations in time and extent of this study. Further information is required on ice thickness distributions, floe size distributions, and floe velocities as functions of time, position, and floe size.

The ice engineering issues important for the crossing are:

- Large rubble features may be floating in the strait during break-up.
- The ice dynamics increases the total volume of ice produced in the strait.
- The average ice thickness is greater than the thickness of undisturbed landfast ice.
- Rubble grounding is likely, and grounded features are stable.

§8 REFERENCES

1. Prodanovic, A. *Model tests of ice rubble strength*, Fifth International Conference on Port and Ocean Engineering under Arctic Conditions, Trondheim, Vol. I: 89-105. 1979.

2. Cox, G.F.N. and W.F. Weeks, *Equations for determining the gas and brine volumes in sea ice samples.* CRREL: CRREL Report 82-30. 1982.

3. Mellor, M., *Mechanical Behaviour of Sea Ice.* CRREL monograph, Vol. 83-1. . 102. 1983.

4. Bercha & Associates, *High resolution SAR data acquisition and interpretation for Northumberland strait.* Public Works Canada: 1988.

5. Bercha & Associates, *Analysis of photographic data for 1964 and 1965.* Public Works Canada: 1988.

6. Bercha & Associates, *Northumberland strait ridge investigation.* to Delcan/Stone & Webster Joint Venture: 1989.

7. Williams, F.M., J. Everard, and S. Butt, *Ice and snow measurements in support of the operational evaluation of the Nathaniel B. Palmer in the Antarctic winter environment.* Institute for Marine Dynamics: TR-1992-14. 1992.

8. Parsons, B.L., *et al., The influence of beam size on the flexural strength of sea ice, freshwater ice, and iceberg ice.* Philosophical Magazine A, **66**(6): p. 1017-1036. 1992.

9. Personal communication, Charlottown weather office, 1993.

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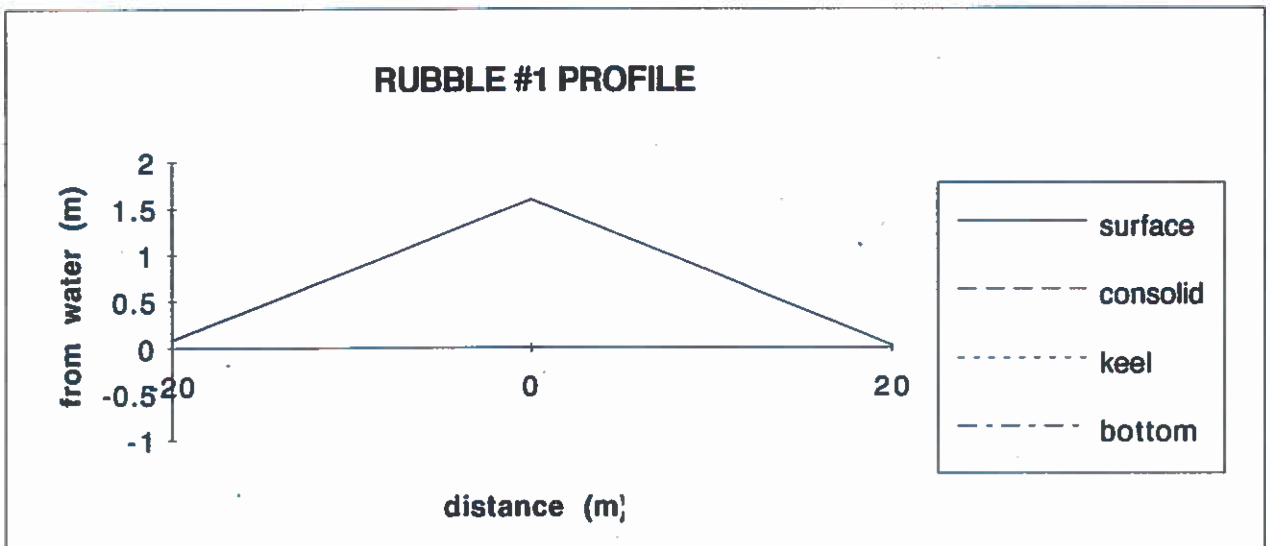
Table 1: STRENGTH OF SMALL BEAMS

TIME	l (m)	b (m)	h (m)	P2 (N)	σ (kPa)	core T (°C)	depth (m)
1420	1.00	0.137	0.099	384	429	-3.5	0.40-0.50
1612	1.00	0.122	0.100	313	385	-2.7	0.05-0.15
1623	1.00	0.098	0.102	253	372	-3.3	0.20-0.30
1630	1.00	0.096	0.101	186	285	-3.4	0.20-0.30
1830	1.00	0.115	0.102	498	624	-4.2	0.05-0.15
1836	1.00	0.115	0.102	373	474	-5.1	0.20-0.30
1843	1.00	0.122	0.103	290	336	-4.7	0.40-0.50
1850	0.70	0.111	0.102	487	443	-5.3	0.10-0.20
average					418	-3.2	

rubble#1

dd/mo/93	25/02	time (AST)	1230	Cape John	
lat	45°48.6	long	63°08.3	w_depth (m)	
to shore (m)	900	shear line (m)	600	moving (m/s)	landfast
length (m)		width (m)		orientation	E-W
sail max (m)	1.6	sail med (m)		sail descript.	blocks .23x.55x.55
keel max (m)		keel med (m)		keel descript.	
consol T (°C)		consol S (ppt)			

distance	surface	consolid	keel	bottom	freeboard ratio
-20	0.08	-0.78	-0.78		0.93
0	1.6				
20	0.03	-0.265	-0.265		0.92



rubble#2

dd/mo/93	25/02	time (AST)	1530	knock on window	
lat	45°52.8	long	63°33.6	w_depth (m)	
to shore (m)	800	shear line (m)	400	moving (m/s)	landfast
length (m)		width (m)		orientation	E-W
sail max (m)	3.4	sail med (m)	2	sail descript.	blocks 0.3x2.0x2.0
keel max (m)		keel med (m)		keel descript.	
consol T (°C)		consol S (ppt)			

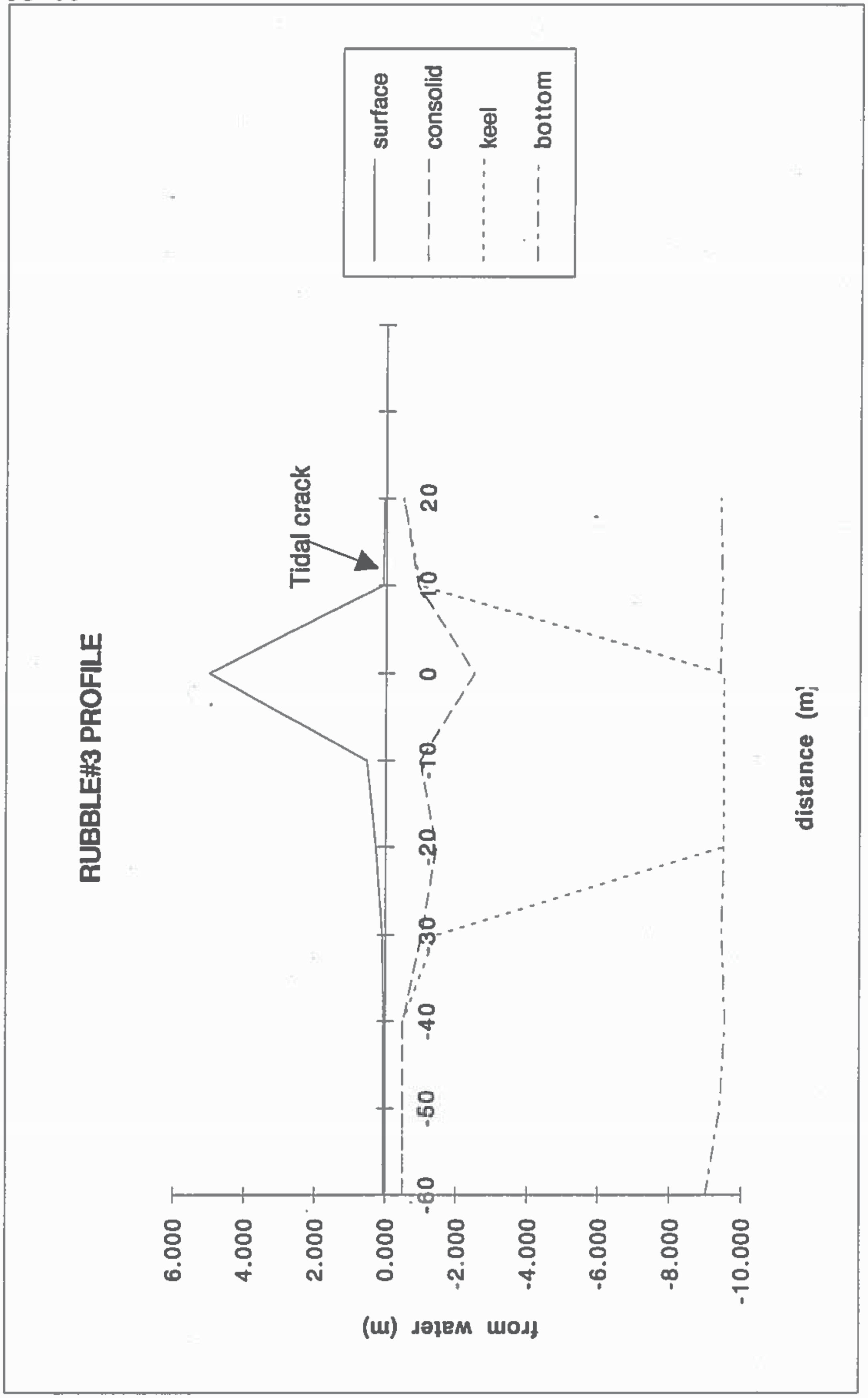
distance	surface	consolid	keel	bottom	freeboard ratio
20	0.12	-0.96	-0.96		0.91

rubble#3

dd/mo/93	26/02 04/03	time (AST)	1010 930	smoked fish	
lat	46°14.7	long	64°16	moving (m/s)	landfast
to shore (m)	1000	shear line (m)	20		
length (m)	80	width (m)	35	orientation	E-W
sail max (m)	5	median (m)	3	description	blocks 0.9x1.4x2.5
keel max (m)	grounded	keel med (m)	grounded	keel descript.	slush
consol T (°C)	-9.1	consol S (ppt)	1.84	core#1	
	-3.3		2.2	core#2	
	-3.6		2.9	core#13	
	-3.9		4.2	core#14	
water T(°C)	-2.1	water S (ppt)	25	w_depth (m)	9.31 1030 AST

distance	surface	consolid	keel	bottom	freeboard ratio
-60	0.053	-0.497	-0.497	-9.0	0.93
-50	0.065	-0.495	-0.495	-9.4	0.91
-40	0.055	-0.490	-0.490	-9.6	0.92
-30	0.100	-1.000	-1.410	-9.5	0.96
-20	0.290	-1.420	-9.500	-9.5	0.99
-10	0.540	-0.960	-9.500		0.97
0	5.000	-2.500	-9.500	-9.4	0.67
10	0.100	-0.890	-0.950	-9.5	0.93
20	0.050	-0.480	-0.480	-9.4	0.93

rubble#3

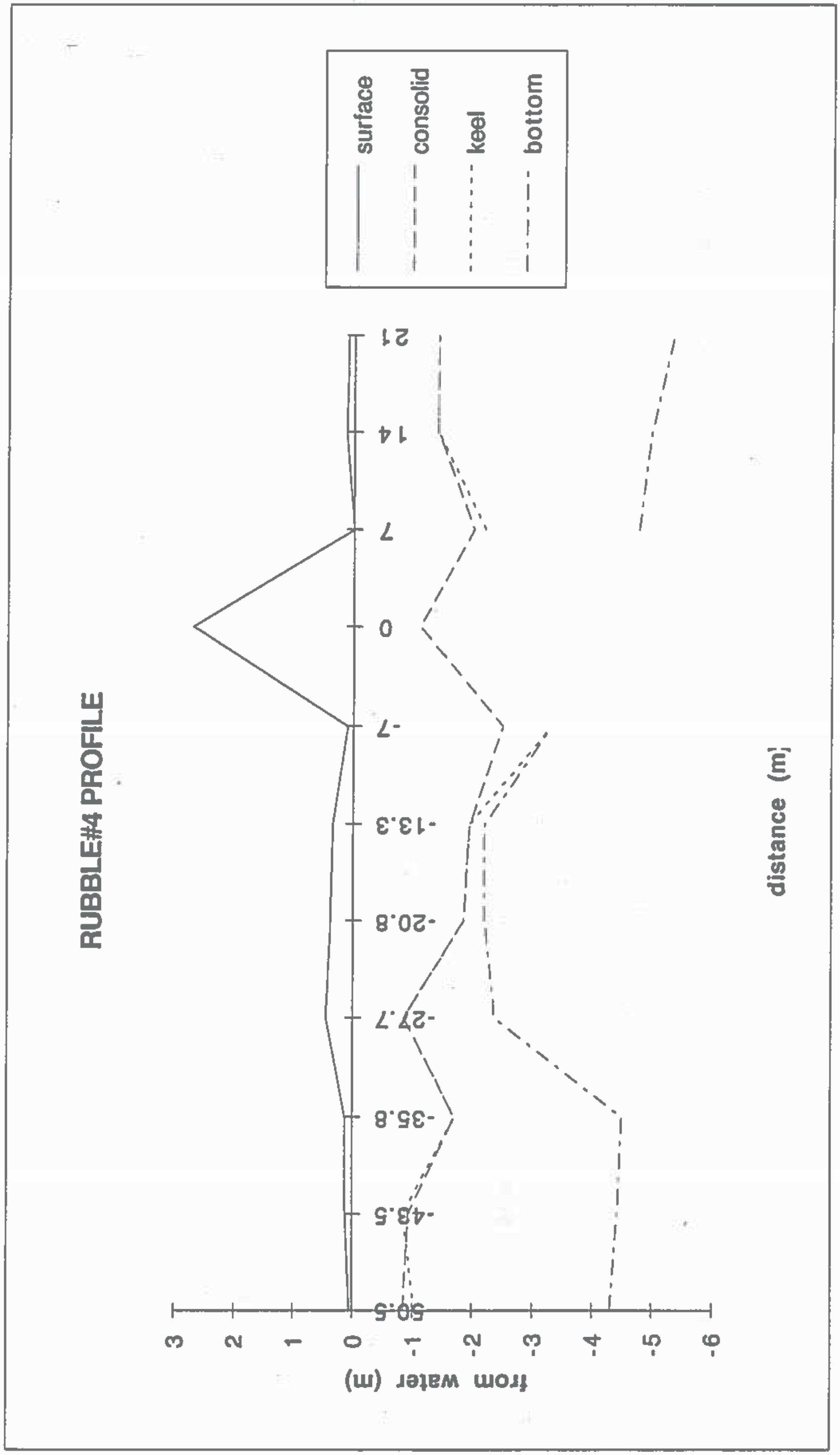

RUBBLE#3 PROFILE
Tidal crack
surface
consolid
keel
bottom
6.000
4.000
2.000
0.000
-2.000
-4.000
-6.000
-8.000
-10.000
from water (m)
-60
-50
-40
-30
-20
-10
0
10
20
distance (m)

