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A STUDY OF SEVERAL PRESSURE RIDGES AND ICE ISLANDS IN THE CANADIAN BEAUFORT SEA*

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ABSTRACT. The environmental conditions in the southern Beaufort Sea are described with special emphasis on pressure ridges and ice islands. Techniques for determining the geometric configurations and the physical and mechanical properties of sea-ice structures and ice islands are described. Profiles of pressure ridges were determined by surface surveys, drill-hole probes and side-looking sonar scanning. Multi-year pressure ridges with thicknesses up to 20 m and widths up to 120 m were examined in detail. The first-year ridge of 22 m thickness and 100 m width was studied. Results are given for several multi-year and the first-year ridges. Information obtained from dives under the ice is also given. Corresponding data are given for grounded ice islands with particular attention being given to contact between the ice and sea bed. A 20 m thick ice-island fragment grounded in 15 m of water was one of several investigated. Measurements of temperature, salinity, tensile strength, and compressive strength are given for ice taken from old pressure ridges and factors influencing the interpretation of test data were discussed. The data obtained in this study will be used in engineering design studies for offshore structures for drilling and production of hydrocarbons from the Beaufort Sea area. Exploratory drilling in shallow water has already been carried out and offshore drilling from drillships is scheduled to commence in the study area during the open water season of 1976.

RÉSUMÉ. *Une étude de plusieurs rides de pression et îles de glace dans la Mer de Beaufort au Canada.* On décrit les conditions régnant dans le Sud de la Mer de Beaufort avec une attention spéciale sur les rides de pression et les îles de glace. On décrit les techniques employées pour déterminer la configuration géomètrique et les propriétés physiques et mécaniques des structures de glace de mer et des îles de glace. Les profils des rides de glace ont été determinés par des expéditions de surface, des forages et des sondages du sonar. Des rides de pression datant de plusieurs années avec des épaisseurs atteignant 20 m et des largeurs de 120 m ont été examinées en détail. Une ride de première année de 22 m d'épaisseur et de 100 m de large a été également étudiée. Les résultats sont donnés pour plusieurs rides pluriannuelles et une ride de première année. On a également donné les informations recueillies à partir de plongées sous la glace. Les données correspondantes sont rapportées pour des îles de glace fondées sur le sol avec une attention particulière pour le contact entre la glace et le lit de la mer. Un fragment d'île de glace de 20 m d'épaisseur fondée au sol à travers 15 m d'eau fut l'une parmi plusieurs des cas examinés. Des mesures de température, de salinité de résistance à la traction et à la compression ont été faites pour de la glace prélevée dans de vieilles rides de pression et les facteurs influençant l'interprétation des mesures sont discutés. Les données recueillies dans cette étude seront utilisées dans les études de conception de génie civil pour les structures de forage en mer et de production d'hydrocarbures à partir de la zone de la Mer de Beaufort. Des forages exploratoires dans une eau peu profonde ont déjà été réalisés et un forage au large à partir de navire est programmé pour commencer l'étude de cette zone durant la saison d'eaux libres en 1976.

ZUSAMMENFASSUNG. *Eine Studie an einigen Pressrücken und Eisinseln in der Kanadischen Beaufort-See.* Die Umweltbedingungen in der südlichen Beaufort-See werden besonders im Hinblick auf Pressrücken und Eisinseln beschrieben. Verfahren zur Bestimmung der geometrischen Konfigurationen und der physikalischen und mechanischen Eigenschaften von Meereis-Strukturen und Eisinseln werden aufgezeigt. Profile von Pressrücken ergaben sich aus Vermessungen an der Oberfläche, aus Bohrlochproben und aus Abtastungen mit Seitwärts-Sonar. Die Untersuchungen galten im Detail mehrjährigen Pressrücken mit Dicken bis zu 20 m und Breiten bis 120 m. Ein einjähriger Rücken von 22 m Dicke und 100 m Breite wurde studiert. Die Ergebnisse beschreiben mehrere ältere und die einjährigen Rücken. Desgleichen finden sich Ergebnisse von Tauchunternehmungen unter dem Eis. Entsprechende Daten beziehen sich auf gestrandete Eisinseln mit besonderer Berücksichtigung der Kontaktstellen zwischen Eis und Meeresboden. Das Fragment einer Eisinsel von 20 m Dicke, gestrandet in 15 m tiefem Wasser, gehörte zu den untersuchten Objekten. Messungen der Temperatur, des Salzgehaltes, der Zug- und Druckfestigkeit von Eis aus alten Pressrücken werden aufgeführt und die für die Interpretation der Versuchsdaten bedeutsamen Faktoren diskutiert. Die in dieser Studie gewonnenen Daten werden bei ingenieurtechnischen Entwürfen für Bohr- und Pumpinseln zur Erdölgewinnung im Gebiet der Beaufort-See herangezogen. Versuchsbohrungen in flachem Wasser wurden bereits niedergebracht; küstenferne Bohrungen von Bohrschiffen aus sollen im Untersuchungsgebiet während der Sommersaison 1976 beginnen.

