The Occurrence Of Grounded Ice Ridges And Shore Ice Piling Along The Northern Coast Of Somerset Island, N.W.T.

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ABSTRACT. Massive shore ice piles and grounded ice ridges up to 30 m high were examined along the northern coast of Somerset Island between 1973 and 1976. The ice ridges, composed of 1 to 2 m thick ice blocks and occasionally thicker multi-year ice blocks, occurred most frequently along the north and west shores of capes and headlands. 'Cape Fisher' was the site of shore ice piling during each of the four years and one set of ice piles, built 15-60 m inland existed three years. Effects of grounded ice ridges on nearshore morphology were minimal but ice-push features were observed as much as 185 m inland across the beach.

RÉSUMÉ. On a observé des amoncellements de glace littorale et des murs de glace "enracinés" pouvant atteindre 30 m de hauteur, sur la côte Nord de l'Ile de Somerset, entre les années 1973 et 1976. Les murs de glace étaient formés de blocs de glace, de 1 à 2 ms d'épaisseur, parfois plus quand il s'agissait de glace de plusieurs années; on les a rencontrés surtout le long des rivages du Nord et à l'Ouest de caps et promontoires. Pendant ces 4 ans d'observation, les amoncellements de glace littorale se situaient à Cap Fisher; un amoncellement de glaces construisait une butte de 15 à 60 mètres pendant 3 ans. Les effets de ces murs de glace "enracinès" sur la morphologie proche du littoral, étaient très réduits mais des témoins de poussée de glace étaient observés sur la plage avec une taille atteignant 185 mètres (pingos).
Traduit par Alain de Vendegies, Aquitaine Co. of Canada Ltd.

INTRODUCTION

During a reconnaissance flight along northern Somerset Island in 1973, it was apparent that the entire coast is affected to some degree by sea ice, onshore ice-push and ice-melt features were observed, while offshore sea ice ridging, rafting and scouring of the sea bed were found. The present account focuses attention on the distribution and characteristics of massive grounded ice ridges and shore ice piles observed during 1973 to 1976 along northern Somerset Island (Fig. 1).

Knowledge of the interaction of ice floes with the northern shores of Somerset Island is of interest because of future plans by Polar Gas to construct a pipeline across Barrow Strait from Cornwallis to Somerset Island. Polar Gas is a consortium of several North American companies which recently investigated the feasibility of a natural gas pipeline to transport natural gas from the northern Arctic islands to markets in southern Canada. The most recent construction plans indicate tunnelling of all shore approaches in order to protect the pipe from possible ice gouging. However, the occurrence of grounded ice ridges and shore ice piling could present hazards during construction of the shore approaches or to equipment and construction materials stored on the beach.

