Structure of a Multi-Year Pressure Ridge

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ABSTRACT. Three transverse profiles across a large pressure ridge located in the Beaufort Sea are presented. The ridge sail extended 4 m. above sea level and the ridge keel 13 m. below. The cross-sections of the ridge keel can be described as roughly semi-circular. This suggests that form drag coefficients for flow transverse to the long axes of multi-year ridges may be as high as 0.8. Examination of several salinity, temperature and brine-volume profiles shows that much of the ice in the ridge has a very low salinity and is quite strong. All the inter-block voids that initially existed in the ridge at the time of its formation have been completely filled with ice. These observations, coupled with icebreaking experience indicate that multi-year ridges are, indeed, significant obstacles to even the largest icebreaking ship and should be avoided if possible. A very large first year ridge with a sail height of 12.8 m. is also described. This is the largest free-floating ridge yet measured.

RÉSUMÉ: *Structure d'une crête de pression pluri-annuelle.* Les auteurs présentent trois profils en travers d'une grande crête de pression située dans la mer de Beaufort. La partie supérieure de la crête s'élève à 4 m au-dessus du niveau de la mer, et la partie située sous la glace descend à 13 m. Les profils en travers peuvent se décrire comme grossièrement semi-circulaires, ce qui suggère que les coefficients de traînée d'écoulement transversal aux grands axes des crêtes pluri-annuelles peuvent être aussi élevés que 0.8. L'examen de plusieurs courbes de salinité, de température et de volume de saumure démontre que beaucoup de la glace de cette crête a une très faible salinité et est très solide. Tous les vides entre les blocs ont été complètement remplis par de la glace. Ces observations et l'expérience des brise-glace indiquent que les crêtes pluri-annuelles sont de fait des obstacles importants, même pour les plus gros brise-glace, et qu'on doit si possible les éviter. Les auteurs décrivent aussi une très grande crête annuelle atteignant une hauteur de 12.8 m au-dessus de la glace, ce qui en fait la plus grande crête flottante jamais mesurée.

РЕЗЮМЕ. *Строение многолетнего вала сжатия.* Представлено три поперечных профиля через крупный вал сжатия в морском льду моря Бофорта. Гребень вала поднимался на 4 м выше ур. моря, его киль спускался до 13 м ниже этого уровня. Поперечное сечение киля имело, грубо говоря, полукруглую форму. Анализ нескольких профилей солености и температуры льда, а также объёма заключенного в нем рассола показал, что вал слагается преимущественно льдом очень низкой солености и высокой прочности. Все межглыбовые пустоты, возникшие в валу при его формировании, оказались совершенно заполненными льдом. Эти наблюдения, вместе с опытом ледокольных работ, показывают, что многолетние валы сжатия могут представлять серьезное препятствие даже для самых крупных судов ледокольного типа, и что при наличии возможности их следует обходить. Приводится также описание очень крупного вала, имеющего максимальную из когда либо измеренных высоту гребня — 12,8 м; возраст этого вала оказался менее одного года.

INTRODUCTION

A major problem in the development of the Arctic is the lack of a cheap, reliable, large volume transportation system that is capable of year-around operation. In many arctic areas such as the Canadian Archipelago, some variety of sea

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route seems to be the only possible solution. The principal obstacle to the development of such a route is, of course, the highly variable and, at times, extremely formidable sea ice cover which has restricted the operation of surface ships to a few months each summer. Even then there are areas where icebreaker assistance is still required. However, the recent test cruises of the S. S. *Manhattan* clearly showed that "super" cargo vessels can be designed and built within the framework of current marine technology that are capable of the winter navigation of arctic waters. To optimize any such design one must fully understand the nature of the more significant obstacles that can be expected in the ice cover along the route. Similar information is also needed for the safe design of offshore structures and harbour facilities. In this case because most such structures are fixed, they cannot attempt to manoeuvre around the more obvious obstacles but must take the ice as it comes.

With the exception of ice islands which are rare and can usually be easily recognized by radar, the most formidable obstacles in the ice pack are the pressure ridges and hummocks (i.e., those linear to irregular accumulations of ice caused by the compressive and shear interactions between ice floes); such features may become very large indeed. As described later in this paper, the highest free-floating ridge sail that we are aware of was 12.8 m. above sea level whereas the deepest keel currently recorded in the submarine sonar data extended some 47 m. below sea level (Lyon, personal communication). Impressive as these figures are, ridges of this size fortunately appear to be quite rare. Indeed ridge sails in excess of 5 m. are rare.