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Introduction

The search for new sources of hydrocarbon energy has carried the petroleum industry into increasingly hostile offshore environments. During the period 1963–69, permits to explore for oil and gas were issued for most of the Canadian continental shelf of the Beaufort Sea which extends some 120 to 160 km from shore, into water depths of approximately 600 ft (180 m) as shown in Figure 1. In 1970, joint industry research commenced through a non-profit-making association of oil companies known as the Arctic Petroleum Operators' Association (APOA). To date, over 100 research projects amounting to some 15 million dollars have been completed, most of them connected with an understanding of the Beaufort Sea environment and developing the technology to drill safely and economically and to produce hydrocarbons from the area.

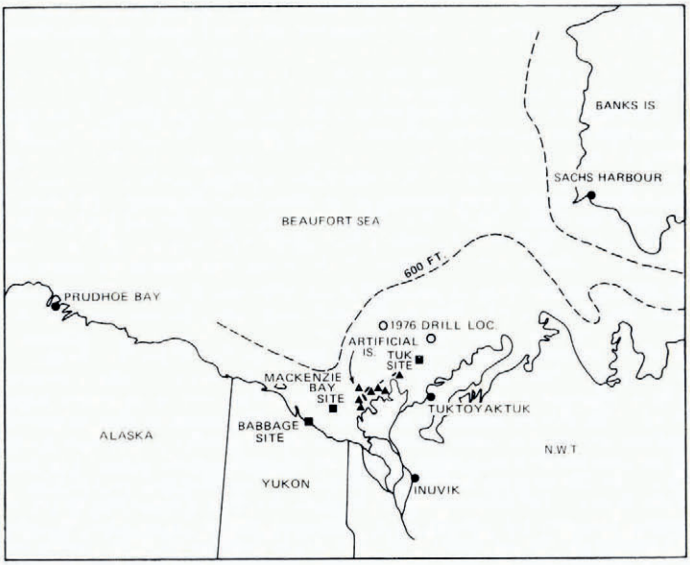

Fig. 1. Location map.

In early 1971, a group of APOA member companies saw a need to understand the geometry of pressure ridges more fully, particularly the geometry of multi-year ridges since they had not been previously studied in detail. Multi-year pressure ridges and ice-island fragments were considered to be the most formidable features which drilling and producing platforms would be required to withstand.

A very severe storm in September 1970 had blown in and grounded a great deal of multi-year ice and a few ice-island fragments. In April 1970, a study of four multi-year pressure ridges, one first-year pressure ridge, and some grounded ice-island fragments was undertaken as APOA Project 17 at a cost of 102 000 dollars. The operator of the project was Gulf Oil Canada Limited, the contractor was Creare Inc. of Hanover, New Hampshire and the primary investigators were Mr Austin Kovacs and Dr Malcolm Mellor who were on leave of absence from the U.S. Army Cold Regions Research and Engineering Laboratory. They had just completed the first detailed investigation of multi-year pressure ridges on the AIDJEX project the month before (Kovacs and others, 1973). Following the APOA project, the same group continued with a detailed investigation of a nearby grounded ice-island fragment for the Department of Public Works of the Government of Canada (Kovacs and Mellor, 1971). The study sites are shown on Figure 1.

To date, research in the Beaufort Sea has led to the construction and drilling of eleven artificial islands in water depths up to 23 ft (6.9 m) as shown in Figure 1. Oil or gas were discovered on three of the islands. During the summer of 1976, artificial islands may be built in water depths of 40 ft (12 m). The much more expensive Canadian Marine Drilling Ltd three drillship system, which cost some 200 million dollars, will, during the 1976 open-water season, drill wells which will cost over 40 million dollars each. The locations of the drillship operations are shown in Figure 1. Should these ventures reveal the presence of hydrocarbons in commercial quantities, the information derived from the study of pressure ridges will be most useful in designing the necessary platforms from which to drill and produce the oil or gas.

The Beaufort Sea environment

The southern Beaufort Sea off Canada is usually ice covered for nine months of the year and it is during the three or four months of open water or thin ice that exploratory drilling from a floating vessel will be undertaken in 1976. With the onset of winter in early October, freeze-up typically progresses seaward with relatively smooth ice extending for some 25 or 30 km to an average water depth of 30 ft (9 m). Here, a rough pressure-ridged band of ice grows outward, generally to the 60 ft (18 m) water depth where in November, and at times as late as December, it stabilizes and becomes part of the fast-ice zone. In winter, the ice cover near shore is, in a sense, an extension of land, remaining relatively undeformed and reaching a thickness on the order of 7 ft (2 m). A recurring open-water lead exists at the edge of this land-fast ice. Beyond the shore-fast ice is the seasonal pack-ice zone which extends to, and on occasion some distance beyond, the edge of the continental shelf. Here the ice canopy is in perpetual motion, compacting in one area, rarefying in another, with the result that it consists of floes with innumerable shapes, sizes, and surface irregularities. Multi-year ice, up to 12 ft (3.5 m) in thickness, and glacial ice islands may also be incorporated in this zone. Beyond the seasonal pack-ice zone is the polar pack-ice zone which is comprised primarily of old multi-year ice. The overall movement of the ice in the seasonal and polar pack-ice zones is in a clockwise rotation in the Beaufort Sea. Yearly ice movements on the rim of this gyre average under 3 km per day but in spring can reach 24 km per day.

Break-up commences in early July, influenced by the Mackenzie River inflow, the Amundsen Gulf open-water polynya, southerly winds, and increased temperatures. In severe years, such as 1974, the area remains largely ice covered as northerly winds replenish the ice in coastal areas.