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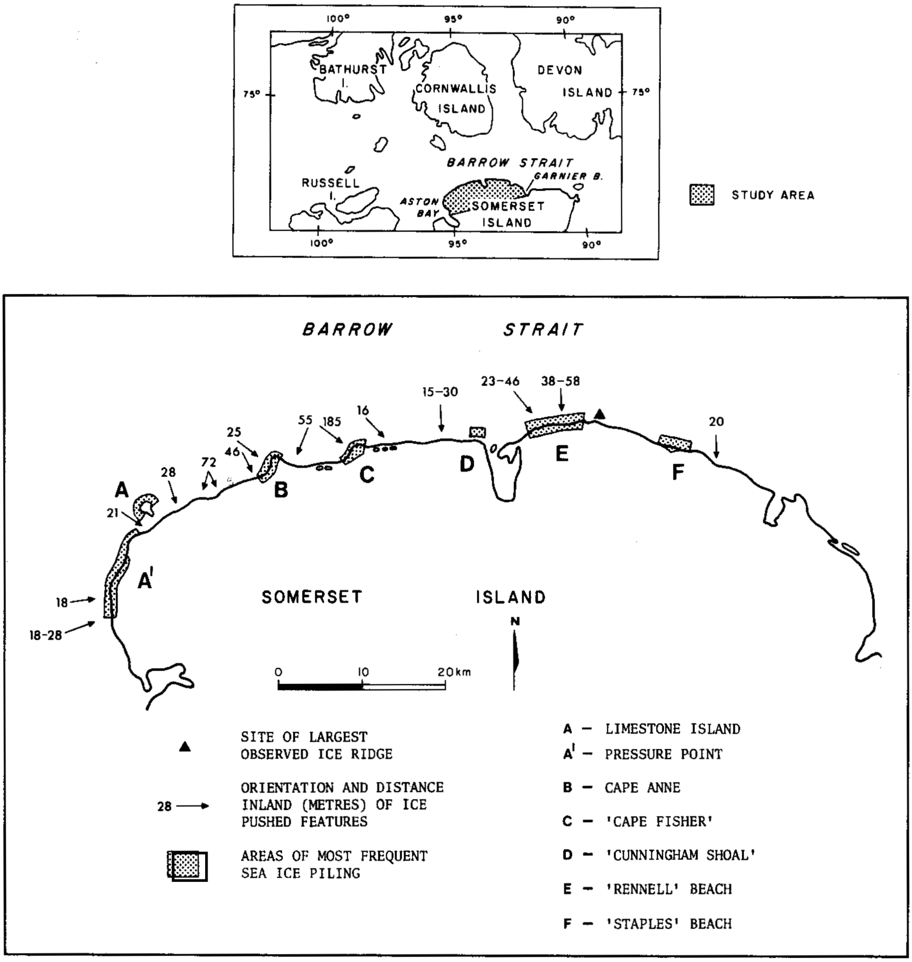


FIG. 1. Location of study area and shores characterized by large scale ice-push features, frequent shore ice piling and grounded ice ridges.

PREVIOUS RESEARCH

Earliest reference to ice ridges were made by explorers whose travels in the Arctic were directly affected by sea ice conditions. McClintock and Haughton (1858, p. 228) and Stefansson (1921, p. 509, 514) both describe grounded ice ridges estimated to be 12 to 18 m in height along the coasts of Prince Patrick and Ellef Ringnes Islands. Ice ridges of 26 to 36 m above sea level have been reported by Sverdrup (1904, Vol. 1, p. 375) along the southwest coast of Axel Heiberg Island.

More recently, grounded ice ridges in the coastal zone have been discussed by several scientists conducting research in various parts of the northern hemisphere. Zubov (1945) and Glukhova (1964) present examples of ice ridges, "stamuki", of normally 5 to 8 m and up to 50 m in height, built along the shoals of the Caspian and White Seas. In Scandinavia, Brunn and Johannsson (1971) examined the interaction of ice with shore structures and Alestalo and Häikiö (1976) looked at "ice thrust features" formed along the shores of Finland.

In the literature, by far the largest number of examples of nearshore ice ridging come from the Beaufort Sea. Kovacs (1976), Kovacs and Gow (1976), Kovacs *et al.* (1976) and Reimnitz *et al.* (1977) have dealt with ice ridges found in the grounded ice zone of the land fast ice. These ice features are formed by the shearing of mobile pack ice against the edge of the fast ice or by local pressuring. Mention is also made by Kovacs (1976) of ice ridge formations built on shoals and found within the fast ice zone. Kry (1978) examined ice rubble fields up to 13 m high, in the vicinity of artificial islands in the Canadian Beaufort Sea. In the eastern Canadian Arctic, the only recently reported example of ice ridges on shore was by Owens and McCann (1970) on southwest Devon Island.

Nearly all of the above examples have involved newly formed ice of one metre thickness or less that has been pressured into ridges during the fall or early winter. The grounded ice ridges and shore piles which are discussed in the present paper differ from the above examples because of the time of formation and the greater thickness of sea ice involved. In this paper the term 'grounded ice ridge' refers to ice ridges which have formed in the nearshore and whose keels extend to the nearshore bottom. 'Shore ice piles' or 'piling' refer to ridges of ice formed across the beach. 'Nearshore' refers to the waters within one kilometre of the shoreline.