Operational experience has also shown that the bulk properties of geometrically similar ridges may vary greatly. For instance the S.S. *Manhattan* was able to progress with relative ease through most first-year ridges but encountered considerable difficulty with apparently similar multi-year ridges. Actually it might be expected that the properties of first-year pressure ridges would be highly variable. This would primarily depend upon the degree of bonding developed between the ice blocks that comprise the ridge. The best bonding should develop when the ice being incorporated into the ridge is very cold. Many of the first year ridges that have been studied in detail were poorly bonded (Weeks, *et al.* 1971). In a multi-year ridge, on the other hand, the meltwater produced during the summer can drain downward into the core of the ridge. Here the water refreezes, cementing the ice blocks together into a solid resistant mass of low salinity ice. For the voids between the ice blocks to become completely filled at least two melt seasons are usually required (Allan Gill, personal communication). That the core of an old multi-year ridge was usually a particularly resistant obstacle to ships was recognized quite early by Russian investigators (Burke 1940; Zubov 1945).

Considering that multi-year ridges are commonly considered the most formidable obstacles in the pack, it is rather amazing that there are no detailed observations on either their overall structure or the state of the ice comprising them. The only published investigation of a multi-year ridge of which we are aware is by Spichkin (Gakkel' 1959) who determined the cross-sectional profile of such a ridge where it was intersected by a lead. This revealed that the below-water portion of the ridge was massive compared to the above-water portion. No other data were apparently obtained.

The current report presents the results of a study designed to add additional information on the structure and properties of multi-year ridges. The observations were made in the Beaufort Sea roughly 550 km. north of Tuktoyaktuk, Northwest Territories, at Camp 200 of the Canadian Polar Continental Shelf Project, the base of the 1971 Arctic Ice Dynamics Joint Experiment (AIDJEX) pilot study. The observations include the determination of the surface relief of the ridge and the snow thickness using standard surveying techniques, the profiling of the ridge keel using a sonar technique developed by Kovacs (1971), and the sampling of the ice in the inner portions of the ridge by drilling and coring.