rubble#4

dd/mo/93	26/02 03/03	time (AST)	1615 1420	barking dog	
lat	46°11.1	long	63°58.4	moving (m/s)	landfast
to shore (m)	300	shear line (m)			
length (m)	55	width (m)	15	orientation	300°-120°
sail west (m)	2.4	sail east (m)	3.9	sail descript.	blocks 0.5x1.5x2.0
keel max (m)	grounded	keel med (m)	grounded	keel descript.	blocks, slush
consol T (°C)	-5 -4.8 -4.7	consol S (ppt)	3.81 1.7 2.6	core#3 core#4 core#12	
water T (°C)	-1.9	water S (ppt)	18.2	w_depth (m)	3.92

distance	surface	consolid	keel	bottom	freeboard ratio	
-50.5	0.06	-0.83	-1.03	-4.3	0.97	
-43.5	0.13	-0.92	-0.93	-4.42	0.90	
-35.75	0.14	-1.7	-1.7	-4.49	0.95	
-27.7	0.45	-0.84	-0.84	-2.37	0.67	
-20.8	0.38	-1.85	-1.85	-2.2	0.85	
-13.25	0.35	-1.95	-1.95	-2.2	0.87	
-7	0.1	-2.5	-3.3	-3.3	0.99	slush under 3ı
0	2.7	-1.1	-4	-4	0.61	
7	0	-2.01	-2.2	-4.76	1.03	block at -2.2
14	0.14	-1.4	-1.4	-4.97	0.93	some blocks t
21	0.1	-1.41	-1.41	-5.34	0.96	

rubble#4

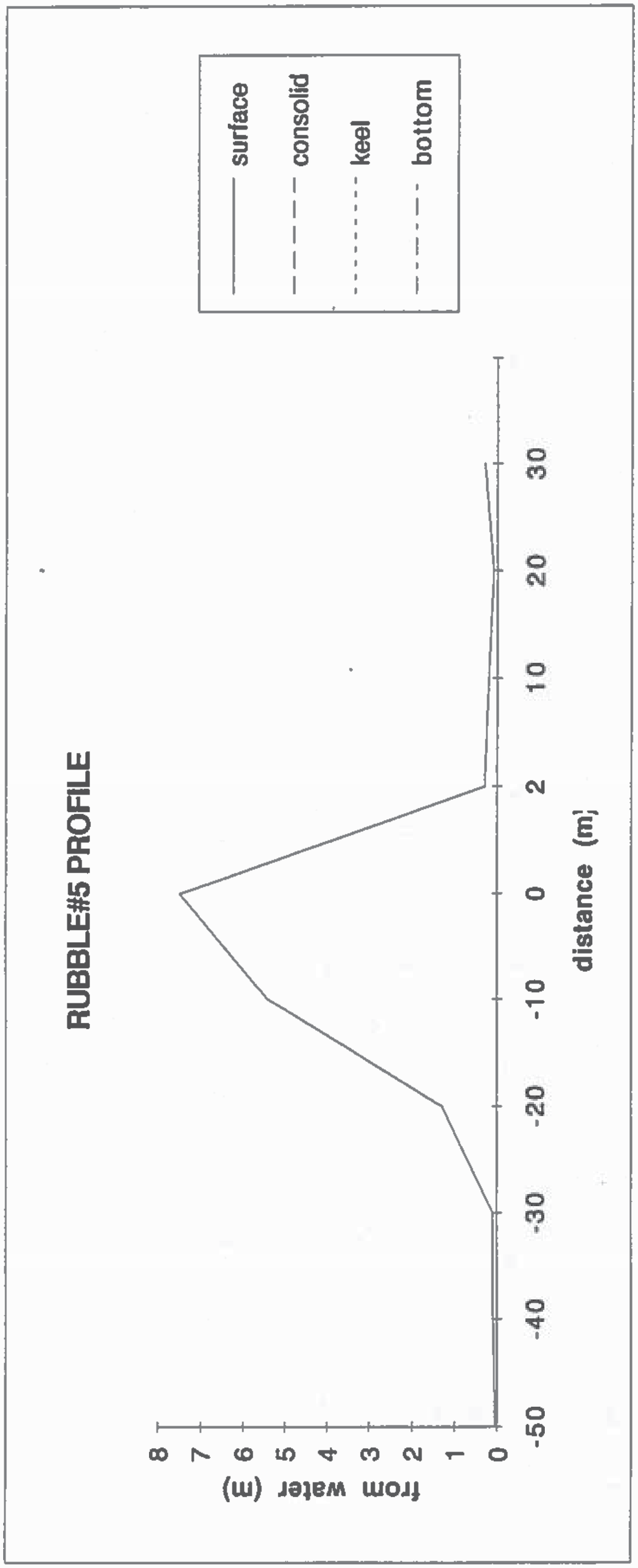

RUBBLE#4 PROFILE
surface
consolid
keel
bottom
from water (m)
3
2
1
0
-1
-2
-3
-4
-5
-6
-50.5
-43.5
-35.8
-27.7
-20.8
-13.3
-7
0
7
14
21
distance (m)

rubble#5

dd/mo/93	27/02	time (AST)	1550	blue ribbon	
lat	46°10.85	long	63°55.01	moving (m/s)	grounded
to shore (m)	900	shear line (m)	0		
length (m)	41	width (m)	20	orientation	E-W
sail max (m)	7.5	sail med (m)	4	sail descript.	inshore blocks .6x2.1x2.4 offshore lumps & mortar
keel max (m)		keel med (m)		keel descript.	
consol T (°C)		consol S (ppt)		w_depth (m)	11.7

distance	surface	consolid	keel	bottom	freeboard ratio
-50	0.05				
-40	0.1				
-30	0.1				
-20	1.3				
-10	5.4				
0	7.5				
2	0.3				
10	0.2				
20	0.1				
30	0.3				

rubble#5

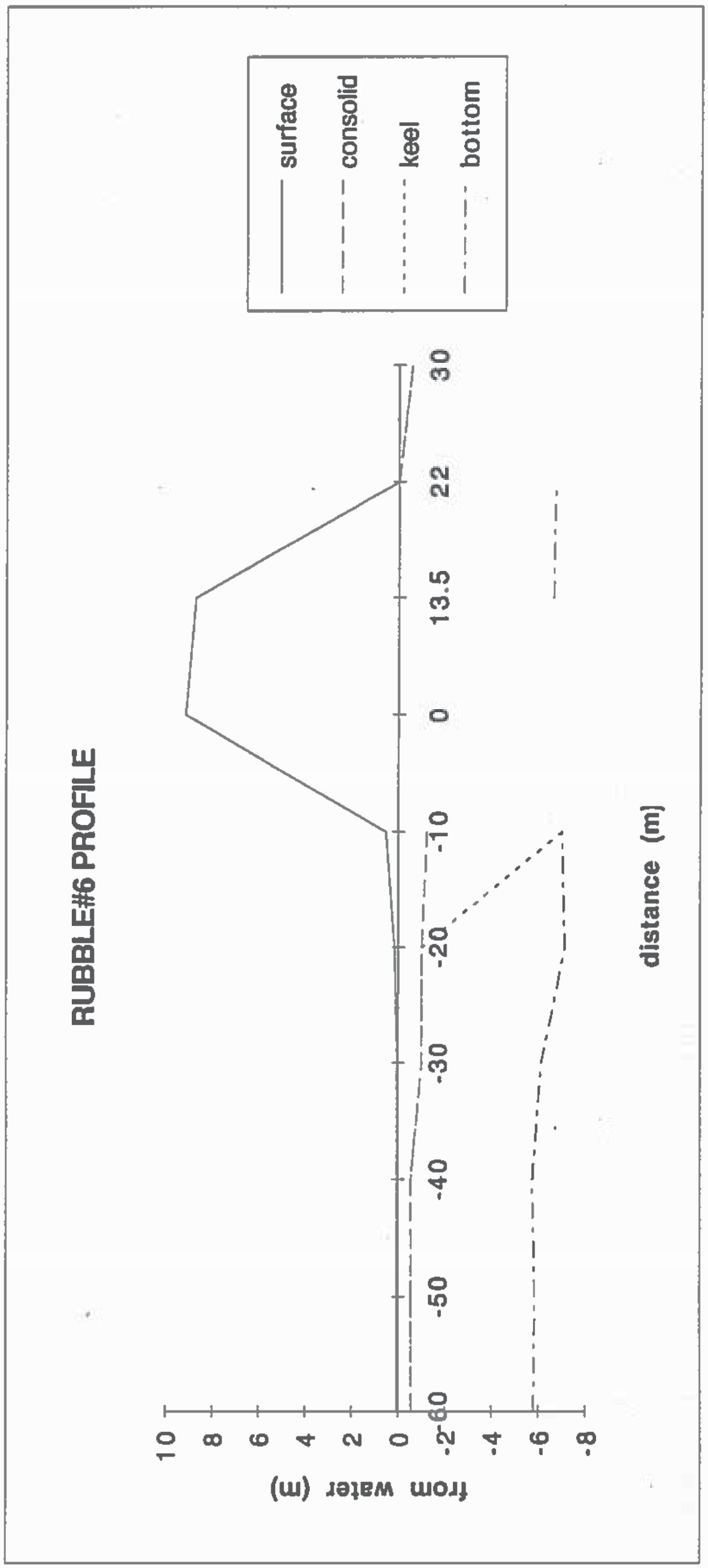

RUBBLE#5 PROFILE
surface
consolid
keel
bottom
from water (m)
0
1
2
3
4
5
6
7
8
distance (m)
-50
-40
-30
-20
-10
0
2
10
20
30

rubble#6

dd/mo/93	28/02	time (AST)	1000	West Cape Cemetary	
lat	46°40.1	long	64°25.2	moving (m/s)	landfast
to shore (m)	800	shear line (m)	0		
length (m)	75	width (m)	35	orientation	N-S
sail max (m)	9.1	sail med (m)		sail descript.	blocks .6x2x2.4 inshore blocks & mortar offshore
keel max (m)	7.1	keel med (m)		keel descript.	slush and soft blocks, no vo
consol T (°C)		consol S (ppt)		w_depth (m)	7.1

distance	surface	consolid	keel	bottom	freeboard ratio
-60	0.06	-0.55	-0.55	-5.8	0.92
-50	0.06	-0.56	-0.56	-5.85	0.93
-40	0.075	-0.54	-0.54	-5.75	0.90
-30	0.055	-0.985	-0.985	-6.1	0.97
-20	0.17	-0.99	-0.99	-7.11	0.87
-10	0.55	-1.2	-6.99	-6.99	0.95
0	9.15				
13.5	8.75			-6.6	
22	0	0	0	-6.7	
30	0.05	-0.55	-0.55		0.94

rubble#6


RUBBLE#6 PROFILE
surface
consolid
keel
bottom
10
8
6
4
2
0
-2
-4
-6
-8
from water (m)
-60
-50
-40
-30
-20
-10
0
13.5
22
30
distance (m)

floe#1

dd/mo/93	25/2	time (AST)	1130	Cape John, 250 m W headland	
lat	45°48.2	long	63°08		
to shore (m)	250	shear line (m)	1500	moving (m/s)	shorefast
length (m)		width (m)		orientation	
nom thick (m)	0.245	freeboard (m)	0.02	freeboard ratio	0.94
max level (m)	0.275	r_sail (m)		surface	rough
mean T (°C)	-3.2	mean S (ppt)	3.5		
w_depth (m)		w_S (ppt)			

floe#2

dd/mo/93	25/02	time (AST)	1200	Cape John, N of rubble#1	
lat	45°48.3	long	63°08	moving (m/s)	landfast
to shore (m)	300	shear line (m)	700		
length (m)		width (m)		orientation	
nom thick (m)	0.51	freeboard (m)		freeboard ratio	
2nd thick (m)	0.86	freeboard (m)	0.08	freeboard ratio	0.93
3rd thick (m)	0.295	freeboard (m)	0.03	freeboard ratio	0.92
4th thick (m)	0.445	freeboard (m)	0.035	freeboard ratio	0.94
max level (m)	0.086	r_sail (m)		surface	bonded floes
mean T (°C)		mean S (ppt)			
w_depth (m)		w_S (ppt)			

comments:
sand suspended in ice
sand in clumps in ice
snow ice 10 cm of 25 cm in one floe

floe#3

dd/mo/93	27/2	time (AST)	1053 1137 helo 1		
lat	46°16.20 46°16.39	long	63°48.26 63°47.84	moving (m/s) deg from N	0.24 57
length (m)	363	width (m)		orientation	
nom thick (m)	0.54 0.57	freeboard (m)	0.04 0.03	freeboard ratio freeboard ratio	0.95 0.97
max level (m)		r_sail (m)	1	surface	
mean T (°C)	-5.9	mean S (ppt)	4.27		
w_T(°C)	-1.4	w_S (ppt)	31.4		

floe#4

dd/mo/93	27/2	time (AST)	1142 1255		
				73 mins	
lat	46°15.06	long	63°47.42	moving (m/s)	0.30
	46°14.82		63°46.45	° from N	110
length (m)	353	width (m)		orientation	
nom thick (m)	0.745	freeboard (m)	0.065	freeboard ratio	0.94
	>2.5		0.73	freeboard ratio	
	0.89		0.07	freeboard ratio	0.94
	0.47		0.04	freeboard ratio	0.94
	0.69		0.08	freeboard ratio	0.91
max level (m)	>2.5	r_sail (m)	1.5	surface	rafted
mean T (°C)	-6.1	mean S (ppt)	6.83	core #6	
	-8.1		3.41	core #7	
w_depth (m)		w_S (ppt)			

floe#5

dd/mo/93	27/02	time (AST)	1255 1404		
lat	46°13.01 46°13.09	long	63°46.22 63°46.37	moving (m/s) ° from N	0.06 307
length (m)	1200	width (m)		orientation	
nom thick (m)	0.46	freeboard (m)	0.045	freeboard ratio	0.92
	0.42		0.04	freeboard ratio	0.93
	0.42		0.042	freeboard ratio	0.92
max level (m)		r_sail (m)	3.3	surface	composite
mean T (°C)	-6.3	mean S (ppt)	3.7		
w_T (°C)	-1.9	w_S (ppt)	31.9		