FIELD OBSERVATIONS

Distribution

The general drift of sea ice eastward through Barrow Strait and the prevailing winds from the northwest quadrant during the summer (Taylor, 1977), result in considerable amounts of ice impinging on the shores of northern Somerset Island (Fig. 2). Based upon three seasons of field work, maps were drawn showing the location of shore ice ridging and the shorelines which are characterized by large scale ice-push features (Fig. 1). It was the north and west facing shores, especially of capes and headlands, which were most frequently and most severely affected by ice action. In particular, six coastal areas were observed to be most frequently subjected to ice ridging. They were: (1) Pressure Point and Limestone Island; (2) Cape Anne; (3) 'Cape Fisher'; (4) 'Cunningham' shoal; (5) 'Rennell' beach (Fig. 3); and (6) 'Staples' beach (Fig. 1). It was also observed that ice island fragments and large multi-year ice blocks could ground virtually anywhere along the northern Somerset coast, not just in the six areas mentioned above.

At 'Cunningham' shoal and 'Staples' beach only grounded ice ridges were observed but both grounded ice ridges and shore ice piles were found at the other four areas. Grounded sea ice ridges occurred where shoals or grounded

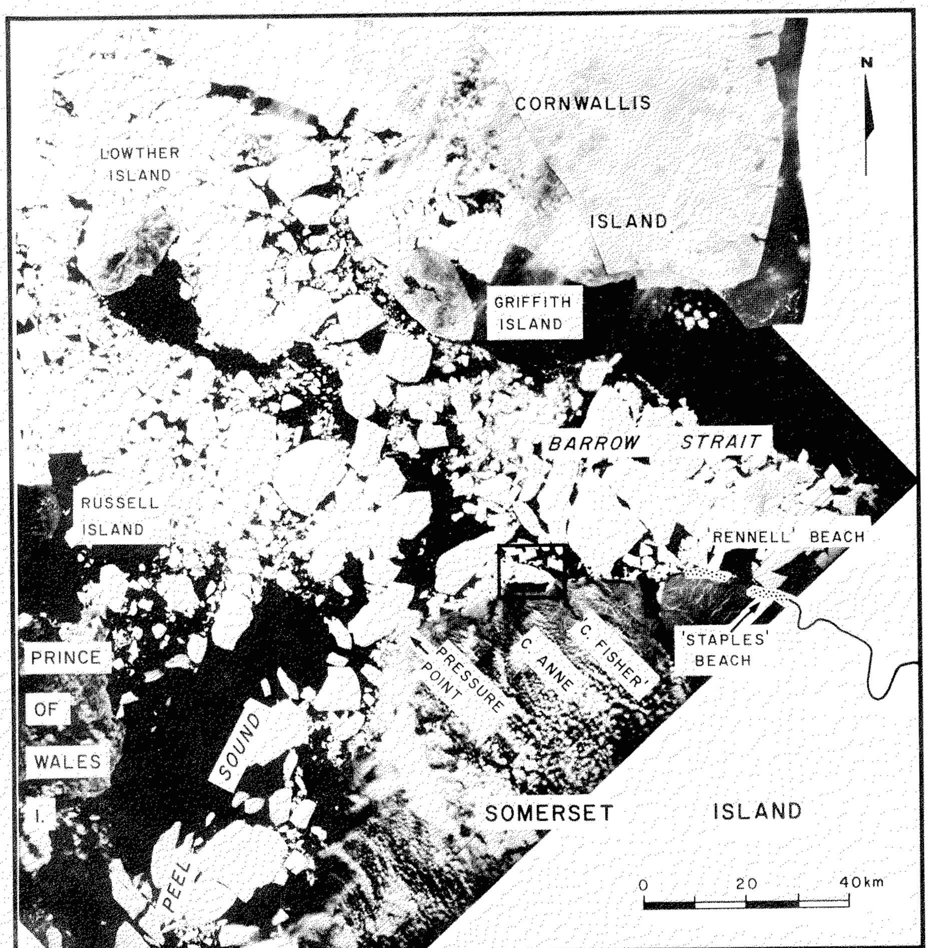
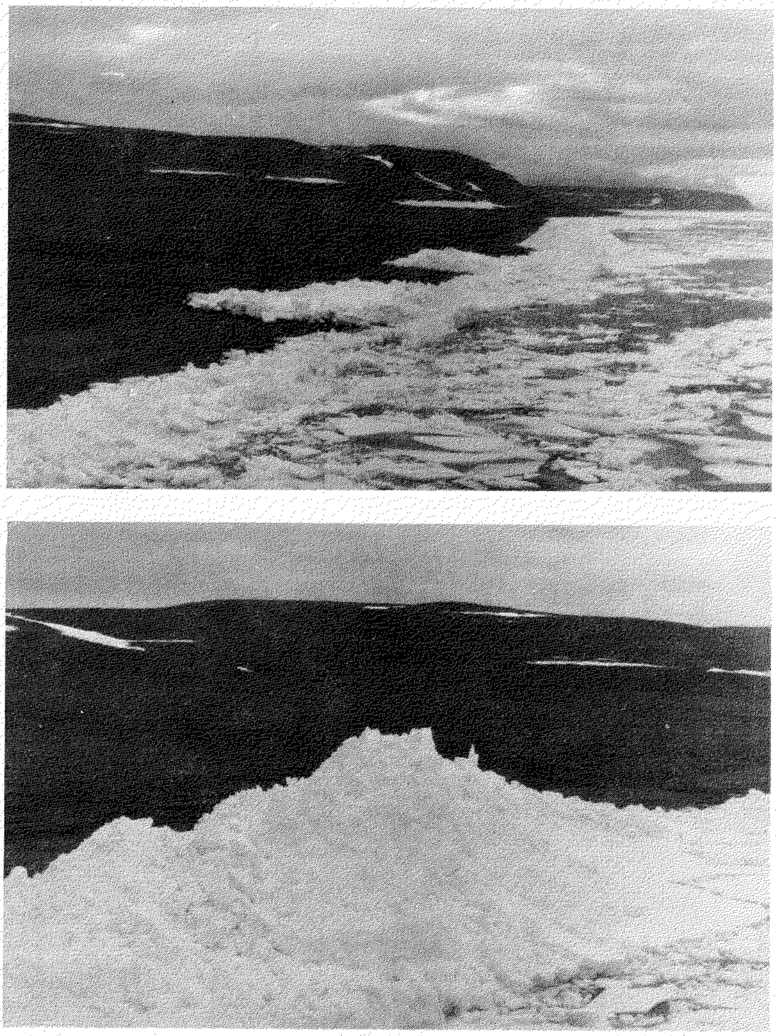