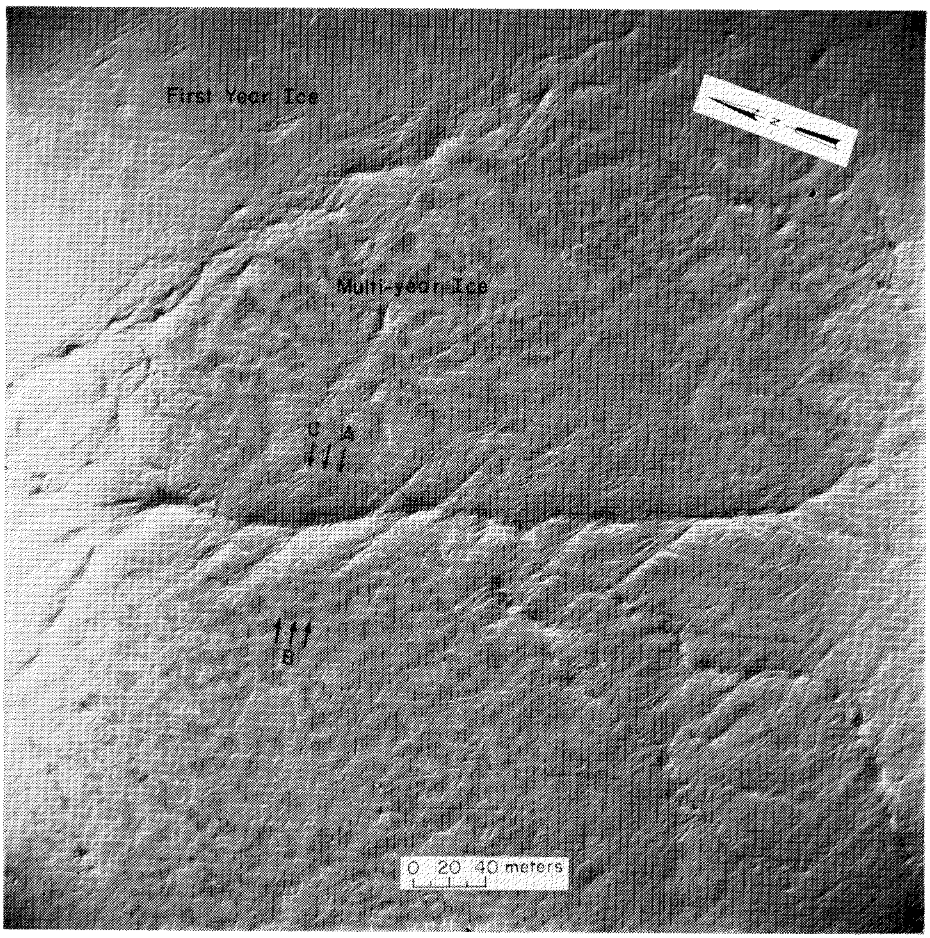

FIG. 1. Aerial view of the multi-year ridge studied (centre of photograph) and the surrounding terrain. The photograph was taken after the study was completed and a storm had swept the ice surface clean of a major portion of its snow cover. First-year ice can be seen in the upper left-hand corner. The position of each profile line is marked.

PROFILES

An aerial view of the ridge is shown in Fig. 1. The location of each of the three profiles is marked. The detailed cross-sections are shown in Fig. 2; this figure also shows the longitudinal ridge crest elevation profile on which the location of each transverse cross-section is indicated. In the area profiled, the ridge crest elevation ranged between 1.5 and 4.0 m. Also the 3 ice thicknesses at the intersections of the longitudinal and the transverse profiles are plotted. A fence diagram showing the cross-sections in perspective is given in Fig. 3; although the actual distance between the cross-sections is 8 m., in this drawing the cross-sections have been laterally displaced from one another to provide an unobstructed view of their geometry. The highest elevation on cross-section A was 3.9 m., whereas its keel extended to a depth of some 12 m. Similarly, on cross-section B the ridge sail was 3.9 m. high and the keel some 13 m. deep. In cross-section C only half of the subsurface contour of the keel was determined. By using

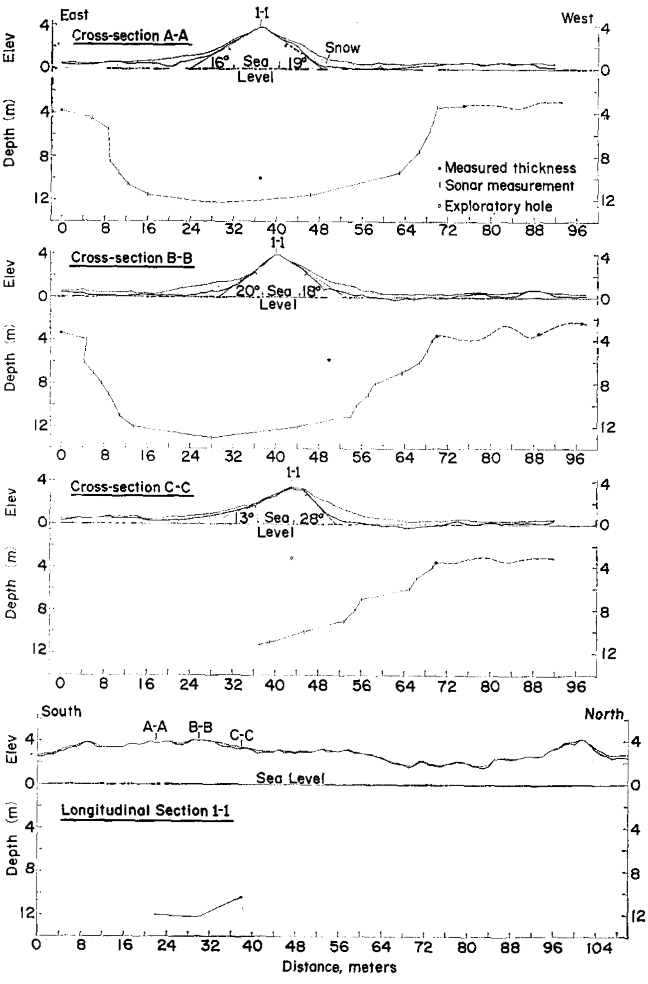

FIG. 2. Transverse and longitudinal cross-sections of the multi-year ridge.