Extreme temperatures range from -45 to 25°C, with an annual mean of -11°C. Winds average 19 km h^{-1} but, on rare occasions, can reach 150 km h^{-1}; when large fetches exist, these extreme winds can generate significant waves of up to 20 ft (6 m). In mid-summer visibility is restricted by fog, and in winter by blowing snow.

The sea bottom consists of clays and silts in the westerly areas and silts and sands in the easterly areas. Sea-bottom permafrost has also been detected during coring operations. The sea floor is scored or gouged by ice features to about the 150 ft (45 m) depth. However, frequency of new scours in specific areas and water depths is not known. Coastal currents are variable but, in summer, average less than 0.3 m s^{-1}. Storm tides up to 8 ft (2 m) have been reported while normal tides are on the order of 1.5 ft (0.5 m).

The southern Beaufort Sea is inhabited by many species of fish, ringed and bearded seals, some walrus, beluga and bowhead whales, seabirds, polar bears, and white fox. Since the native peoples in the Mackenzie Delta area utilize this wildlife and marine life extensively, disturbance and reduction in wildlife numbers must be minimized.

Pressure ridges

When ice-floes impinge upon weaker ice which is unable to resist the contact pressure, deformation occurs. The result is a combination of deformation structures which give the canopy its rough and often formidable appearance. These structures can be broadly categorized as rafted, ridged, hummocked, or sheared formations (Kovacs, 1972). The first three of these formations are well-known features resulting primarily from compressional deformation, while the fourth occurs when the forces acting are primarily shear in character.

The highest free-floating ridge ever observed was seen near the 1971 AIDJEX Pilot Study camp 420 km north of Tuktoyaktuk. It rose 42 ft (14 m) above sea level (Kovacs, unpublished data). However, ridges higher than 20 ft (6 m) are rare.

Where the sea is shallow, the keels of ridges or hummocks may ground, allowing increased accumulation of ice blocks on the upper portion of the ridge without further settlement of the keel. A number of grounded ridges were observed off the east coast of Herschel Island in 1970 (Kovacs, 1972). The highest was some 55 ft (16.5 m) above sea-level and was grounded in about 45 ft (13.5 m) of water.

Floes and deformation structures which survive at least one summer melt season are referred to as multi-year ice. During the summer melt seasons, the angular ice blocks incorporated in the ridges and hummocks gradually round off, the voids between them fill with the re-frozen melt of snow and ice, and the overall relief becomes somewhat rounded. The multi-year ice surrounding an old ridge or hummock also has a characteristically rounded melt topography that is a result of differential surface melting and run-off pooling.

Ice islands

Another feature not uncommon in the sea ice of the Arctic basin is the tabular iceberg commonly called an ice island. These islands originate from ice shelves (up to 200 ft (60 m) thick), along the Beaufort Sea coast of Ellesmere Island. Although they have been sighted throughout the Arctic basin, those that break off from the Ellesmere ice shelves generally drift via the Ellesmere coastal drift stream into the clockwise circulation of the Beaufort or Pacific Gyre. Because of their similar surface topography, ice islands with low freeboards can be difficult to locate among the multi-year floes of the polar pack.

Ice islands approaching the coast often become grounded. Over 400 ice-island fragments were observed by the authors in 1972 off the Beaufort Sea coast of Alaska. Most move on during spring break-up but a few have been known to remain for several seasons. Grounded ice islands help to fix the outer limits of the fast ice by preventing movement of the surrounding plate ice. However, when sufficient force is exerted by the surrounding ice, an ice island will move, its keel gouging its way through the bottom sediments.

Study areas

The waters of Mackenzie Bay are brackish due to the mixing of Mackenzie River water with the saline waters of the Beaufort Sea. During the winter of 1970–71 the bay was filled with multi-year floes extending up to what appeared to be the 25 ft (7.5 m) submarine contour. The multi-year ice and an assortment of small ice islands were driven into Mackenzie Bay the previous September during a severe storm of about 36 h duration. Winds gusting to 135 km h^{-1} were reported. The return period of storms with such gust winds is more than 25 years. It was also estimated that at the peak of the storm the sea-level rose about 8 ft (2.5 m).

In Mackenzie Bay two multi-year ridges were studied on an old polar floe. A short distance to the south was a site where the fractured remains of a small grounded ice island were

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investigated. The area of this field study is shown in Figure 1 as the Mackenzie Bay Site, two other grounded ice-island fragments were investigated at the Babbage Bight Site (Fig. 1).

Investigations were also carried out at two locations in the Beaufort Sea about 48 km north of the village of Tuktoyaktuk. Two multi-year ridges on a small floe were studied, the larger of these was grounded. A grounded first-year ridge was also studied. The area in which these studies were made is shown in Figure 1 as the Tuk Site.

Data acquisition techniques

Direct measurements of ice thickness were obtained by taping through holes cored either with a SIPRE (CRREL) auger or with a 9 in (225 mm) diameter continuous flight auger. The internal structure of the ice was investigated by augering or coring. Augering revealed the presence or absence of cavities and gave a "feeling" for the variation of ice consistency with depth. Coring allowed the recovery of cylindrical cores upon which temperature, salinity, density, and strength determinations were performed.