floe#6

dd/mo/93	27/2	time (AST)	1410 1437		27 mins
lat	46°11.67	long	63°46.36	moving (m/s)	0.26
	46°11.80		63°46.63	° from N	306
length (m)	2200	width (m)	2000	orientation	
nom thick (m)	0.51	freeboard (m)	0.04	freeboard ratio	0.94
	0.475		0.015	freeboard ratio	0.99
	0.72		0.06	freeboard ratio	0.94 rafted
	0.46		0.02	freeboard ratio	0.98
max level (m)	0.72	r_sail (m)	.	surface	level
mean T (°C)	-6.5	mean S (ppt)	5.07		
w_depth (m)		w_S (ppt)			

floe#7

dd/mo/93	27/2	time (AST)	1448 1532		
wind	7 km/hr W				
lat	46°09.85	long	63°46.28	moving (m/s)	0.31
	46°10.10		63°46.80	deg from N	305
to shore (m)		shear line (m)			
nom thick (m)	0.515	freeboard (m)	0.04	freeboard ratio	0.95
2nd thick (m)	0.45	freeboard (m)	0.03	freeboard ratio	0.96
3rd thick (m)	0.45	freeboard (m)	0.032	freeboard ratio	0.95
max level (m)		r_sail (m)		surface	level
mean T (°C)	-6.1	mean S (ppt)	4.31		
w_depth (m)		w_S (ppt)			

floe#8

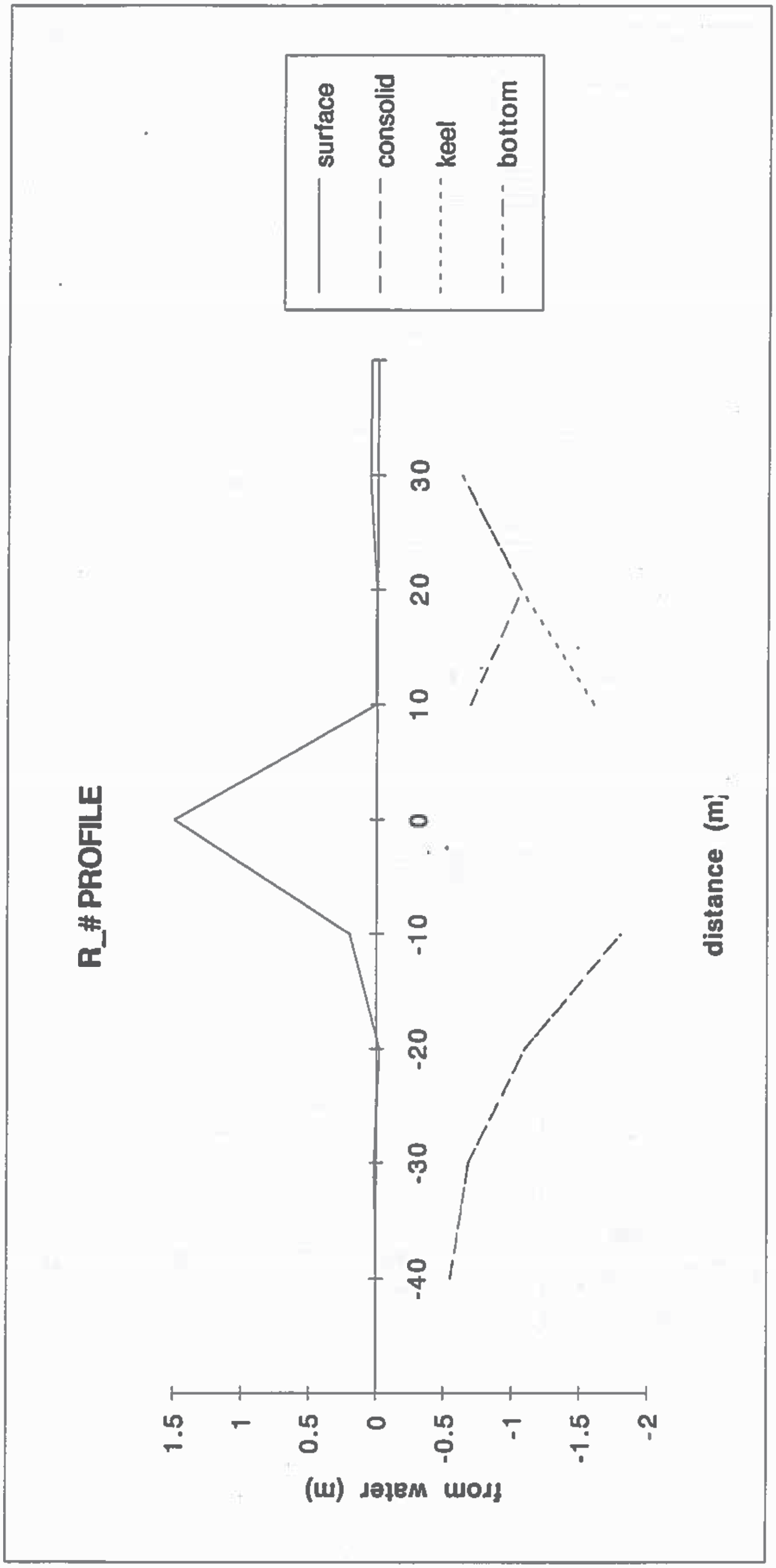
dd/mo/93	0203	time (AST)	1430	Summerside	
lat	46°20.60	long	63°50.30	moving (m/s)	landfast
	46°20.88		63°49.13		
to shore (m)	1500	shear line (m)			
length (m)		width (m)		orientation	
nom thick (m)	0.50	freeboard (m)	0.00	freeboard ratio	1.03 snow
	0.52		0.00	freeboard ratio	1.03 on ice
	0.56		0.06	freeboard ratio	0.92
	0.65		0.03	freeboard ratio	0.98
	0.54		0.01	freeboard ratio	1.01
max level (m)		r_sail (m)		surface	
mean T (°C)		mean S (ppt)			
w_depth (m)		w_S (ppt)			

ridge#1

dd/mo/93	02/03	time (AST)	1500	Greg & Mich	
lat	46°13.62	long	63°57.11	moving (m/s)	yes
to shore (m)		shear line (m)			
length (m)		width (m)	20	orientation	
sail max (m)	1.5	sail med (m)	1.0	sail descript.	
keel max (m)		keel med (m)		keel descript.	
consol T (°C)		consol S (ppt)			

distance	surface	consolid	keel	bottom	freeboard ratio
-40	0	-0.55	-0.55		1.03
-30	0.02	-0.68	-0.68		1.00
-20	-0.02	-1.09	-1.09	flooded	1.04
-10	0.2	-1.8	-1.8		0.92
0	1.5	-1	-1.7		
10	0.01	-0.69	-1.6		1.02
20	0.01	-1.06	-1.06		0.97
30	0.06	-0.62	-0.62		0.95
40	0.05	-0.55	-0.55		

ridge#1


R_# PROFILE
surface
consolid
keel
bottom
distance (m)
from water (m)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-40
-30
-20
-10
0
10
20
30

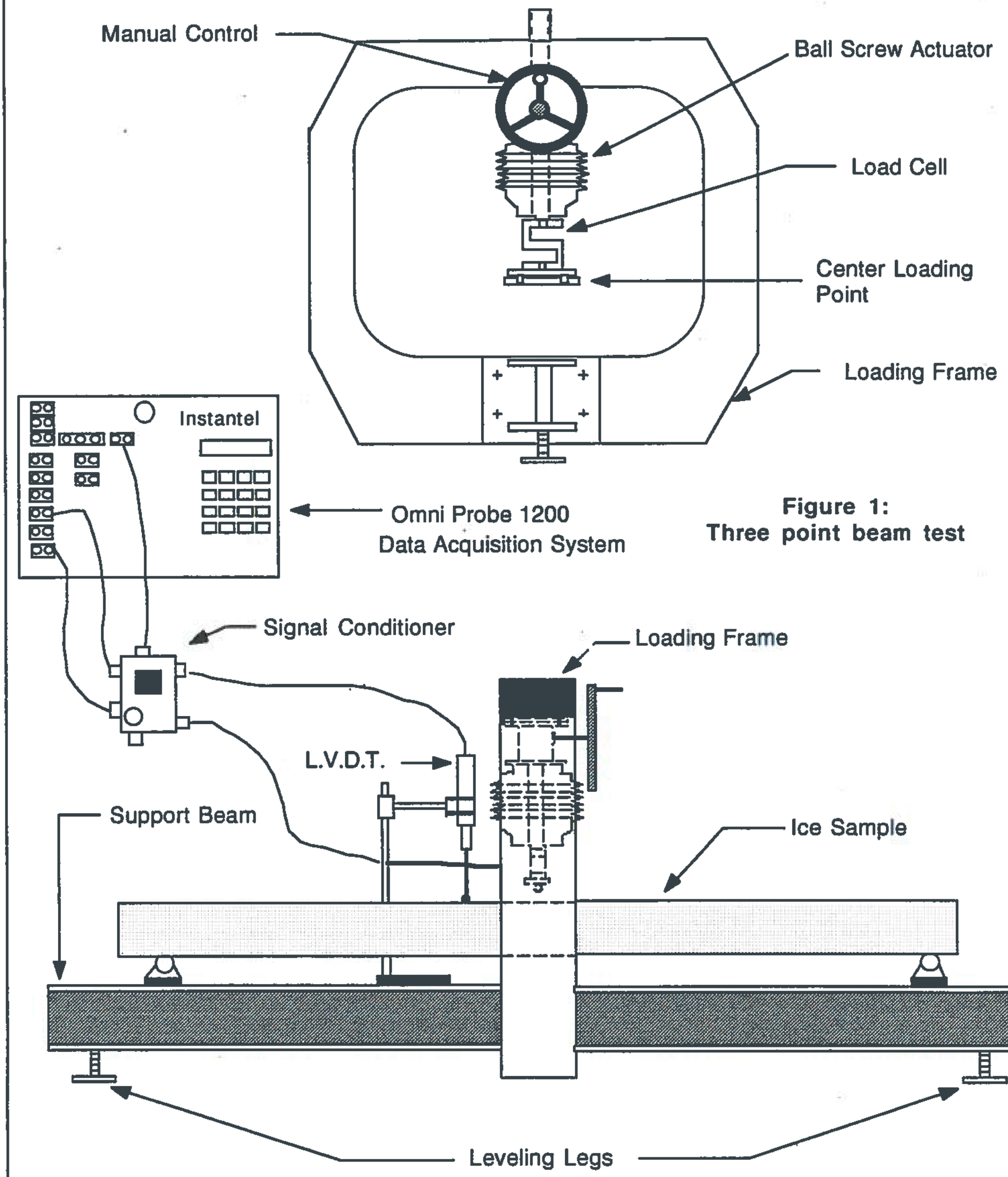
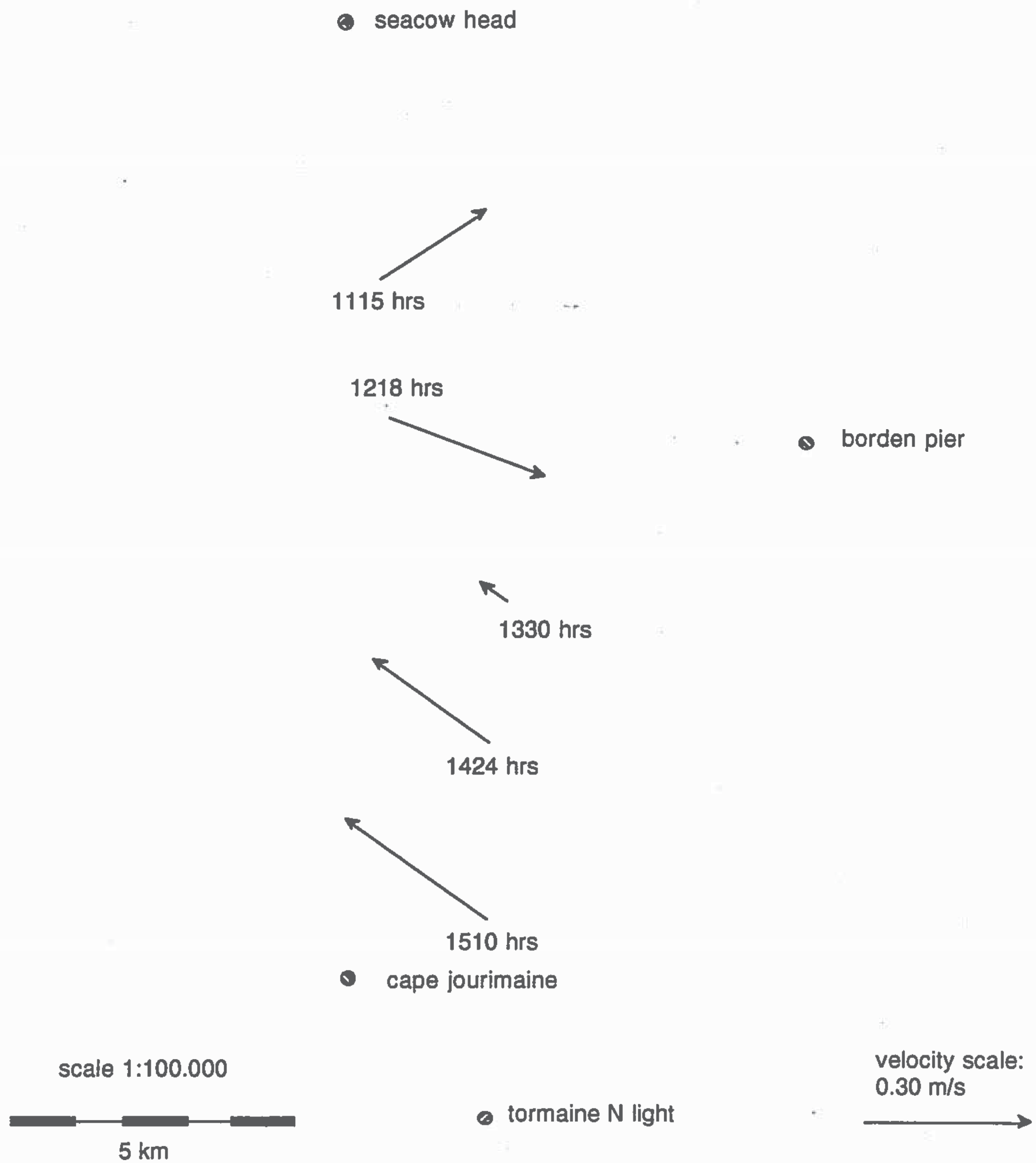