the slope of the contoured portion of the keel and the keel contours from cross-sections A and B as guides, we estimate the keel depth of profile C to be 11.5 m. The height of the sail on cross-section C is 3.4 m. Using the values of sail heights and keel depths reported above, the average freeboard to depth ratio for *this* multi-year ridge was calculated to be 1 to 3.3. This ratio is lower than the 1 to 4.5 ratio recently determined by Kovacs (1971) for first-year pressure ridges but is in excellent agreement with the ratio proposed by Wittmann and Schule (1966) for the Makarov pressure ridge model. The cross-sections also clearly show that the subsurface portion of the ridge is significantly wider than the above-water portion. Note that in cross-section B-B there is a major discrepancy between the ice thickness obtained by drilling and by sonar. We have no explanation for this except to observe that the drilled thickness is a point measurement whereas sonar "samples" an appreciable area. In a general way the transverse profiles of the ridge keel can be described as roughly semi-circular to semi-eliptical. Drag coefficients for such form roughness elements are discussed in Hoerner (1965) and range from 0.8 for a semi-circular shape to 0.5 for a semi-eliptical shape. Because of the "streamlining" effects of the summer melt season and the snow drifts, the drag coefficient for the ridge sail would be significantly lower.

In most of the profiles, the upper ice surface at the edges of the ridge sails shows a downward deflection. This phenomenon has been observed in most first-

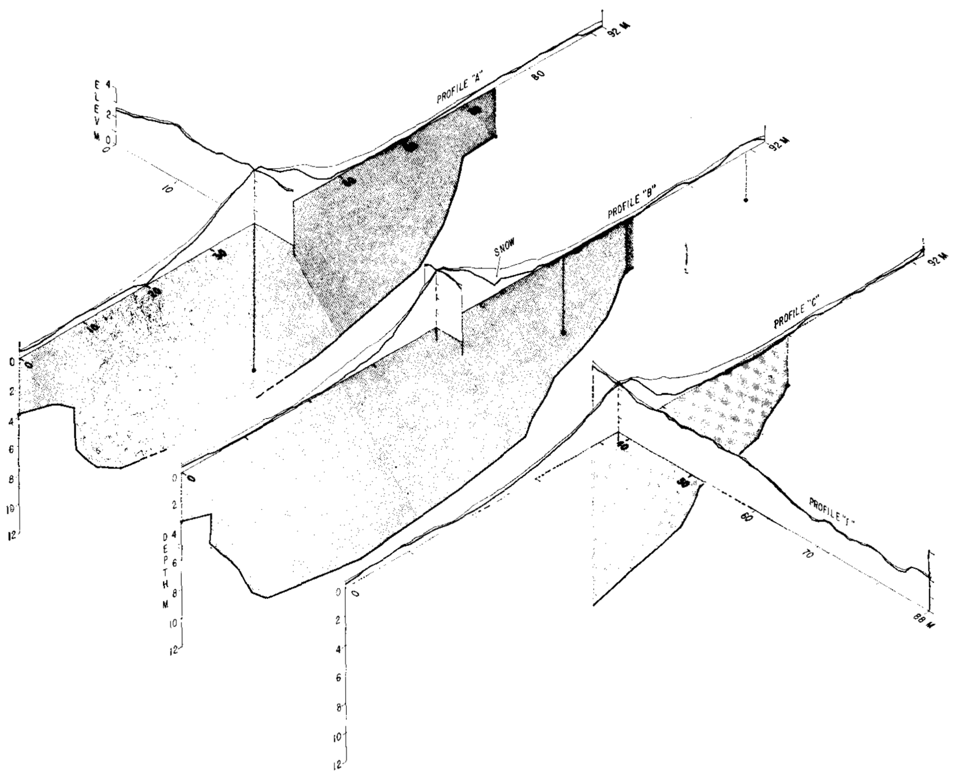

FIG. 3. Fence diagram showing the relative positions of cross-sections A, B and C.

year ridge studies (Weeks and Kovacs 1970; Kovacs 1971). In the case of first-year ridges this deflection is clearly caused by load transfer from the sail to the surrounding plate ice as a result of an isostatic imbalance produced during the initial ice pile-up. In the current ridge the deflection is believed to be partly related to snow loading and partly to keel ablation. The latter would cause the ridge to subside in the process of seeking isostatic equilibrium. It is expected that during the next melt season these depressions will fill with melt water from the ablating ridge sail. When these ponds refreeze the following fall, these deflected areas will probably no longer be discernible.