Temperatures were obtained with the use of a thermistor bridge. After the temperature profile was obtained, the core was cut into sections, logged, and then allowed to melt in individual sealed containers. The salinity of the melt water was determined with an electrical conductivity measuring device.

To determine ice density the initial core was first cut to length in a miter box. The resulting length and diameter of the sample were measured with calipers and the mass of the specimen was determined on a triple-beam balance. The volume of the specimen and the density were calculated.

Two types of ice strength measurement were made, indirect tension and unconfined compression. The indirect tensile strength was determined by the Brazil test. Tests were performed on a screw press driven by a $\frac{3}{4}$ in (19 mm) electric drill at a platen speed of 2 in min^{-1} (50 mm min^{-1}). The press was fitted with a double proving ring. Unconfined compression test specimens were obtained by core drilling. These tests were also carried out using the screw press.

Three methods were used to obtain the cross-sectional profile of the ridges presented in this report: standard surveying techniques for surface elevations, direct drilling for ice thickness, and sonar ranging for the keel contours.

Fig. 2. Diving operations.

The sonar equipment consisted of a narrow three-degree-beam transducer attached to the end of a rigid assembly of buoyant lowering rods. The transducer was positioned at a selected depth beneath the ice with its beam maintained in a horizontal plane and pointed at the chosen keel. The horizontal distance between the keel and transducer was then measured acoustically and recorded on a strip-chart recorder. Repetition of this measurement at a set azimuth and at many depths provided a record from which the keel contour could be determined.

Dives were made through six holes blasted in the ice as shown in Figure 2. Two divers were used to gather information on the geometry and surface state of ridge and ice-island keels, to investigate the ice–soil interface of grounded ridges and ice islands for evidence of scoring and plowing related to keel drag, to obtain samples from the sea bottom in undisturbed and scored areas, and to obtain still and television photography. In addition, bottom samples were collected in cans pushed into the seabed.

Ridge profiles

Figure 3 shows a general impression of a multi-year ice-floe in Mackenzie Bay which contains large pressure ridges. The multi-year floe was some 1 400 ft (420 m) long in the north–south direction by 850 ft (255 m) at its widest point. The old ridges (up to 15 ft (4.5 m) above sea level) had an undulated surface but an overall rounded relief.

Fig. 3. Multi-year floe in Mackenzie Bay.

A cross-section of Ridge 1, investigated at the Mackenzie Bay Site (Fig. 1), is shown in Figure 4. The thickness of the low-lying ice north of Ridge 1 was about 17 ft (5.4 m) while south of the ridge it was 7 to 8 ft (2 to 2.4 m). The deepest portion of the keel under the ridge was displaced to the north in relation to the highest portion of the sail. Of the 25 exploratory holes drilled into or through the ridge and surrounding ice, only two revealed the existence of cavities.

Ridge 2 was also located at the Mackenzie Bay Site (Fig. 1). The cross-section of Ridge 2 is shown in Figure 5. Direct drilling determined that the ridge keel extended 82 ft (6.6 m) below sea-level while sonar measurements indicated 26 ft (7.8 m). Sonar measurements permit the construction of a profile much more representative of the overall keel contour than do drill-hole measurements.

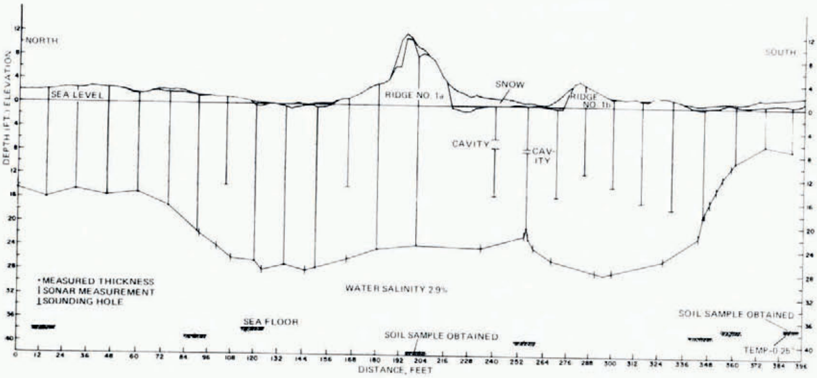

Fig. 4. Profile of multi-year Ridge 1.

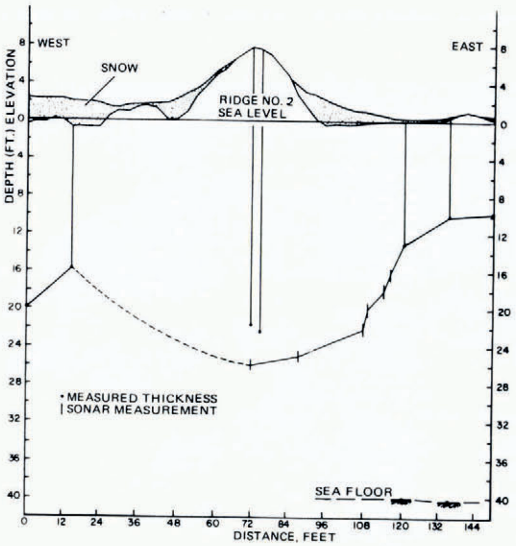

Fig. 5. Profile of multi-year Ridge 2.