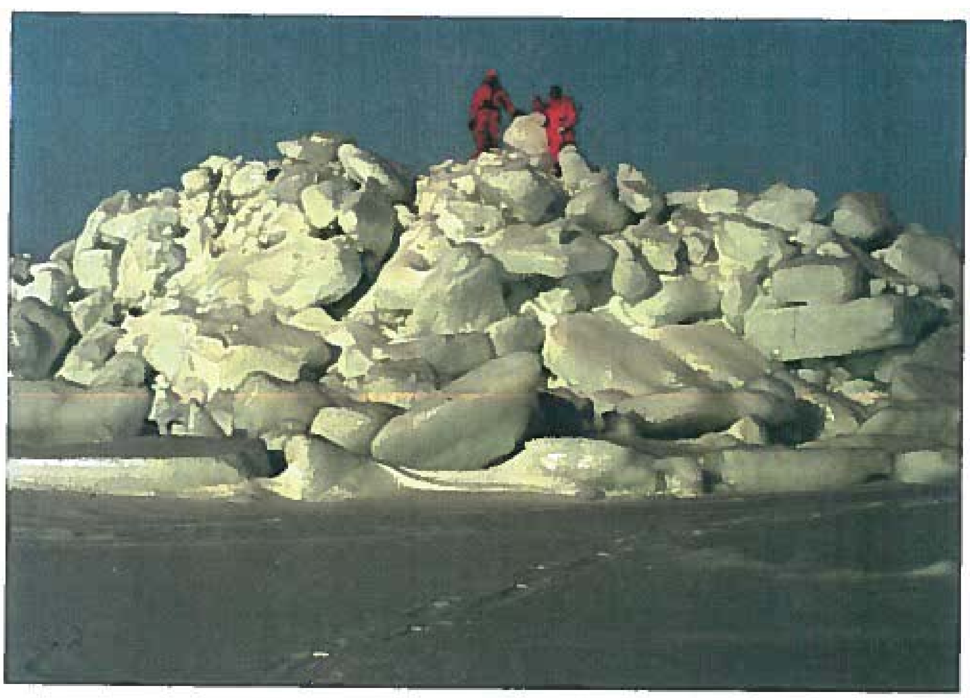
Figure 1: Three point beam test

Figure 2: ice floe velocities February 27, 1993



PHOTOGRAPHS

Rubble #4 sail with N-S axis viewed from SW near core site



Rubble #5 inshore face of sail with N-S axis viewed from W

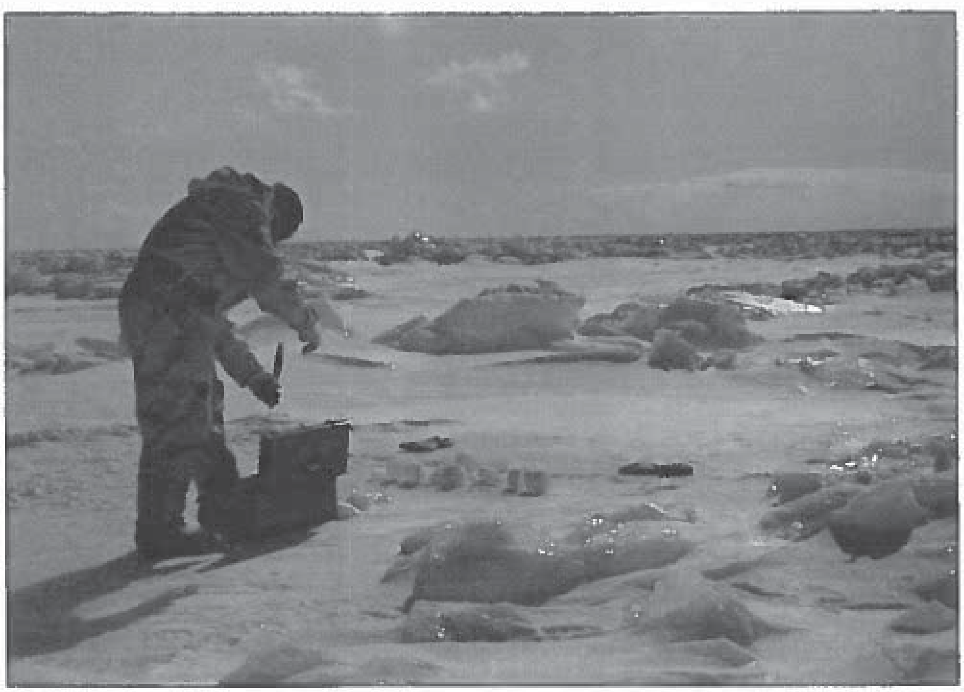
Rubble #5 sail, offshore face, showing ground ice packed between blocks

Rubble #5 offshore face of sail with N-S axis viewed from NE

Rubble #3 offshore face of sail and adjacent level ice with tide crack

Rubble #4, submergence, flooding, and flexure crack in adjacent ice sheet

Floe #4. Foreground ice is rafted, 0.89 m thick; under helicopter is 0.47 m



Floe #4 at core site, showing level sections and seams joining them

Summerside to Tormentine transect, large floes with open water and nilas

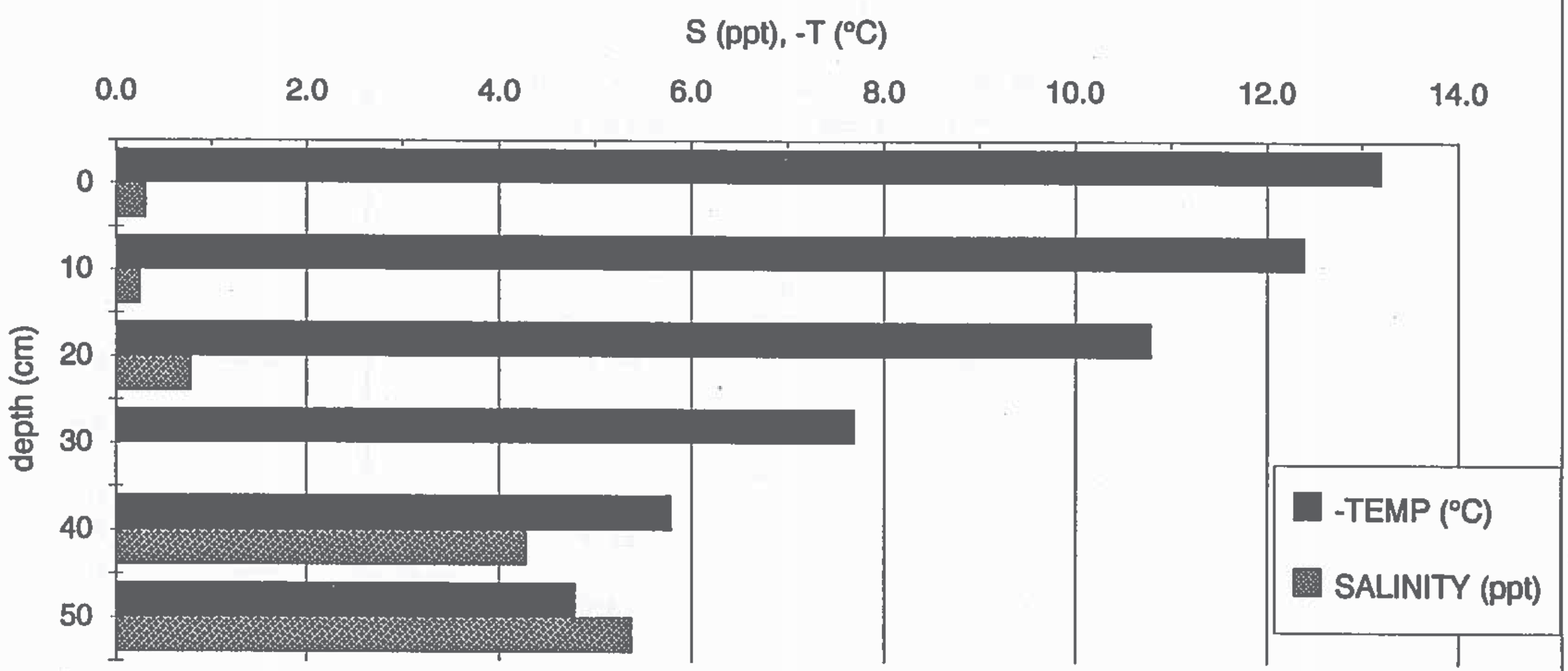
Helicopter view westward during ridge count flight

Appendix A

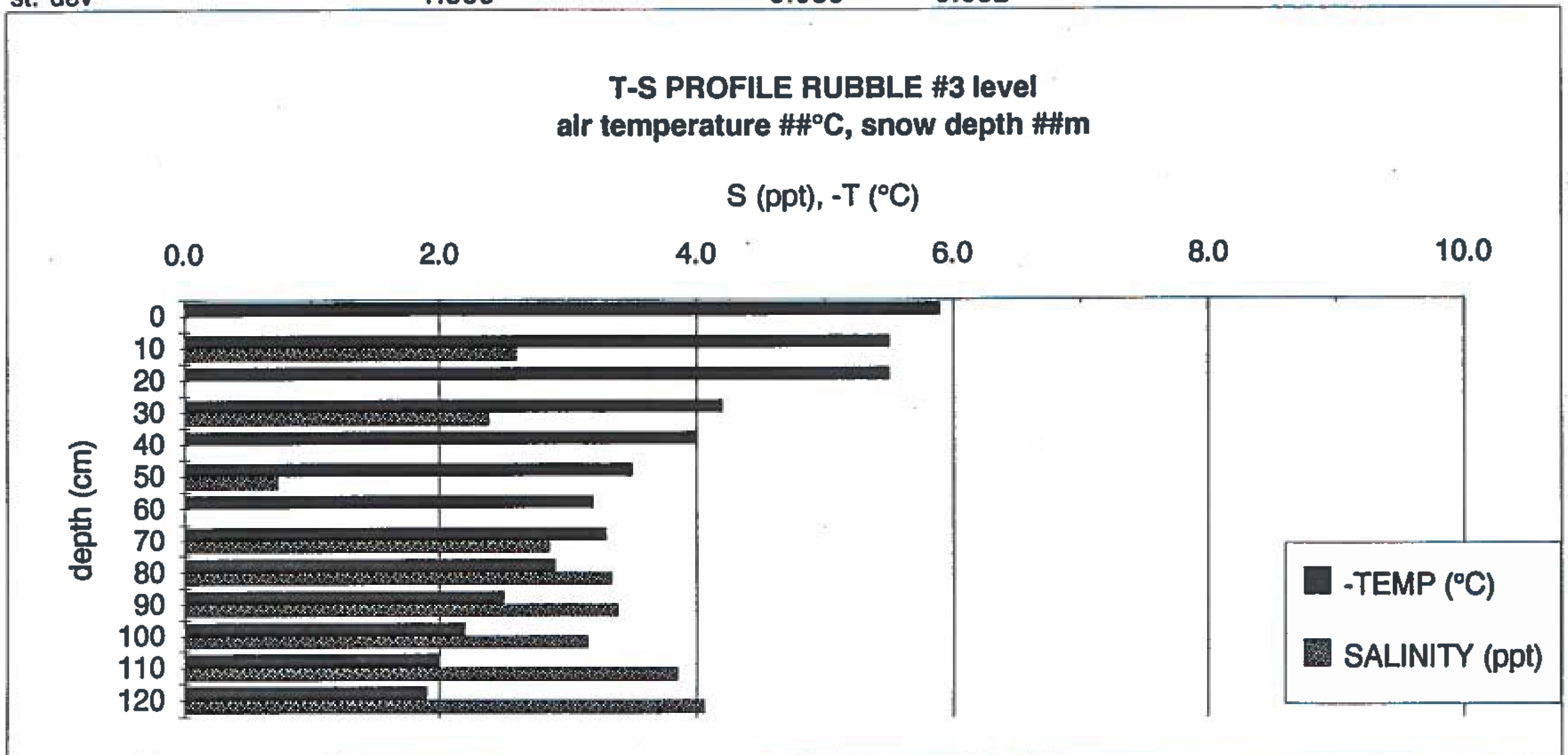
Ice Temperature and Salinity Profiles

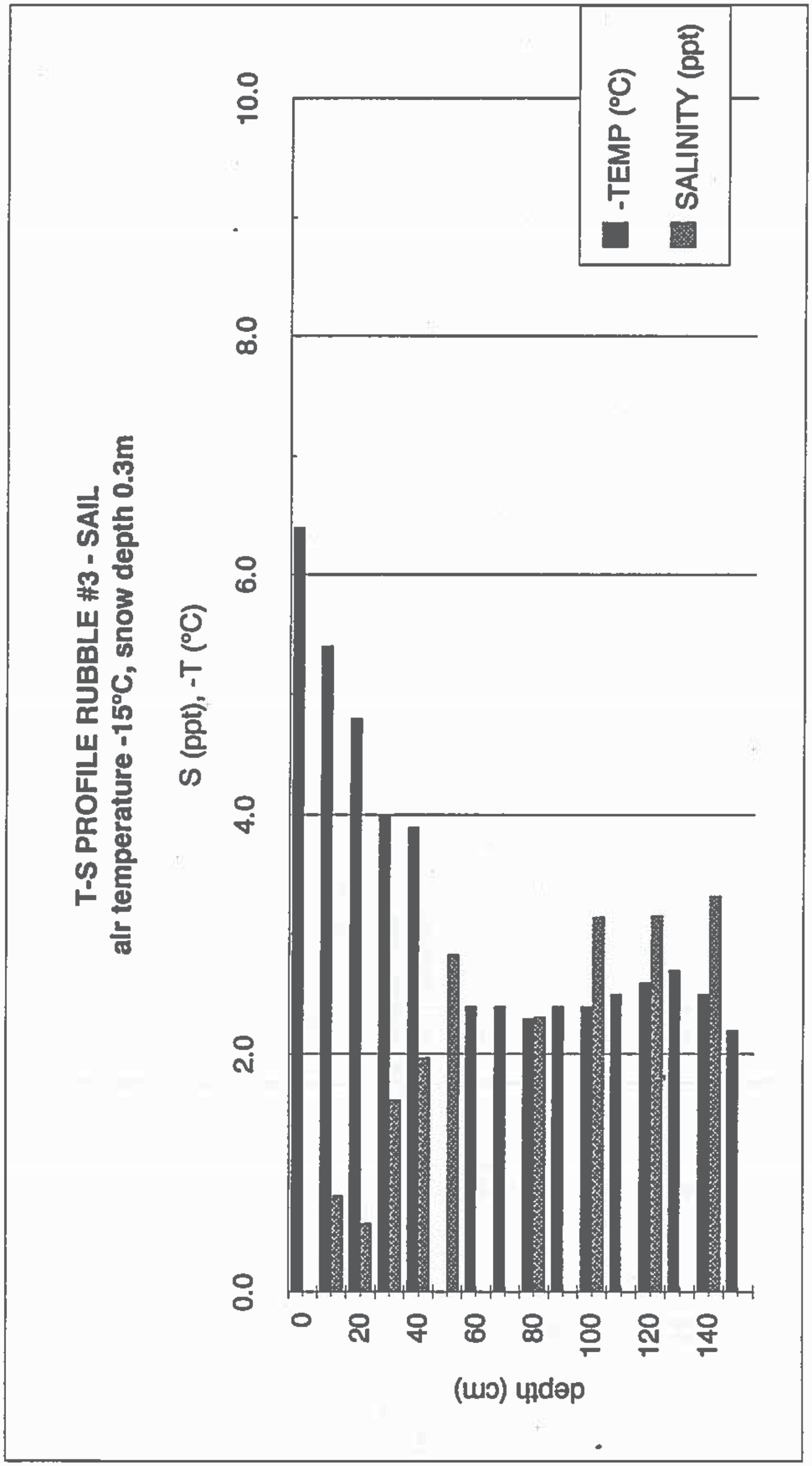
DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb
0	13.2	-13.2	0.57	0.32	0.001
10	12.4	-12.4	0.47	0.26	0.001
20	10.8	-10.8	1.37	0.80	0.004
30	7.7	-7.7			
40	5.8	-5.8	6.96	4.28	0.038
50	4.8	-4.8	8.65	5.38	0.056
average		-9.1	average	2.21	0.020
st. dev		3.519	st. dev	2.435	0.025