The slope of the ridge sail was determined by measuring the angle of the profile lines shown in the cross-sections (Fig. 2). The slope varied between 13 and 28 degrees and averaged 19 degrees. This is 5 degrees less than the average surface slope determined by Kovacs (1971) for first-year pressure ridges. This difference, which may well be general, is undoubtedly due to the modification of the shape of the ridge sail by ablation. No attempt was made to determine the slope of the keel which has a bowl-like shape.

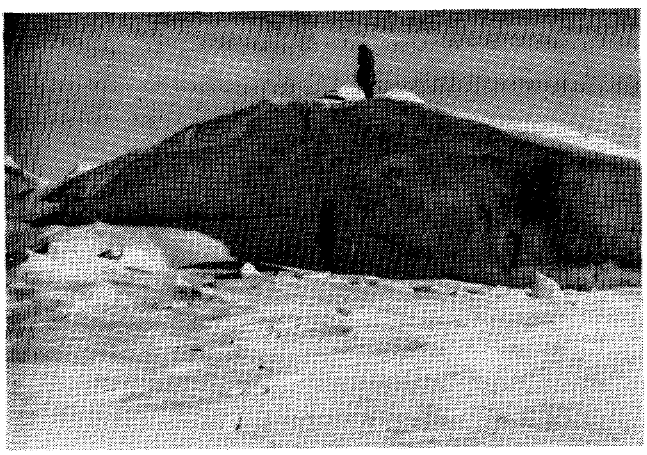

FIG. 4. View of the sail of a multi-year pressure ridge located in the Beaufort Sea. Note the massive nature of the ice.

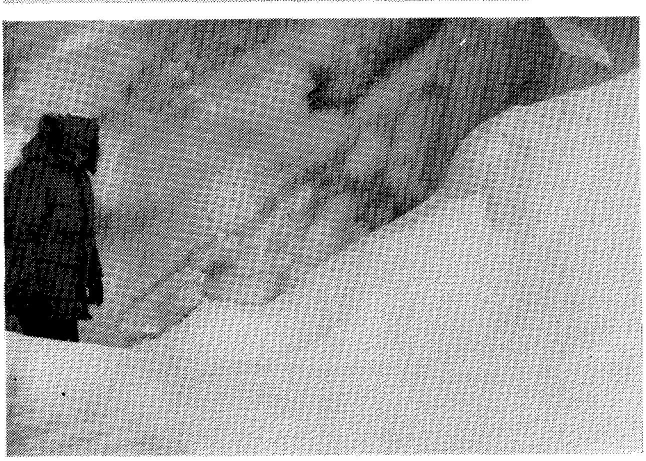

FIG. 5. Internal structure of a multi-year pressure ridge from the Beaufort Sea. Note the lack of voids between the angular blocks comprising the ridge.

The fact that pressure ridges act as snow fences is again clearly illustrated in the cross-sections. The greatest snow accumulation was in excess of 1-metre thick and occurred along the toe of the sail.

INTERNAL PROPERTIES

Exploratory coring at metre 37 on cross-section A, at metres 50 and 60 on cross-section B, and at metre 43 on cross-section C (see Fig. 2) revealed no cavities of any type and showed the ice to be sound, as indicated by augering resistance. There were no wide cracks or leads that transected the ridge so an actual profile could not be examined. However Kovacs (unpublished data) has examined cross-sections of several similar multi-year ridges in the Beaufort Sea. Fig. 4 shows a general view of such a ridge which has split. Note that the ice is extremely massive. Fig. 5 shows a detail of the internal structure of another multi-year ridge. The distribution and size of the subangular ice blocks incorporated into this ridge as well as the refrozen water between the blocks is clearly shown. The lack of interblock voids is striking. Note also the dark plankton band within the largest ice block. Based on this information, our coring observations and, as mentioned earlier, the considerable difficulties experienced when ships attempt to break through multi-year ridges, we suggest that the ice blocks composing most multi-year ridges are completely bonded together by the freezing of interstitial water.