Dives at this site revealed that portions of the subsurface ice were covered with deteriorated ice in the form of long platelets. This layer was several feet thick on occasion and offered virtually no resistance to penetration of the arm. What the sonar may have recorded under Ridge 2 was this deteriorated layer, which would not have been recovered by coring or been easily detected by direct bore-hole measurement.

Figure 6 gives the salinity, temperature, and density profiles for the ice on Ridge 2 as well as the brine-volume profile. The salinity of the ice at Ridge 2 gradually increased from near zero at the surface to approximately one part per thousand at sea-level.

The density increased from approximately 840 kg m^{-3} at the surface to approximately 865 kg m^{-3} at sea-level. Below sea-level it immediately increased to more than 880 kg m^{-3} and continued to increase at about the same rate with depth as it did above sea-level. The ice at the bottom of the ridge had a density on the order of 940 kg m^{-3}.

The next two multi-year ridges investigated were located at the Tuk Site (Fig. 1). The ridges had formed close to each other and were part of a much larger floe. The east end of

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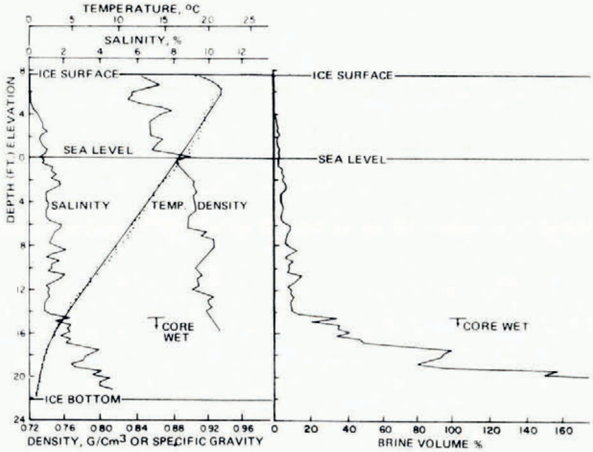

Fig. 6. Temperature, salinity, density, and brine volume profiles on multi-year Ridge 2.

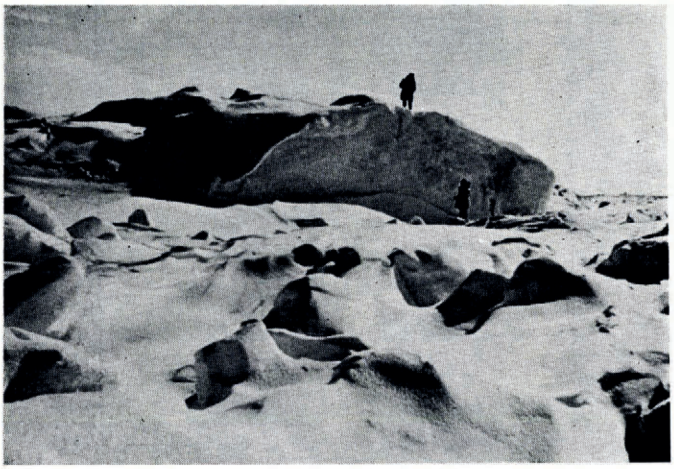

Fig. 7. Broken multi-year ridge.

the ridge had a near-vertical face where the floe had split apart, this face was similar to that shown in Figure 7. First-year ice had piled over 12 ft (3.5 m) high at one end of the floe which led us to believe that the floe was grounded. The cross-section of this multi-year floe is shown in Figure 8. It is readily apparent that the keel of Ridge 3 was grounded and the keel of Ridge 4 was not. Whilst this is true for this cross-section, it may not be true for the keel further to the west; here the top of Ridge 4 was slightly higher and the keel presumably deeper.

Along the profile line, the floe was approximately 350 ft (105 m) long. The highest elevation on the profile was 18.2 ft (5.5 m) above sea-level. The keel was grounded in 44 ft (13.2 m) of water. Ridge 3 was therefore at least 62 ft (18.6 m) thick. Ridge 3 is certainly impressive by itself, but, coupled as it is to Ridge 4, the overall floe becomes a massive formation which must not be considered lightly in the design of an off-shore structure.

The cross-section of the last ridge studied, located at the Tuk Site, is shown in Figure 9. It had formed earlier in the season as indicated by the thickness of the ice blocks incorporated

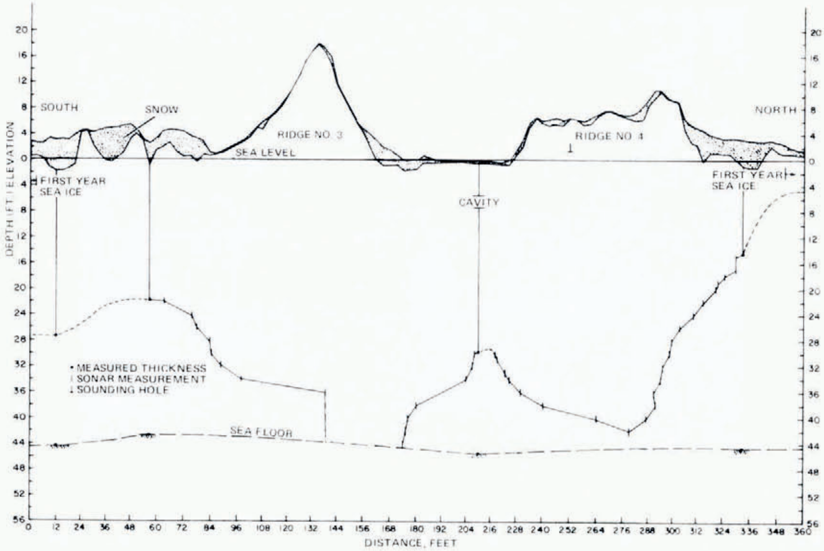

Fig. 8. Profiles of multi-year Ridges 3 and 4.