T-S PROFILE RUBBLE #3 - LEVEL
air temperature -15°C, snow depth ##m

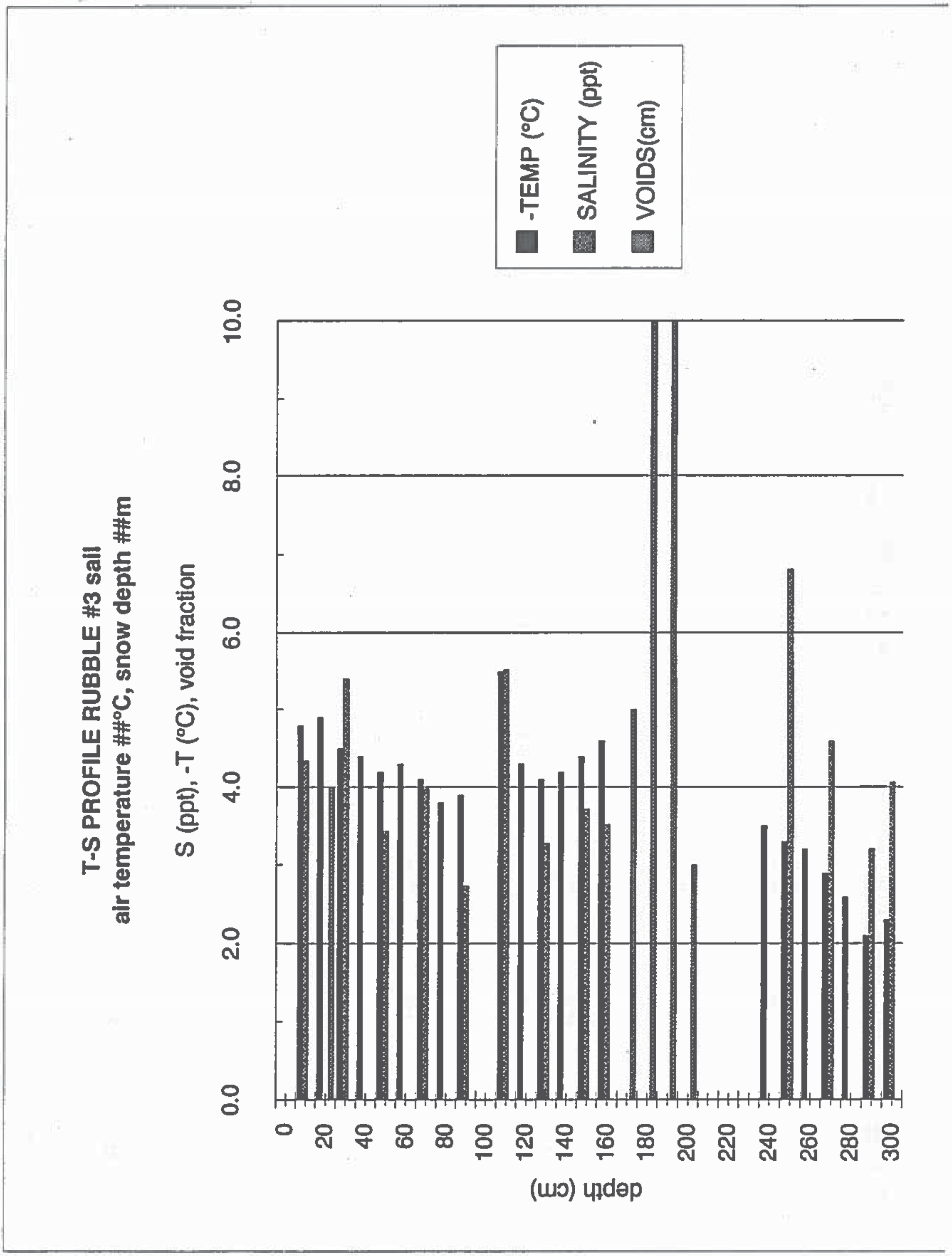


DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m·	SALINITY (p	BRINE VOLb	
0	5.9	-5.9				
10	5.5	-5.5	4.31	2.60	0.024	
20	5.5	-5.5				4 cm void
30	4.2	-4.2	3.97	2.39	0.028	
40	4.0	-4.0				
50	3.5	-3.5	1.27	0.74	0.010	
60	3.2	-3.2				
70	3.3	-3.3	4.72	2.86	0.042	
80	2.9	-2.9	5.49	3.34	0.056	
90	2.5	-2.5	5.57	3.39	0.066	
100	2.2	-2.2	5.20	3.16	0.070	
110	2.0	-2.0	6.29	3.85	0.095	
120	1.9	-1.9	6.62	4.06	0.106	
average		-3.6		2.9	0.055	
st. dev		1.366		0.986	0.032	




T-S PROFILE RUBBLE #3 - SAIL
air temperature -15°C, snow depth 0.3m
S (ppt), -T (°C)
0.0
2.0
4.0
6.0
8.0
10.0
-TEMP (°C)
SALINITY (ppt)
depth (cm)
0
20
40
60
80
100
120
140

DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb
0	6.4	-6.4			
10	5.4	-5.4	1.39	0.81	0.008
20	4.8	-4.8	1.00	0.58	0.006
30	4.0	-4.0	2.71	1.61	0.020
40	3.9	-3.9	3.30	1.97	0.025
50			4.68	2.83	
60	2.4	-2.4			
70	2.4	-2.4			
80	2.3	-2.3	3.85	2.31	0.049
90	2.4	-2.4			
100	2.4	-2.4	5.18	3.15	0.064
110	2.5	-2.5			
120	2.6	-2.6	5.20	3.16	0.059
130	2.7	-2.7			
140	2.5	-2.5	5.46	3.32	0.065
150	2.2	-2.2			
average		-4.0	average	1.69	0.022
st. dev		-1.529	st. dev	0.870	0.017

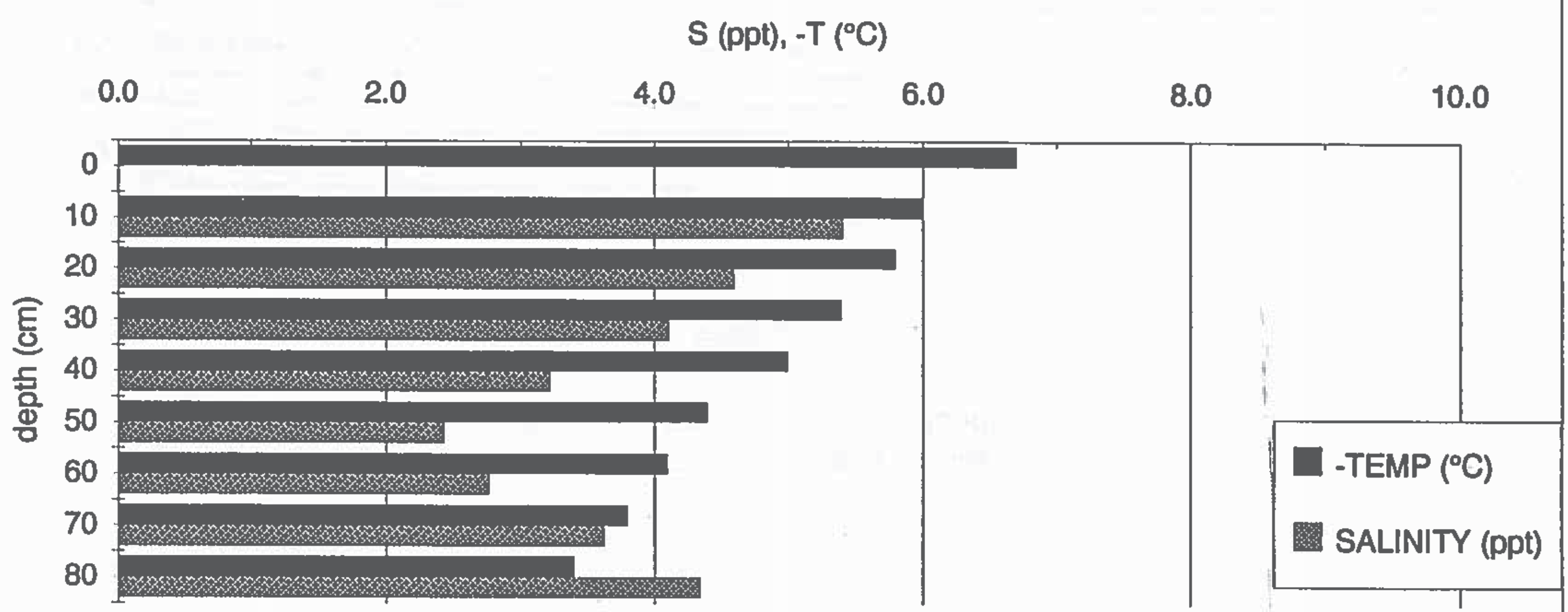

T-S PROFILE RUBBLE #3 sail
air temperature ##°C, snow depth ##m
S (ppt), -T (°C), void fraction
-TEMP (°C)
SALINITY (ppt)
VOIDS(cm)
0.0
2.0
4.0
6.0
8.0
10.0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
depth (cm)

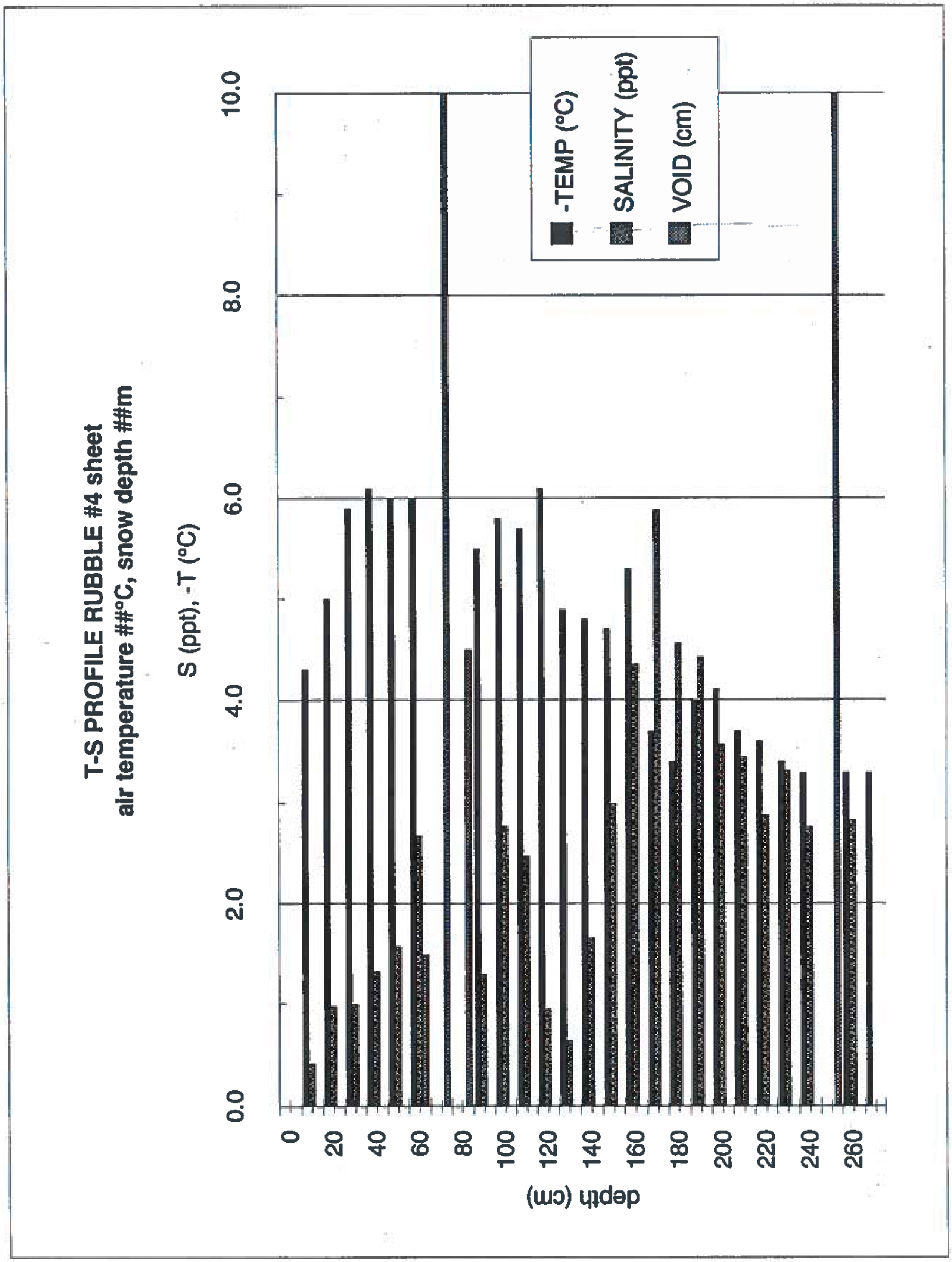
RUBBLE #3 SAIL

DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m·	SALINITY (p	BRINE VOLb	VOIDS(cm)
0						
10	4.8	-4.8	7.06	4.35	0.045	
20	4.9	-4.9				4
30	4.5	-4.5	8.69	5.41	0.060	
40	4.4	-4.4				
50	4.2	-4.2	5.63	3.43	0.040	
60	4.3	-4.3				
70	4.1	-4.1	6.49	3.98	0.048	
80	3.8	-3.8				
90	3.9	-3.9	4.53	2.74	0.035	
100						
110	5.5	-5.5	8.87	5.53	0.051	
120	4.3	-4.3				
130	4.1	-4.1	5.39	3.28	0.039	
140	4.2	-4.2				
150	4.4	-4.4	6.08	3.72	0.042	
160	4.6	-4.6	5.76	3.51	0.038	
170						5
180						10
190						10
200						3
210						
220						
230						
240	3.5	-3.5				
250	3.3	-3.3	10.80	6.82	0.101	
260	3.2	-3.2				
270	2.9	-2.9	7.44	4.59	0.077	
280	2.6	-2.6				
290	2.1	-2.1	5.28	3.21	0.075	
300	2.3	-2.3	6.62	4.06	0.087	
average		-3.9	average	4.2	0.1	
st. dev		0.868	st. dev	1.140	0.021	