FIG. 2. ERTS-1 imagery July 24, 1973, showing sea ice floating east into Barrow Strait and striking the Somerset coast - square outlines the ice floe which caused the shore ice piling at 'Cape Fisher'.

multi-year ice existed alongshore. At 'Cunningham' shoal the ice ridges occurred in water depths of 3 to 5 m. Although sea ice was often observed rafted 10 to 30 m inland and ice-push features were found even further inland (Fig. 1), shore ice piling rarely occurred more than 15 m inland from the mean high tide limit.

Morphology

Detailed observation of grounded ice ridge and shore ice pile characteristics were collected at 'Rennell' beach (Fig. 3), 'Cunningham' shoal and 'Cape Fisher' (Fig. 6-9). Profiles across shore ice piles were made using conventional survey techniques. For the grounded ice ridges, sail height was measured using the altimeter of a helicopter.



A

B

FIG. 3. Shore ice piles which formed along 'Rennell' beach on July 12, 1975: (a) view alongshore; (b) the landward side of ice pile (GSC photos 165618, 165624).

Along Somerset Island the sail height of the grounded ice ridges and the shore ice piles generally varied from 3 to 15 m above sea level (a.s.l.). However, one near conical shaped grounded ice ridge did extend to an estimated height of 24 to 30 m a.s.l. This ridge (Fig. 5) was located just east of Cape Rennell within 600 m of shore (Fig. 1). The maximum sail heights of grounded ridges observed by Kovacs (1976), Kovacs and Mellor (1974) and Kry (1978) in the Beaufort Sea were only 13 to 15 m. No measurements were made of the width or length of the grounded ice ridges on Somerset Island but they appeared to closely resemble the dimensions of the ice piles on shore. Their length was less than 400 m and their width, measured at the base was 10 to 50 m (Table 1).