in its sail. These varied in thickness from 393 to 409 mm. The plate ice had been deflected upward and fractured by the advancing keel below. Ridge 5 was grounded in 57 ft (17.1 m) of water. The sail of the ridge was 16.6 ft (5.0 m) high where the surface profile passed over the top of the ridge. The highest point was 6.1 ft (1.8 m) higher. This first-year pressure ridge is shown in Figure 10. The voids between the ice blocks incorporated in the ridge sail were bridged with snow, but little snow had accumulated on the blocks themselves.

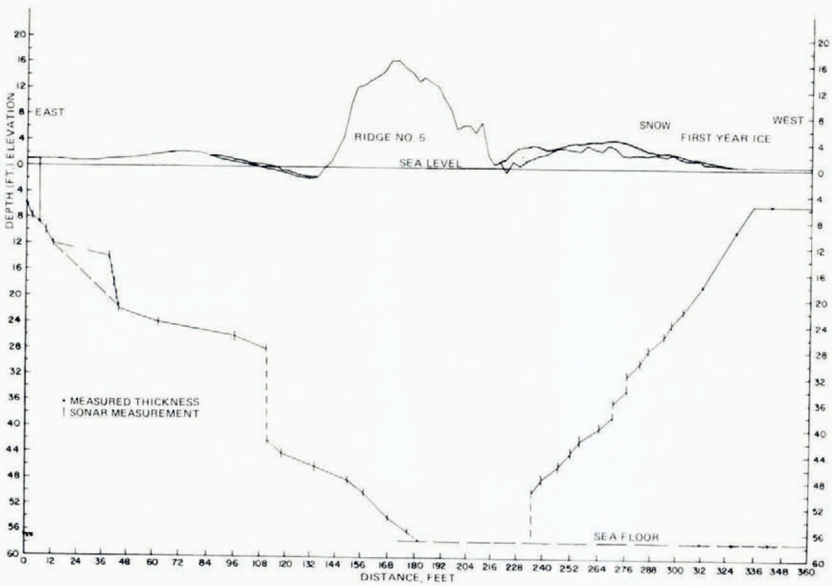

Fig. 9. Profile of first-year ridge.

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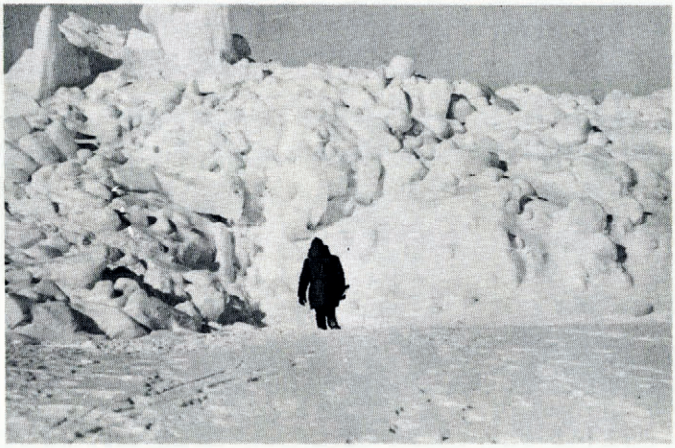

Fig. 10. Sail of first-year ridge.

The undeformed first-year ice in the area was 6.2 ft (1.9 m) thick. The ice structure near the ridge consisted of an assortment of ice blocks interfaced by newer ice. The ice at one station was 19.4 ft (5.8 m) thick, the first 7 ft (2 m) of which was "firm" with the remainder being very "soft". At another station, the ice was 10.2 ft (3 m) thick with the last 3 ft (1 m) consisting of soft ice. No evidence of keel grooving was noted.

Ice-island fragment data

Three fragments of an ice island which broke upon grounding in Mackenzie Bay were investigated at the Mackenzie Bay Site (Fig. 1). The separation between fragments is shown in Figure 11.

Flooding occurred when the auger cut through the ice cover. This may have been because the fragments were grounded, and a combination of ice-keel ablation and soil stress consolidation was causing load transfer to, and negative deflection of, the adjoining ice.

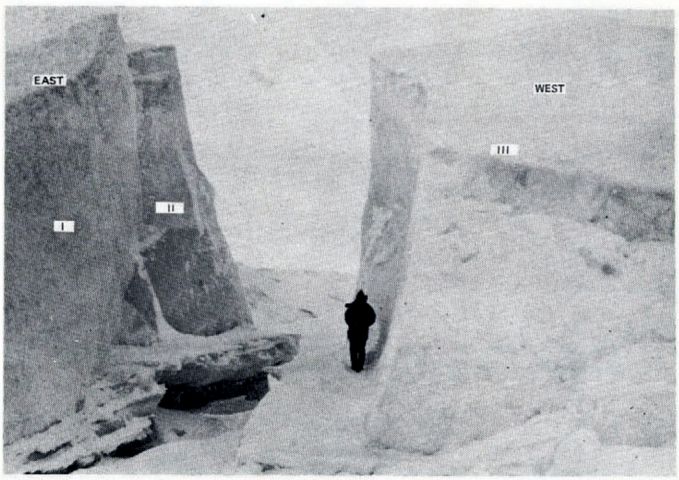

Fig. 11. Ice-island fragments.