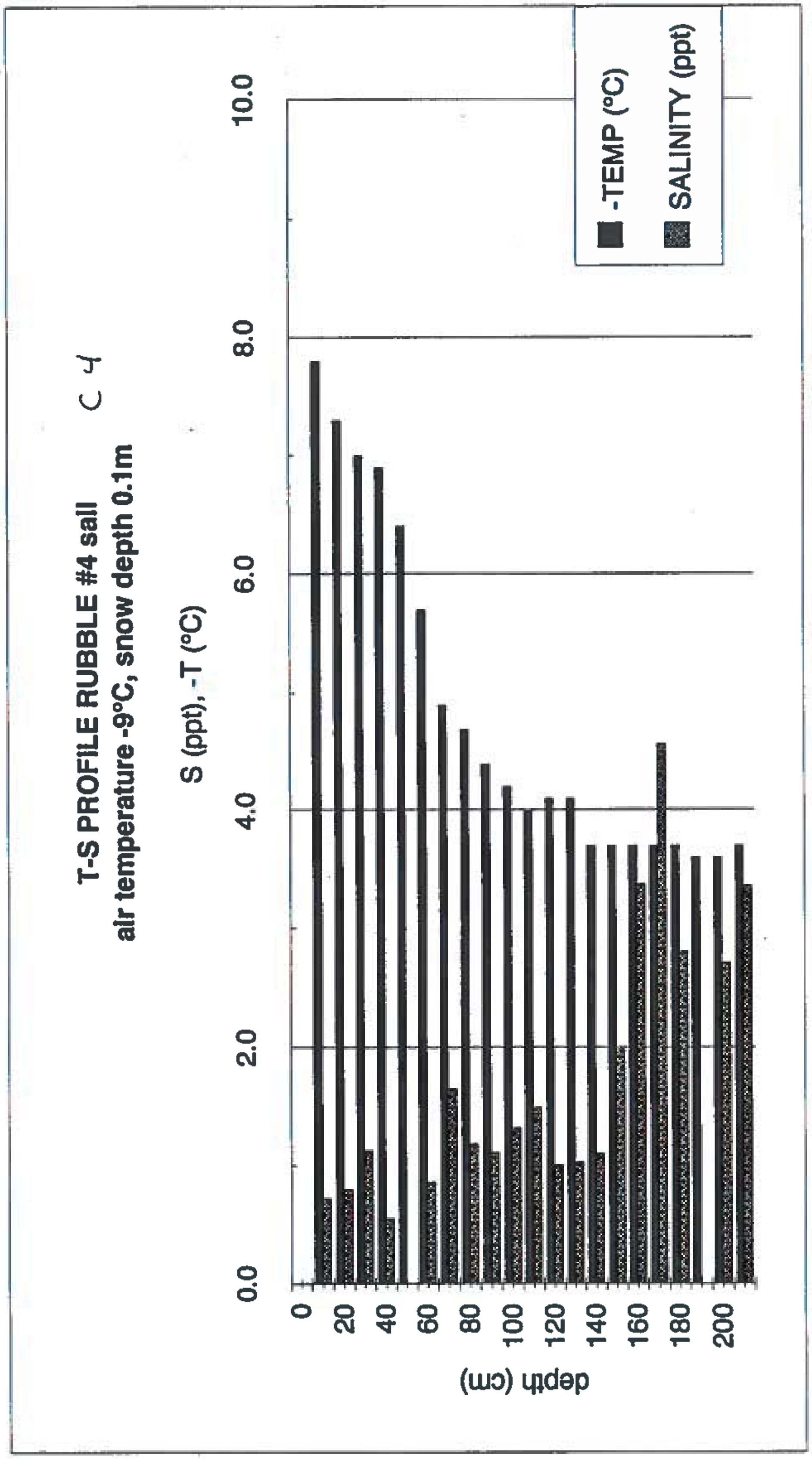
DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb	
0	6.7	-6.7				
10	6.0	-6.0	8.69	5.41	0.046	
20	5.8	-5.8	7.45	4.60	0.040	
30	5.4	-5.4	6.69	4.11	0.038	
40	5.0	-5.0	5.30	3.22	0.032	
50	4.4	-4.4	4.04	2.43	0.027	
60	4.1	-4.1	4.57	2.76	0.033	
70	3.8	-3.8	5.93	3.62	0.047	
80	3.4	-3.4	7.06	4.35	0.063	rafted underneath
average		-5.0	average	3.81	0.041	
st. dev		1.109	st. dev	0.996	0.011	

T-S PROFILE RUBBLE #4 sheet C 3
air temperature -9°C, snow depth ##m



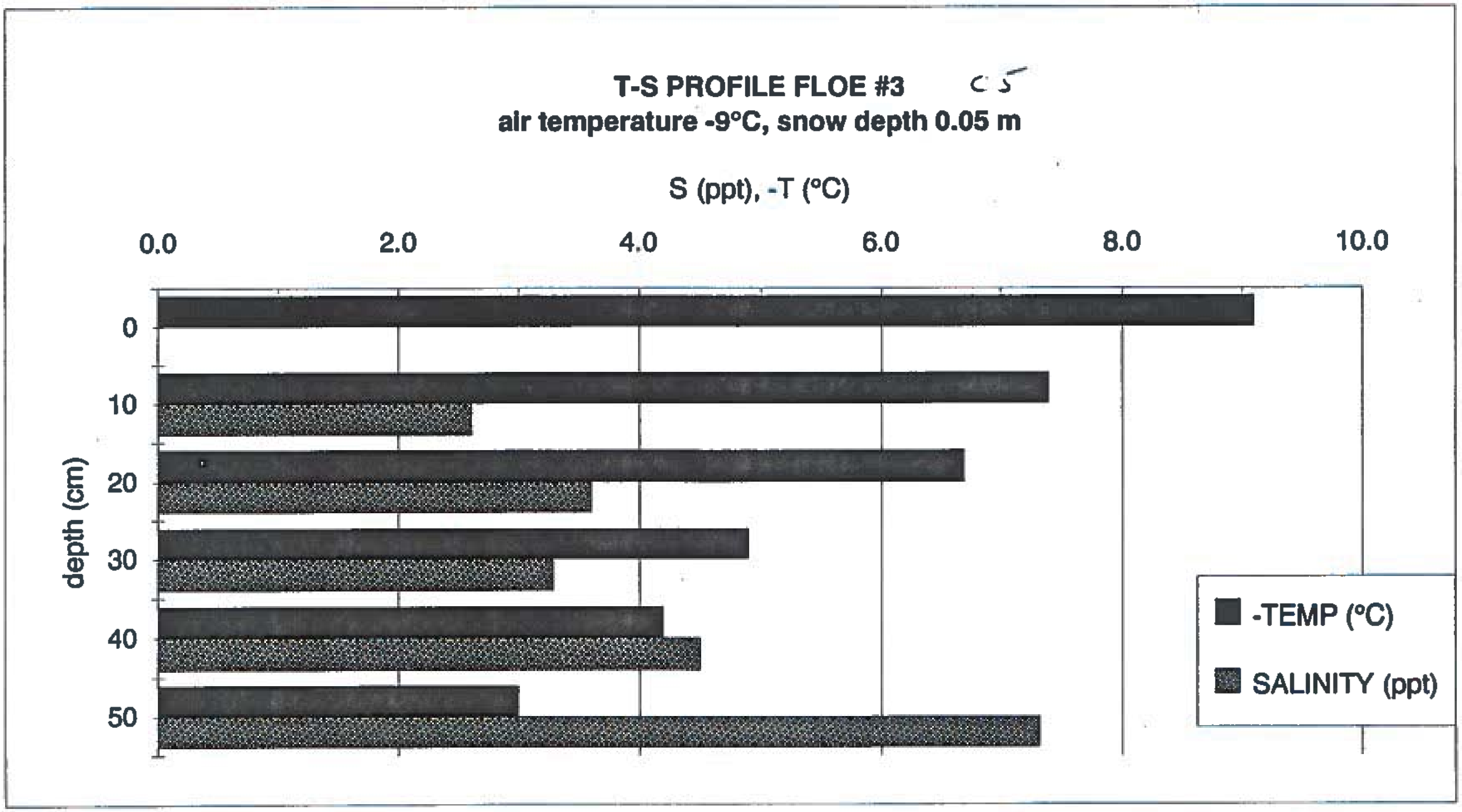

T-S PROFILE RUBBLE #4 sheet
air temperature ##°C, snow depth ##m
S (ppt), -T (°C)
0.0
2.0
4.0
6.0
8.0
10.0
-TEMP (°C)
SALINITY (ppt)
VOID (cm)
depth (cm)
0
20
40
60
80
100
120
140
160
180
200
220
240
260

DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb	VOID (cm)
0						
10	4.3	-4.3	0.73	0.42	0.005	
20	5.0	-5.0	1.67	0.98	0.010	
30	5.9	-5.9	1.70	1.00	0.009	
40	6.1	-6.1	2.25	1.33	0.011	
50	6.0	-6.0	2.66	1.58	0.013	
60	6.0	-6.0	4.44	2.68	0.023	1.5
70						10
80						4.5
90	5.5	-5.5	2.20	1.30	0.012	
100	5.8	-5.8	4.60	2.78	0.024	
110	5.7	-5.7	4.12	2.48	0.022	
120	6.1	-6.1	1.62	0.95	0.008	
130	4.9	-4.9	1.12	0.65	0.007	
140	4.8	-4.8	2.80	1.67	0.017	
150	4.7	-4.7	4.94	2.99	0.032	
160	5.3	-5.3	7.07	4.35	0.041	
170	3.7	-3.7	9.41	5.89	0.078	
180	3.4	-3.4	7.38	4.55	0.066	
190	4.0	-4.0	7.17	4.42	0.054	
200	4.1	-4.1	5.85	3.57	0.043	
210	3.7	-3.7	5.66	3.45	0.046	
220	3.6	-3.6	4.75	2.88	0.039	
230	3.4	-3.4	5.45	3.32	0.048	
240	3.3	-3.3	4.58	2.77	0.041	
250						10
260	3.3	-3.3	4.69	2.84	0.042	
270	3.3	-3.3				
310	3.3	-3.3				
320	3.3	-3.3				
330	3.3	-3.3				
340	3.3	-3.3				
	slush below					
average		-4.7	average	2.6	0.0	
st. dev		1.036	st. dev	1.433	0.020	

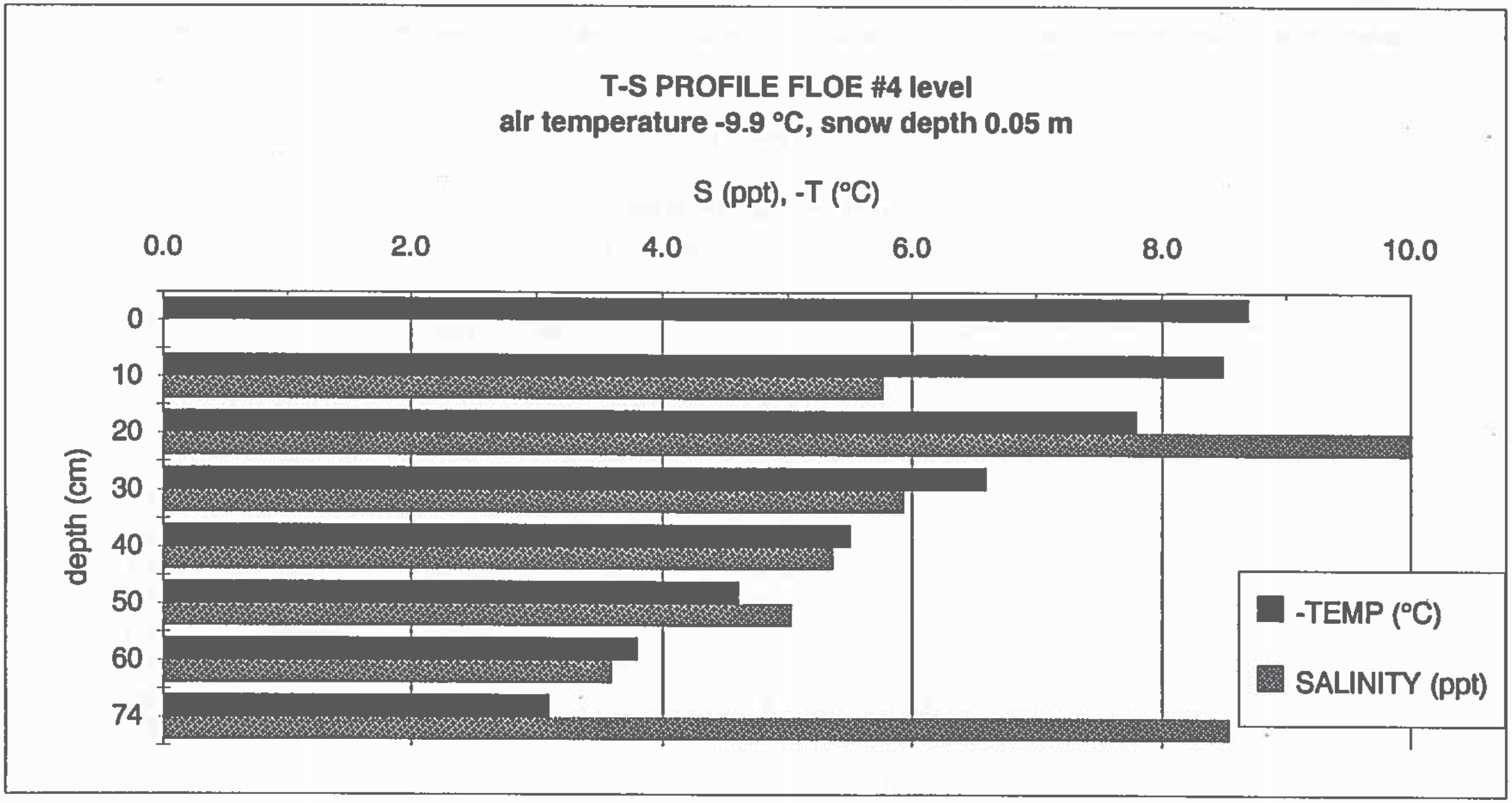

T-S PROFILE RUBBLE #4 sail
air temperature -9°C, snow depth 0.1m
C 4
S (ppt), -T (°C)
0.0
2.0
4.0
6.0
8.0
10.0
-TEMP (°C)
SALINITY (ppt)
depth (cm)
0
20
40
60
80
100
120
140
160
180
200

DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb	
0						
10	7.8	-7.8	1.24	0.72	0.005	
20	7.3	-7.3	1.37	0.80	0.006	
30	7.0	-7.0	1.92	1.13	0.008	
40	6.9	-6.9	0.97	0.56	0.004	
50	6.4	-6.4				
60	5.7	-5.7	1.47	0.86	0.008	
70	4.9	-4.9	2.78	1.65	0.017	
80	4.7	-4.7	2.01	1.19	0.013	sand
90	4.4	-4.4	1.89	1.11	0.013	
100	4.2	-4.2	2.23	1.32	0.016	
110	4.0	-4.0	2.52	1.50	0.018	
120	4.1	-4.1	1.71	1.00	0.012	
130	4.1	-4.1	1.76	1.03	0.012	
140	3.7	-3.7	1.87	1.10	0.015	
150	3.7	-3.7	3.32	1.99	0.026	
160	3.7	-3.7	5.54	3.37	0.045	
170	3.7	-3.7	7.40	4.57	0.061	
180	3.7	-3.7	4.63	2.80	0.037	
190	3.6	-3.6				
200	3.6	-3.6	4.49	2.71	0.037	
210	3.7	-3.7	5.52	3.36	0.045	
average		-4.8	average	1.7	0.0	
st. dev		1.417	st. dev	1.112	0.016	

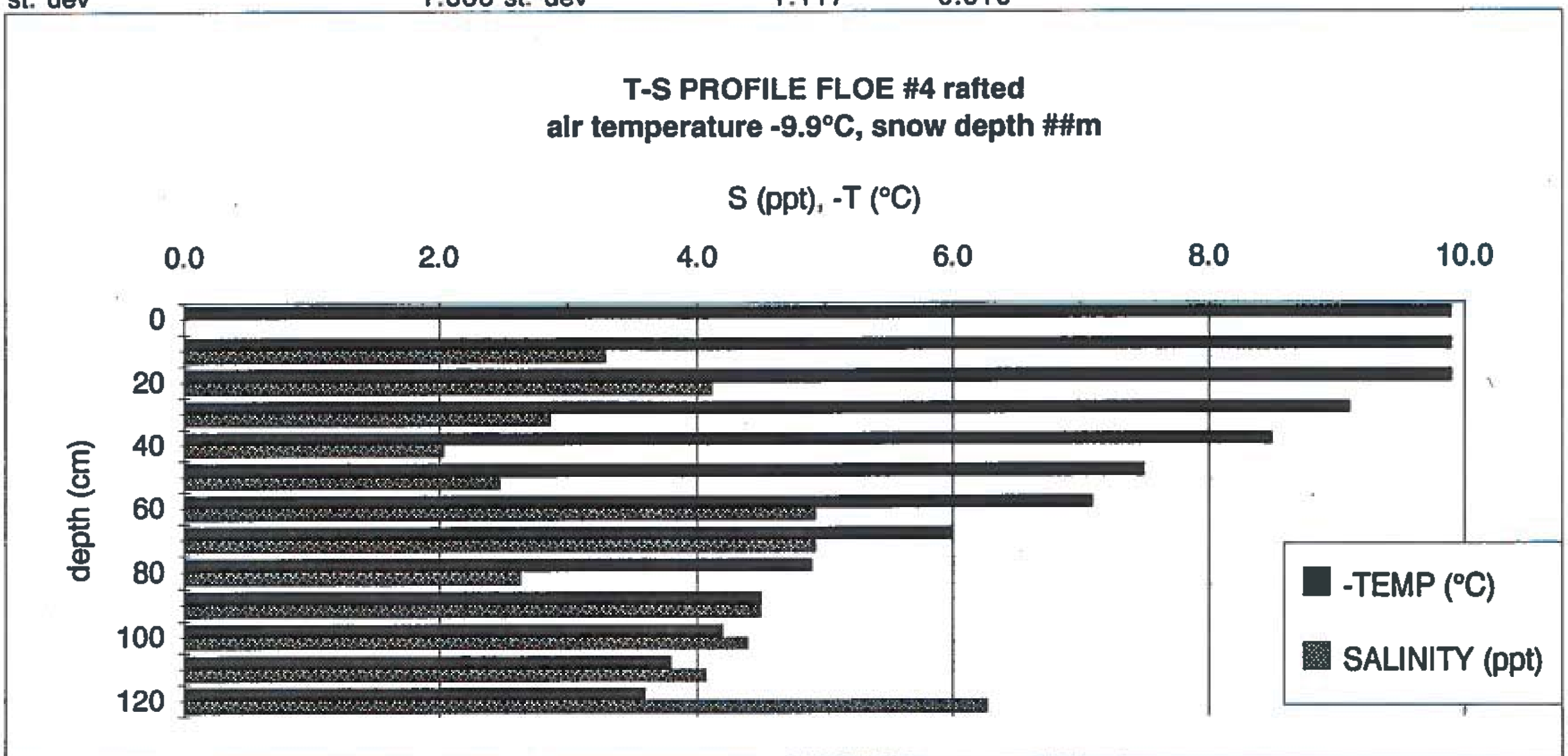
DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb
0	9.1	-9.1			
10	7.4	-7.4	4.33	2.61	0.019
20	6.7	-6.7	5.91	3.61	0.028
30	4.9	-4.9	5.41	3.29	0.034
40	4.2	-4.2	7.30	4.50	0.053
50	3.0	-3.0	11.55	7.32	0.119
average		-5.9	average	4.27	0.050
st. dev		2.255	st. dev	1.839	0.040



DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb
0	8.7	-8.7			
10	8.5	-8.5	9.23	5.77	0.037
20	7.8	-7.8	20.40	13.60	0.093
30	6.6	-6.6	9.48	5.93	0.047
40	5.5	-5.5	8.61	5.36	0.049
50	4.6	-4.6	8.10	5.02	0.054
60	3.8	-3.8	5.89	3.60	0.046
74	3.1	-3.1	13.33	8.54	0.135
average		-6.1		6.83	0.066
st. dev		2.157		3.330	0.035



DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb
0	9.9	-9.9			
10	9.9	-9.9	5.41	3.29	0.019
20	9.9	-9.9	6.71	4.12	0.023
30	9.1	-9.1	4.74	2.87	0.017
40	8.5	-8.5	3.41	2.04	0.013
50	7.5	-7.5	4.11	2.48	0.017
60	7.1	-7.1	7.95	4.93	0.036
70	6.0	-6.0	7.95	4.93	0.042
80	4.9	-4.9	4.38	2.64	0.027
90	4.5	-4.5	7.29	4.50	0.050
100	4.2	-4.2	7.13	4.39	0.052
110	3.8	-3.8	6.63	4.07	0.053
120	3.6	-3.6	9.99	6.27	0.085
average		-8.1	average	3.41	0.024
st. dev		1.833	st. dev	1.117	0.010



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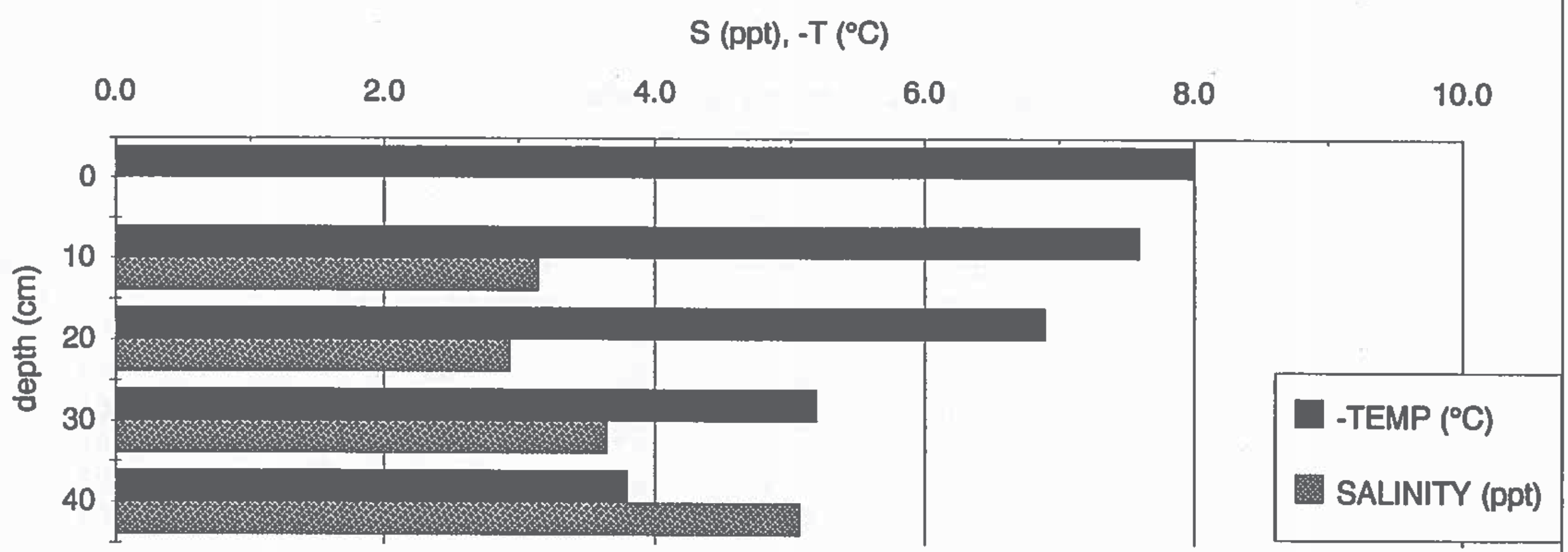
DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m·	SALINITY (p	BRINE VOLb
0	8.0	-8.0			
10	7.6	-7.6	5.18	3.15	0.022
20	6.9	-6.9	4.85	2.94	0.022
30	5.2	-5.2	5.97	3.65	0.035
40	3.8	-3.8	8.18	5.08	0.066
average		-6.3	average	3.70	0.036
st. dev		1.761	st. dev	0.963	0.021

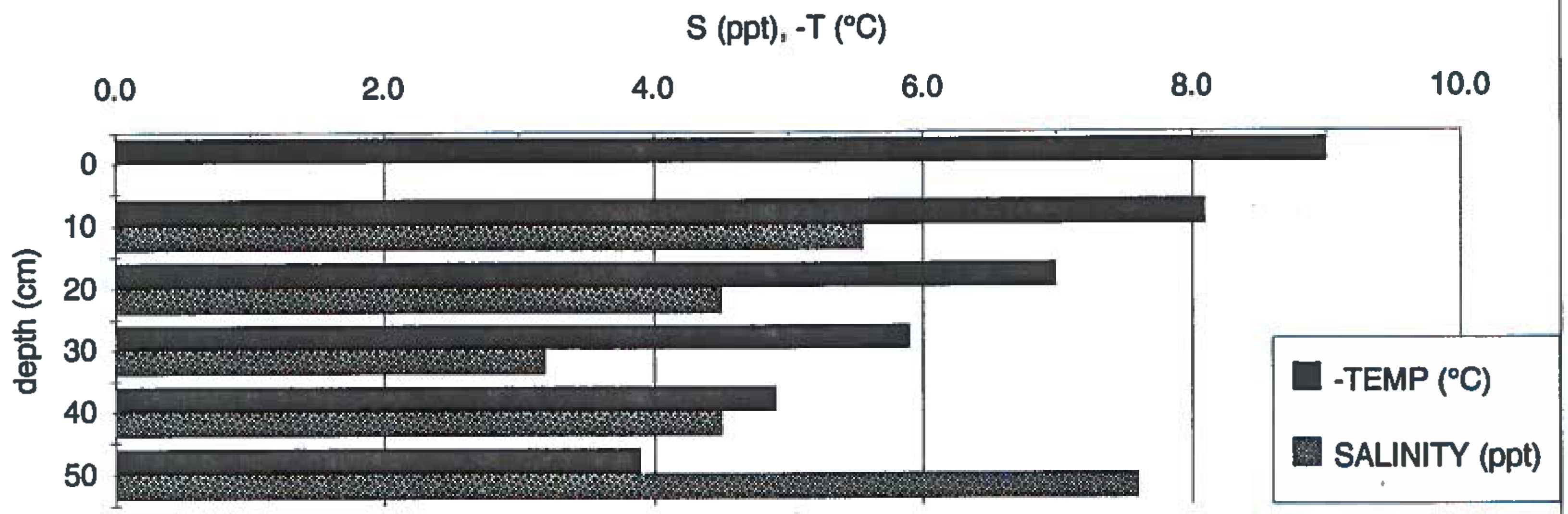
T-S PROFILE FLOE #5 C5
air temperature -9°C, snow depth ##m



DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb
0	9.0	-9.0			
10	8.1	-8.1	8.90	5.55	0.037
20	7.0	-7.0	7.30	4.50	0.034
30	5.9	-5.9	5.26	3.20	0.028
40	4.9	-4.9	7.30	4.50	0.046
50	3.9	-3.9	11.95	7.60	0.096
average		-6.5	average	5.07	0.048
st. dev		1.936	st. dev	1.641	0.028