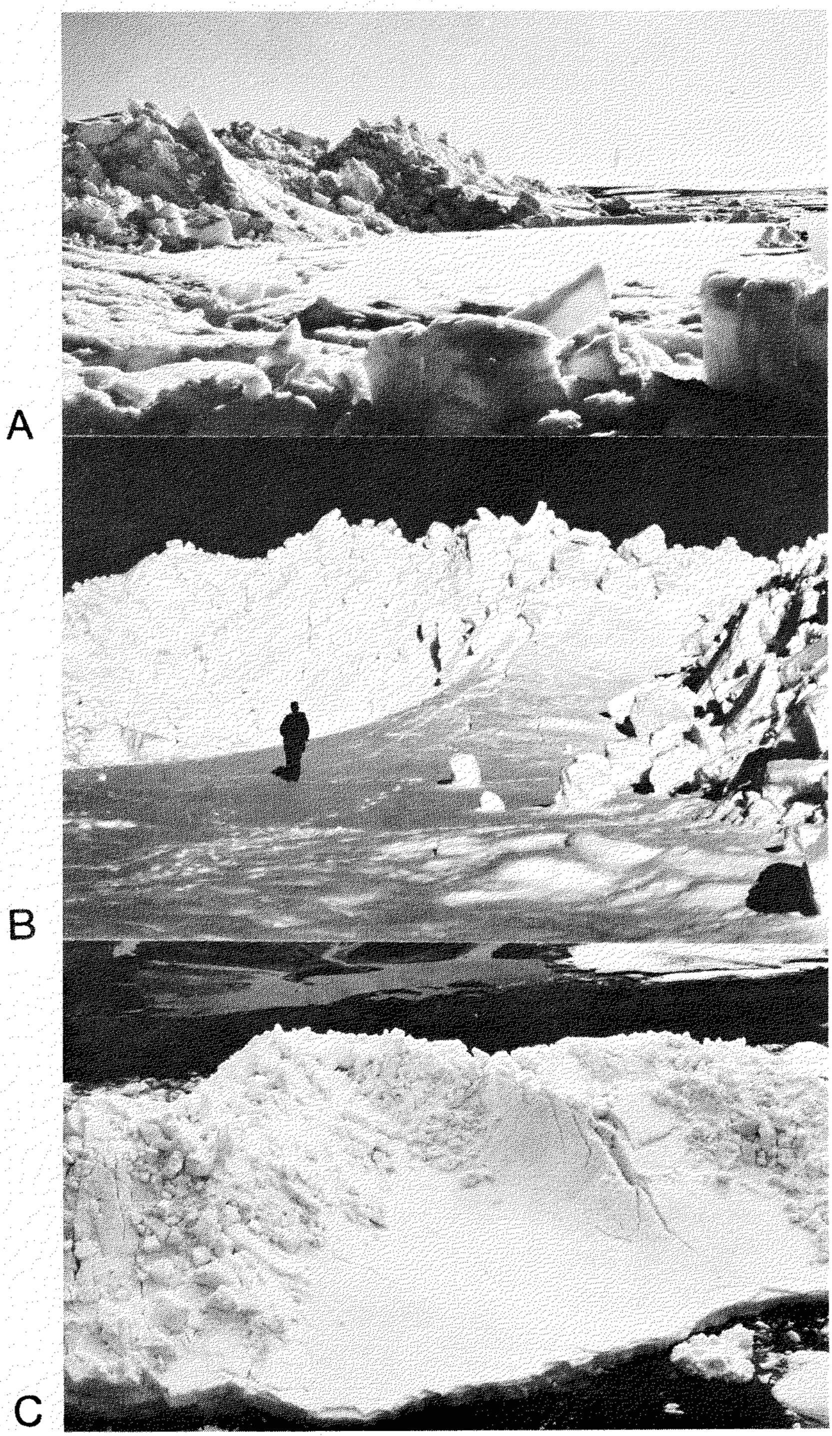


FIG. 4. Shore ice pile morphology: (a) cross-sectional view of the seaward slope of an approx. 9 m high ice pile; (b) closeup of last ice floe to be forced upward across seaward slope; (c) final shape of ice pile with sheared seaward edge (GSC photos 203216 - I, J, E).