Figs. 6, 7 and 8 show the salinity, temperature and brine-volume profiles obtained by coring into the ridge (respectively at metre 37 - Section A, metre 50 - Section B, and metre 43 - Section C). Fig. 8 also gives the density profile of the ice to a depth of some 3.5 m. All the ridge profiles show the salinity to be virtually zero at the surface.

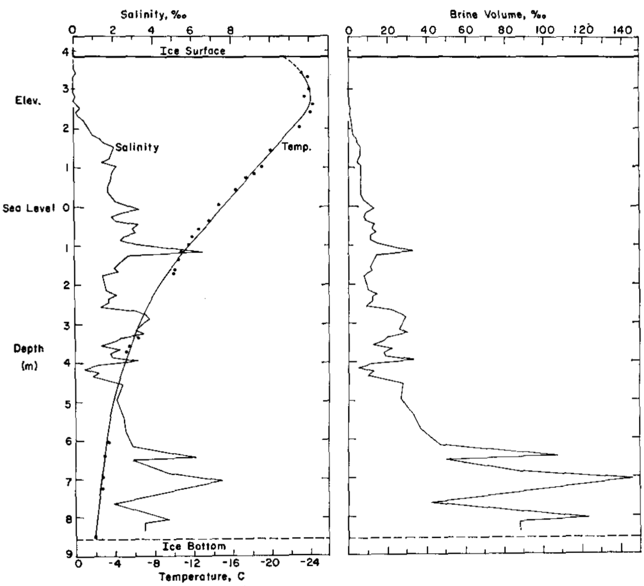

FIG. 6. Salinity, temperature and brine-volume profiles of the ice at Metre 37 on cross-section A.

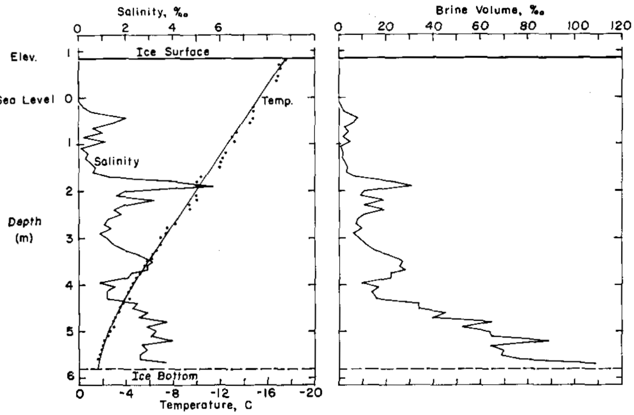

FIG. 7. Salinity, temperature and brine-volume profiles of the ice at Metre 50 on cross-section B.

As shown in Figs. 6 and 7 the ice remains fresh for a depth of one metre. The near surface ice was also found to contain a large number of air bubbles suggestive of extensive brine drainage. This increase in air content is reflected in the sharp decrease in ice density near the top of the ridge sail as shown in Fig. 8. Fig. 9 shows similar profile data obtained from the multi-year ice adjoining the ridge. In all of the profiles there is a gradual increase in the salinity with depth. At the bottom of the ridge the salinity averages roughly 4.5‰ whereas at the bottom of the presumably undeformed multi-year ice, the value is very slightly higher. All the salinity profiles show the wide scatter that is particularly characteristic of multi-year ice (Schwarzacher 1959; Untersteiner 1968) and to a lesser extent of first-year ice (Weeks and Lee 1962). A point of interest is that much of the ice represented by the profile shown in Fig. 9 formed in a melt pond and is, in fact, first year ice. This is suggested by both the ice topography surrounding the coring site and the salinity profile itself. The pond clearly exhibited a pronounced salinity stratification prior to freeze-up.