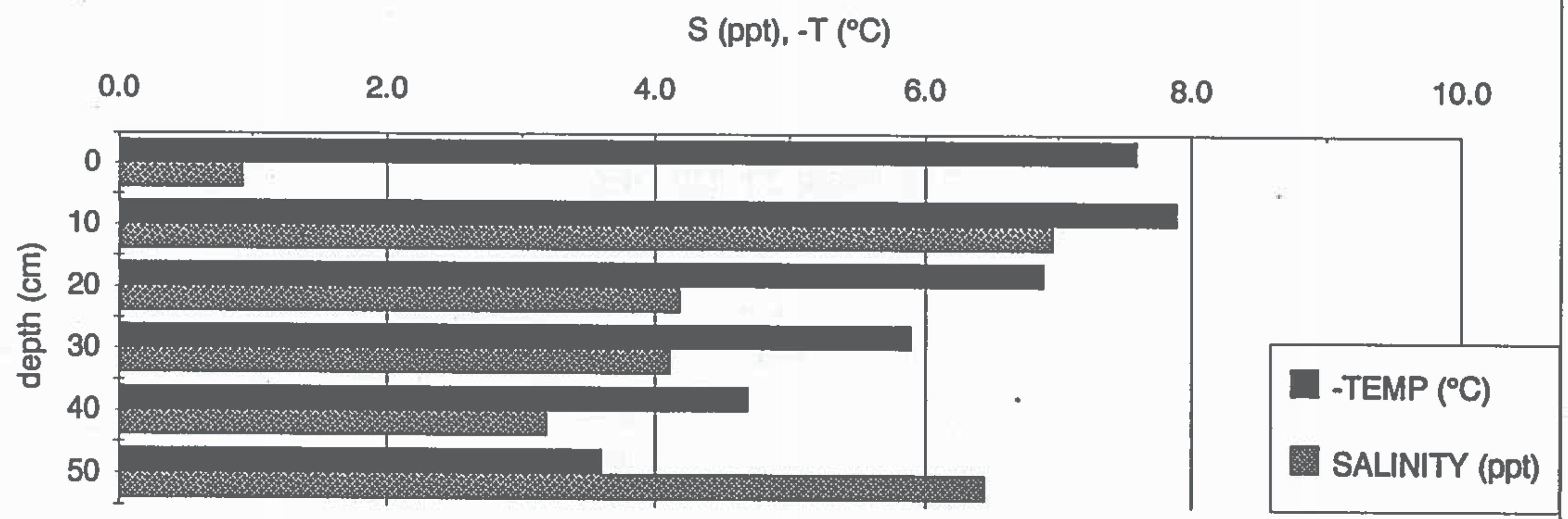
T-S PROFILE FLOE #6 C 9

air temperature -9.2°C, snow depth ##m

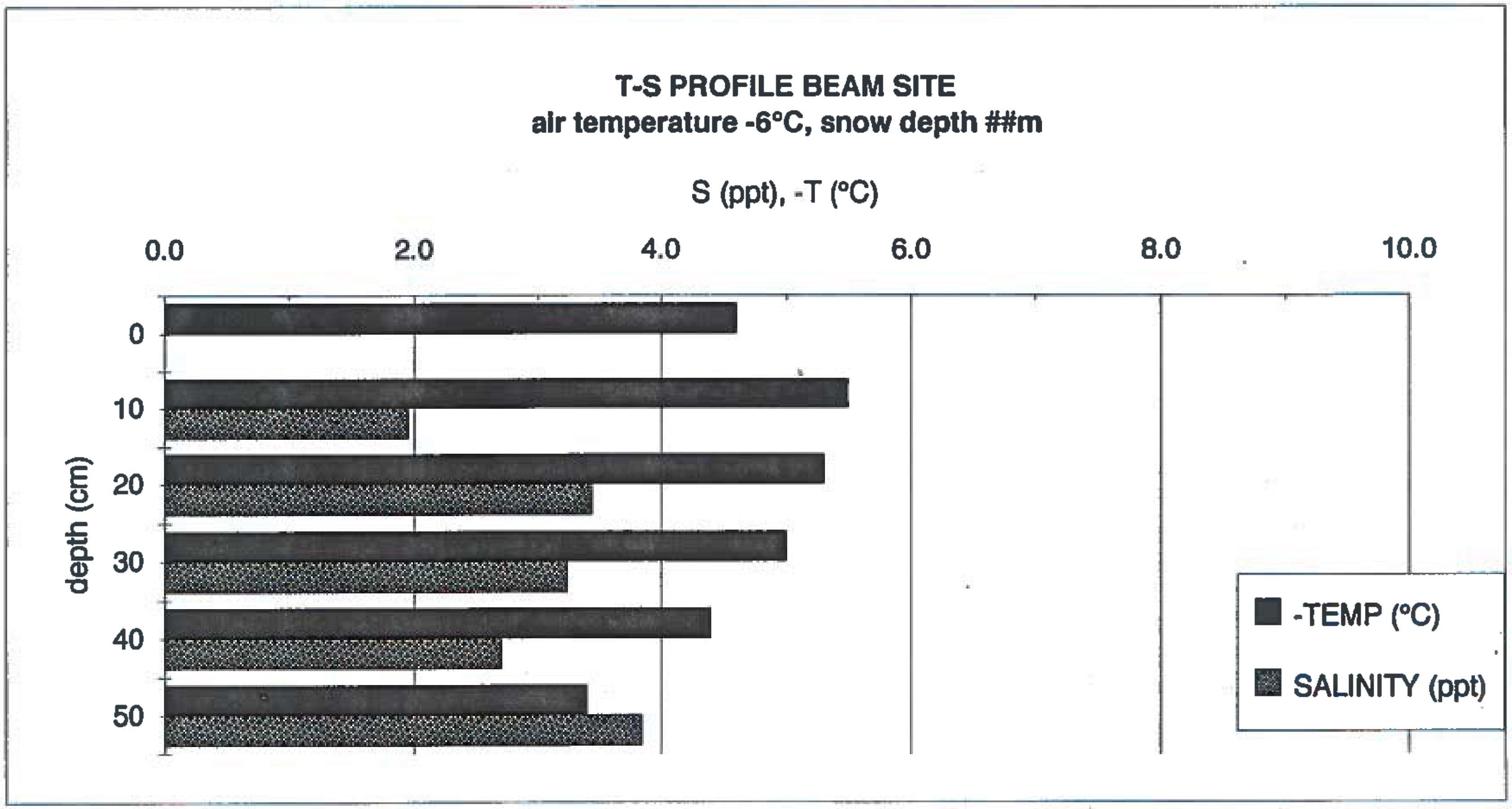


DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m·	SALINITY (p	BRINE VOLb
0	7.6	-7.6	1.59	0.93	0.006
10	7.9	-7.9	11.02	6.97	0.047
20	6.9	-6.9	6.82	4.19	0.032
30	5.9	-5.9	6.71	4.12	0.036
40	4.7	-4.7	5.25	3.19	0.034
50	3.6	-3.6	10.26	6.45	0.088
average		-6.1	average	4.31	0.040
st. dev		1.696	st. dev	2.207	0.027

T-S PROFILE FLOE #7
alr temperature -10.2°C, snow depth ##m



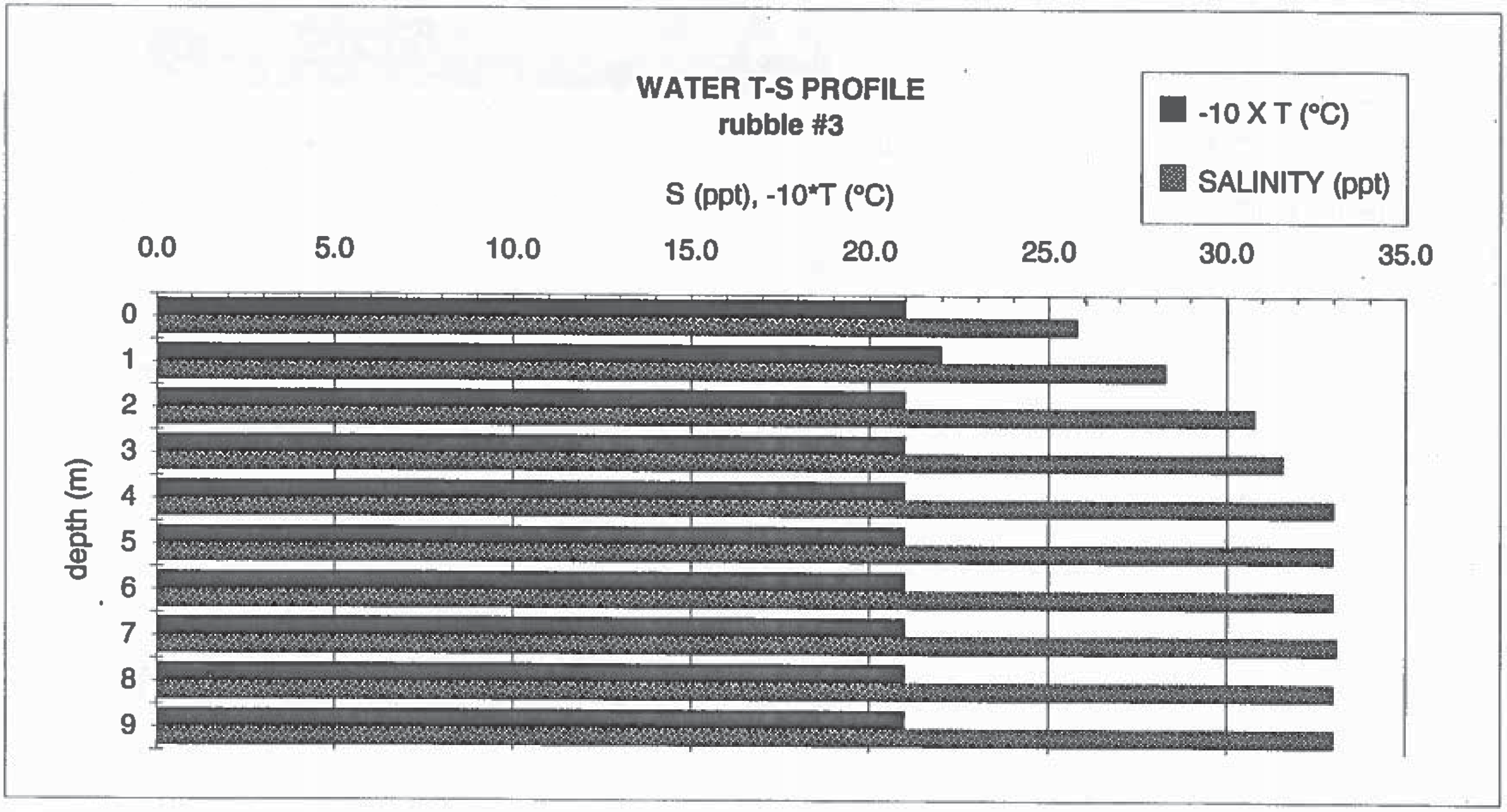
DEPTH (cm)	-TEMP (°C)	TEMP. (°C)	CONDUCT.(m-	SALINITY (p	BRINE VOLb
0	4.6	-4.6			
10	5.5	-5.5	3.27	1.95	0.018
20	5.3	-5.3	5.65	3.44	0.033
30	5.0	-5.0	5.33	3.24	0.032
40	4.4	-4.4	4.48	2.71	0.030
50	3.4	-3.4	6.29	3.85	0.055
average		-4.7	average	3.04	0.034
st. dev		0.759	st. dev	0.733	0.014



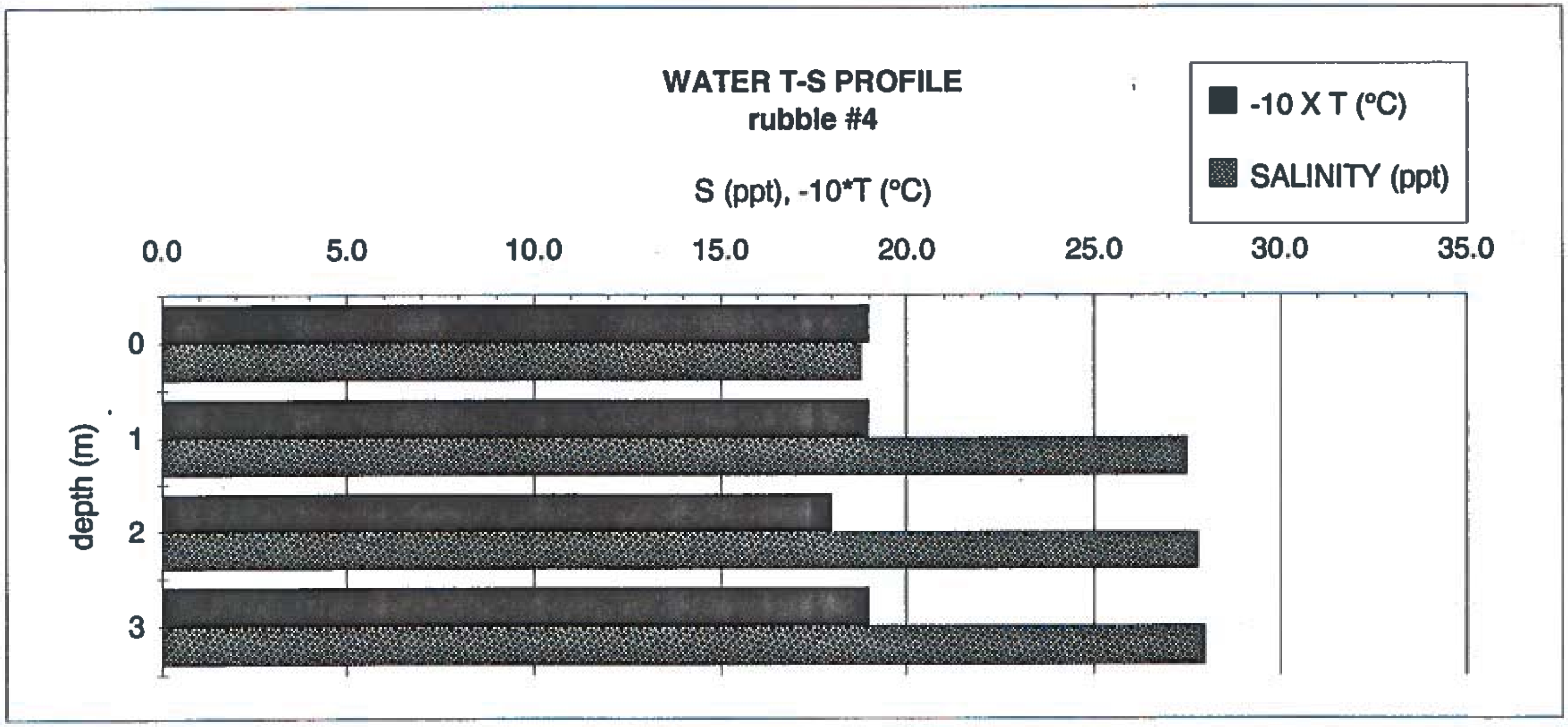
Appendix B

Water Temperature and Salinity Profiles

DEPTH (m)	-10 X T (°C)	TEMP (°C)	SALINITY (ppt)
0	21.0	-2.1	25.8
1	22.0	-2.2	28.3
2	21.0	-2.1	30.8
3	21.0	-2.1	31.6
4	21.0	-2.1	33.0
5	21.0	-2.1	33.0
6	21.0	-2.1	33.0
7	21.0	-2.1	33.1
8	21.0	-2.1	33.0
9	21.0	-2.1	33.0



DEPTH (m)	-10 X T (°C)	TEMP (°C)	SALINITY (ppt)
0	19.0	-1.9	18.8
1	19.0	-1.9	27.5
2	18.0	-1.8	27.8
3	19.0	-1.9	28.0



DEPTH (m)	-10 X T (°C)	TEMP (°C)	SALINITY (ppt)
0	14.0	-1.4	30.3
1	18.0	-1.8	30.3
2	18.0	-1.8	30.3
3	19.0	-1.9	30.3
4	18.0	-1.8	30.3
5	19.0	-1.9	30.3
6	19.0	-1.9	30.3
7	19.0	-1.9	30.3
8	19.0	-1.9	30.3
9	19.0	-1.9	30.3
10	19.0	-1.9	30.3