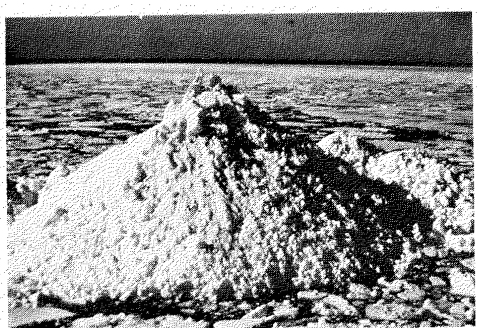


FIG. 5. Largest grounded ice ridge observed along Somerset Island, 30 m high, formed in the nearshore just east of Cape Rennell, July 1976 (GSC photo 203216-F).

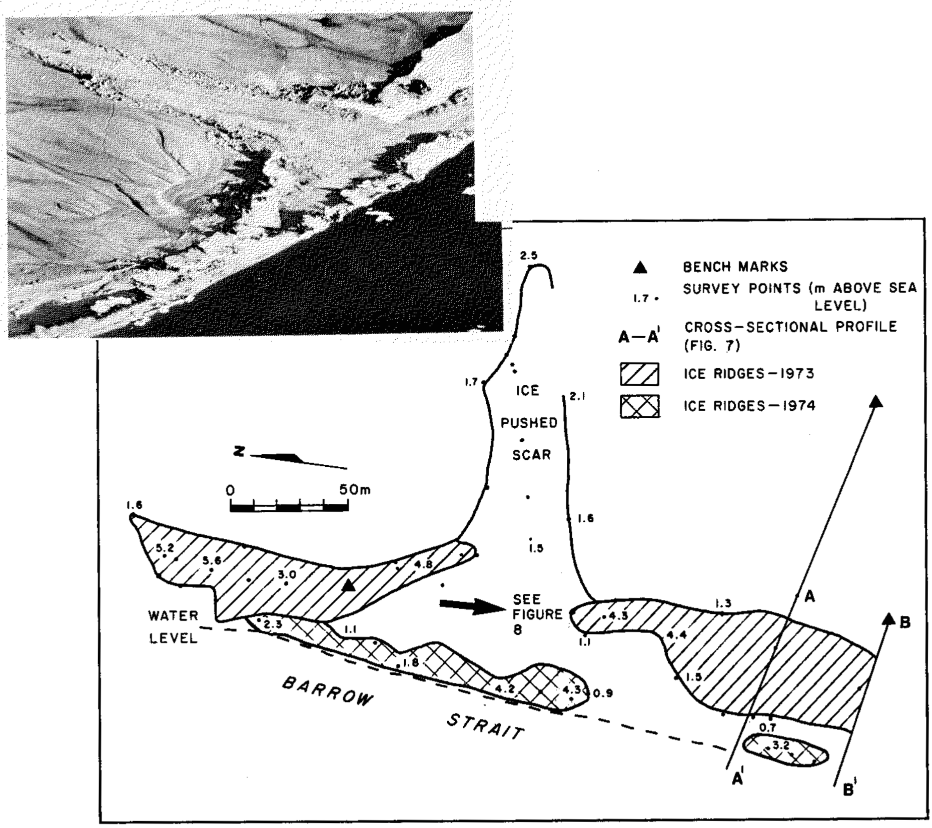


FIG. 6. Photograph and plan map of ice piles formed across the northwest shore of 'Cape Fisher' in 1973 and 1974 (GSC photo 202728-G).

Shore ice piles attained heights of up to 15 m when formed at the edge of the icefoot or beach foreshore (Fig. 3). Ice piles found further inland were generally smaller (Table 1, Fig. 6). This is attributed to the increased loss of energy as the ice moves across the beach surface before ridging begins on land.