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The profile of the east and south faces of Island Fragment I is presented in Figure 12. The profile shows that the east face of the island was vertical down to a depth of 30 ft (9 m), at which depth the keel began to protrude outward. At 36 ft (11 m) the sonar transducer came to rest on the protuberance and no further measurements were possible. However, the general shape of the protuberance was constructed as shown using information gathered by the divers. This "shovel" was not grounded at the leading edge, but tapered back underneath the lip 6 ft (2 m) before contacting the sea floor. A mound of soil a meter high was observed in front of the shovel. All along the north face, the seabed had been pushed upward in a mound which became higher as the divers progressed westward. The peak of this ridge was 10 to 15 ft (3 to 4.5 m) away from the island face, presumably the island moved into the area from the north-west.

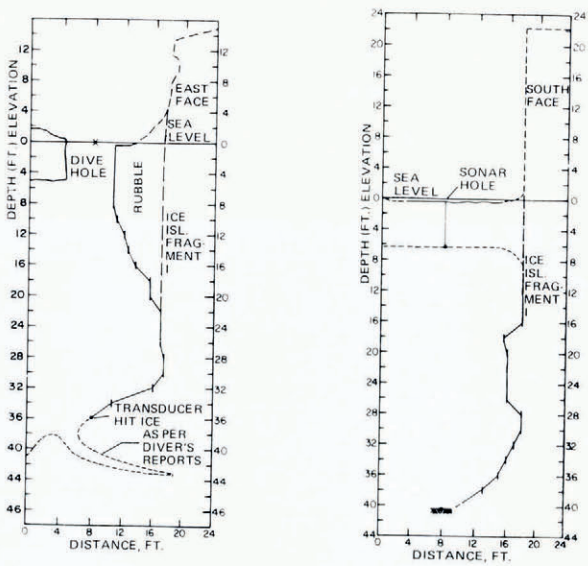

Fig. 12. Profiles of east and south faces of Island Fragment I.

Figure 13 presents the profile obtained from sonar measurements on the west side of Island Fragment III. The ice cover adjacent to the island consisted of pressured first-year ice 25 ft (7.5 m) thick. A dive was made to verify the existence of a trench which was discovered by line soundings. The divers found a trench running in a west to north-west direction. It appeared to be 5 ft (1.5 m) deep but became deeper as they progressed toward Island Fragment III. Along the edge of the trench, a berm of soil had been pushed upward 4 to 7 ft (1.2 to 2.1 m). In places the trench surface exhibited striations, and at several locations the wall had slid along with the island keel. Figure 14 shows a portion of the trench floor which has undergone lateral translation. In one area the trench depth increased to 7 ft (2 m) and the topography became highly irregular.

The keel cross-section of one ice-island fragment investigated at the Babbage Bight Site was obtained for the Federal Government of Canada following the APOA study. Although not part of APOA Project 17, this profile is included for comparison as Figure 15. The cross-section shows that, at this narrow end of the island, the keel is very wide compared with the ice height above water. Where the profile intersected the island, the sail was estimated to be ten meters wide at sea-level. The wave terrace, or bulge, on the northern side of the island

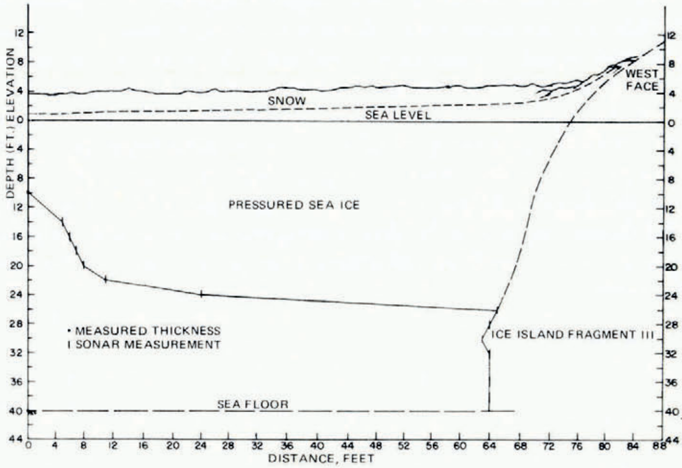

Fig. 13. Profile of face of Island Fragment III.