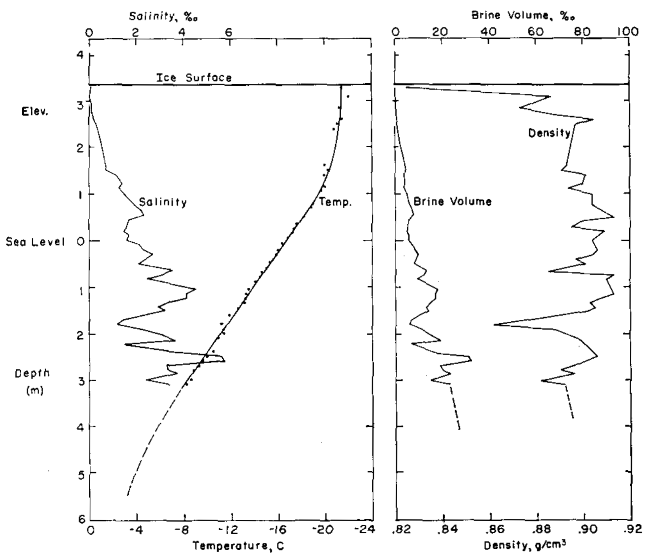

FIG. 8. Salinity, temperature, brine-volume and density profiles of the ice at Metre 43 on cross-section C.

The temperature profiles shown in Figs. 6, 8 and 9 all show by the curvature in their upper portions that a gradual warming of the ice cover is under way. This trend is, however, not yet apparent in Fig. 7 where the thick snow cover formed in the lee of the ridge has caused a delay in the arrival of the warming trend at the ice surface.

The brine volume profiles shown in Figs. 6, 7 and 8 are as expected: effectively nil at the surface with a gradual increase towards the bottom in response to the increase in the temperature and salinity values. Because of the time of year (March), the ice temperatures would be expected to be near their annual minimum corresponding to a maximum in ice strength (Weeks and Assur 1968).

If we assume that the overall ridge is in isostatic equilibrium we can calculate a mean density for the ridge ice by determining the ratio of the ice above sea level to the ice below sea level. The snow cover was converted to an equivalent ice volume by assuming an average snow density of 0.45 g./cm.^{3}. The observed ratio was 1 to 7.7 corresponding to a mean ice density of 0.91 g./cm.^{3}, in good agreement with an average measured density of 0.90 g./cm.^{3}. This suggests that multi-year ridges may be close to being in overall isostatic balance. Although a sample of one can hardly be considered as proof of this conjecture, it is reasonable to assume that this well may be the case.

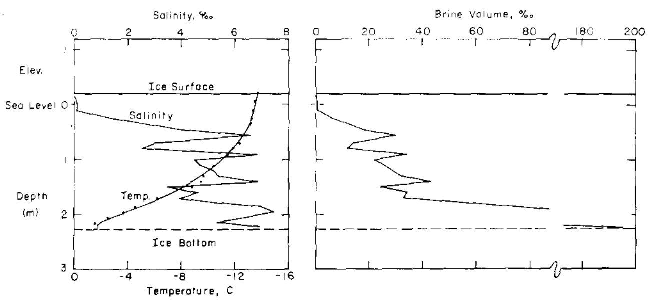

FIG. 9. Salinity, temperature and brine-volume profiles of the ice at Metre 97 on cross-section B.

LARGEST RIDGE SAIL

An extremely large pressure ridge was observed near one of the oceanographic stations (*c*. 10 km. from the AIDJEX base camp). To the best of our knowledge this ridge has the highest free-floating sail yet sighted (and documented) in the Arctic Ocean (12.8 m. above sea level). The ice in the ridge was first year and the large ice block located on the top of the ridge was 2.2 m. thick, 3 m. wide and 7 m. long. The ridge had clearly been active in the recent past and a lead existed along one side of it at the time of our visit. The high portion of the ridge was very limited in lateral extent ($\approx$ 100 m.). If we estimate the keel depth of this ridge by using the (keel depth/sail height) ratio of 4.5 observed by Kovacs (1971) on first year ridges, we obtain a value of 57 m.; some 10 m. more than the deepest currently-observed keel.

CONCLUSIONS

The multi-year ridge studied in this report has proven to be both quite large and structurally massive. All the initial voids between the blocks comprising the ridge have been subsequently filled with solid ice. In addition much of the ice in the ridge has a very low salinity. It is therefore reasonable to assume that ridges of this type represent a significant impediment to shipping and should be avoided if at all possible. They also represent a major problem in the design of potential offshore structures such as shipping terminals and drilling platforms.

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