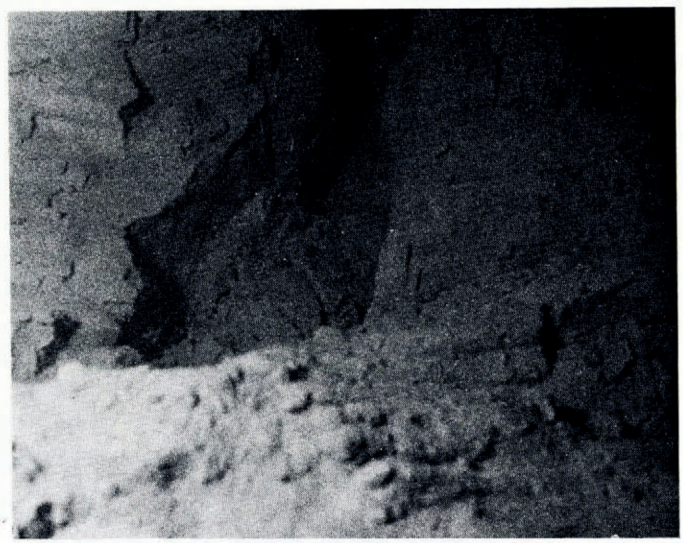

Fig. 14. Lateral translation crack in trench floor.

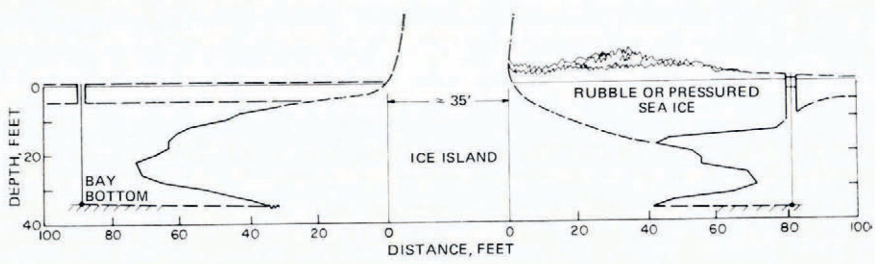

Fig. 15. Profile of narrow portion of an ice-island fragment.

was overlain by a large accumulation of hummocked sea ice. This heavy loading of pressured ice may explain why this end of the island is depressed below its expected flotation level.

Bathymetric data shows that there was no major trench near the island. Divers found small furrows on the seabed 2 to 6 in (5 to 15 cm) deep and about 6 ft (2 m) wide.

Strength of old sea ice

Although Brazil tensile tests were made on specimens of ice obtained by core drilling in old pressure ridges at two separate sites, the test results were considered to be invalid for measuring the uniaxial tensile strength of ice. Direct uniaxial tensile or compressive tests are very difficult to perform on brittle materials to acceptable standards of accuracy, since great precision is called for in the preparation and loading of the test specimens.

The test techniques in this field work were far from ideal, and it is to be expected that values which are generally higher would have been obtained in high-quality laboratory tests. The compressive strength values obtained were mainly in the range 2.5 to 4.5 MPa.

On two occasions very large multi-year pressure ridges which had split apart in the recent past were encountered, so that there were opportunities to examine directly the internal ice structure of old ridges. Such a face is shown in Figure 7.

There was a complete absence of open cavities in the exposed faces. The ridges clearly were composed of a breccia of ice blocks with differing textures and orientations, but the blocks were thoroughly cemented together and the original interblock cavities were completely filled with newer ice. The blocks themselves were sub-angular, the original sharp edges having been subdued by melting and refreezing. There were some streaks and loops of dark-colored ice scattered on the faces. These appeared to be intersects of dark bands in the constituent ice blocks, probably bands of diatomaceous material formed at the underside of the original plate ice.

Logistics

In respect to the SRN6 hovercraft used for transportation and quarters during the APOA field project, it is enough to say here that it proved to be the best method of transport for this project. It is true that several problems did develop with the craft which caused some delays and much discomfort. Nevertheless the advantages of being able to carry all the gear and to stay on site proved to be invaluable.

In traversing rough areas, the craft was forced down to walking speed as it followed a tortuous path through the obstacles. The smaller obstacles, up to a meter or so in height, could be crossed directly. Abrupt obstacles higher than one meter had to be avoided.

Travel over very rough ice took its toll of the vehicle. The skirt was torn in a number of places, but most of the tears were soon mended by riveting on patches. More serious was the damage to the fingers, which could not be repaired so easily.

The craft was able to get to sites which would have been inaccessible by fixed-wing aircraft, and it was a good deal more economical than a helicopter.

In spite of the rough living conditions on the hovercraft, it was a great advantage to live on the site. Long hours could be worked, days with poor visibility were not lost, and food and shelter were available for periodic breaks during the working day. The hovercraft was particularly advantageous for diving operations.

Conclusions

1. Multi-year pressure ridges and ice-island fragments, because of their massiveness and structural integrity, will impose large forces on offshore structures.

2. Multi-year pressure ridges are composed of essentially solid ice except for occasional cavities and for the bottom few meters which were found to be soft.

3. The salinity, density, and brine volumes of the ice in multi-year pressure ridges increased with depth as expected.

4. Multi-year pressure ridges with sails of 5 m and with keels up to 13 m were investigated. Two distinct ridges on the surface may have a common keel. Keels need not lie directly below the sails.

5. The first-year pressure ridge investigated had a sail of 5 m, a keel of 19 m, and a width of 90 m at the profile position.

6. Trenches adjacent to the grounded ice features were on the order of a meter with a maximum of two meters.

7. Sonar profiling is a time-saving and sufficiently accurate method of profiling underwater sea-ice features.

8. The SRN6 hovercraft is an economical and convenient means of transportation and accommodation for conducting winter research on landfast sea ice.

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