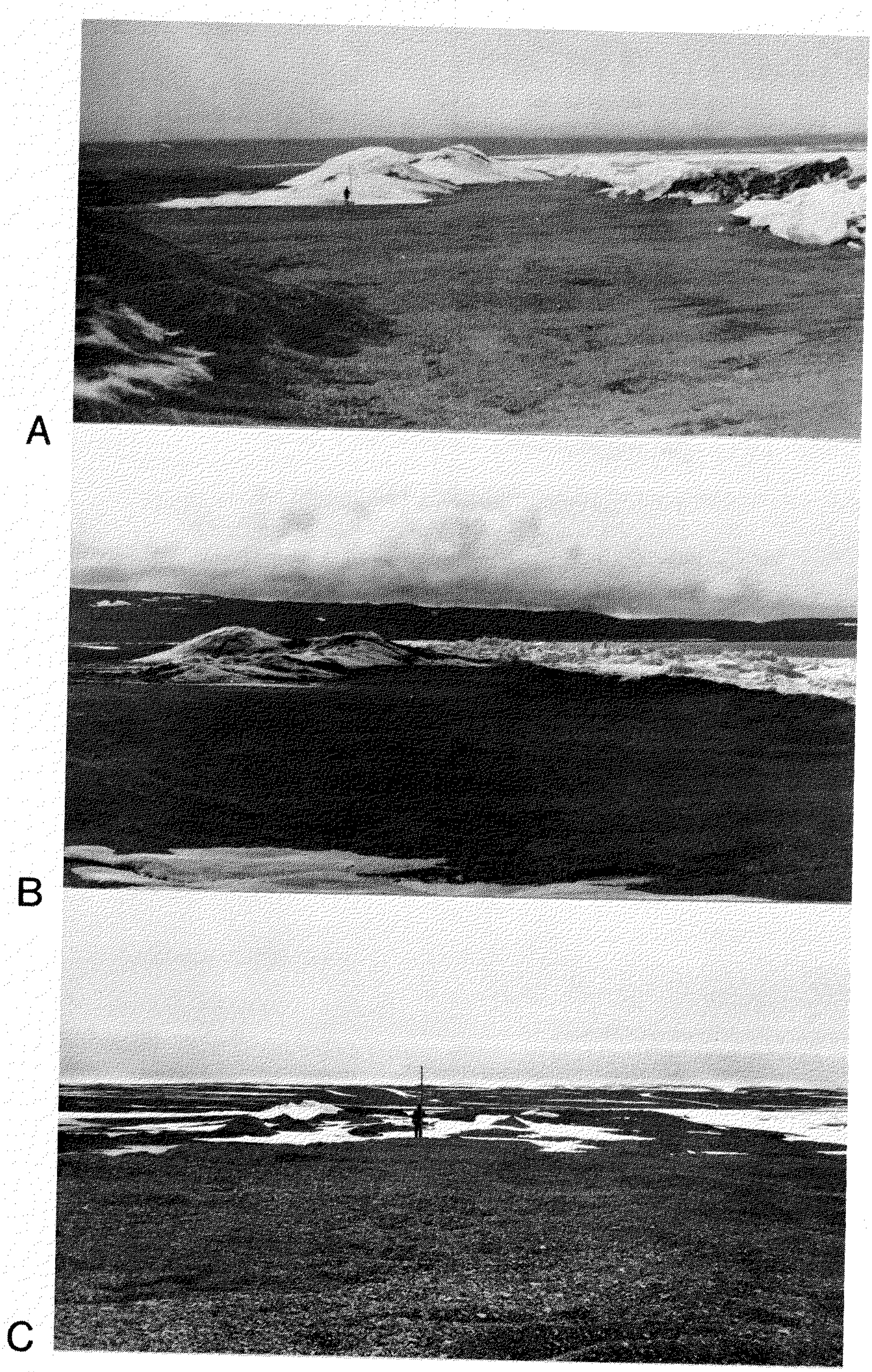


FIG. 7. Changes in shore ice pile morphology over two years: (a) August 27, 1974; (b) July 7, 1975; (c) July 12, 1976, at 'Cape Fisher' (GSC photos 203216-D, 165546 and 169606).

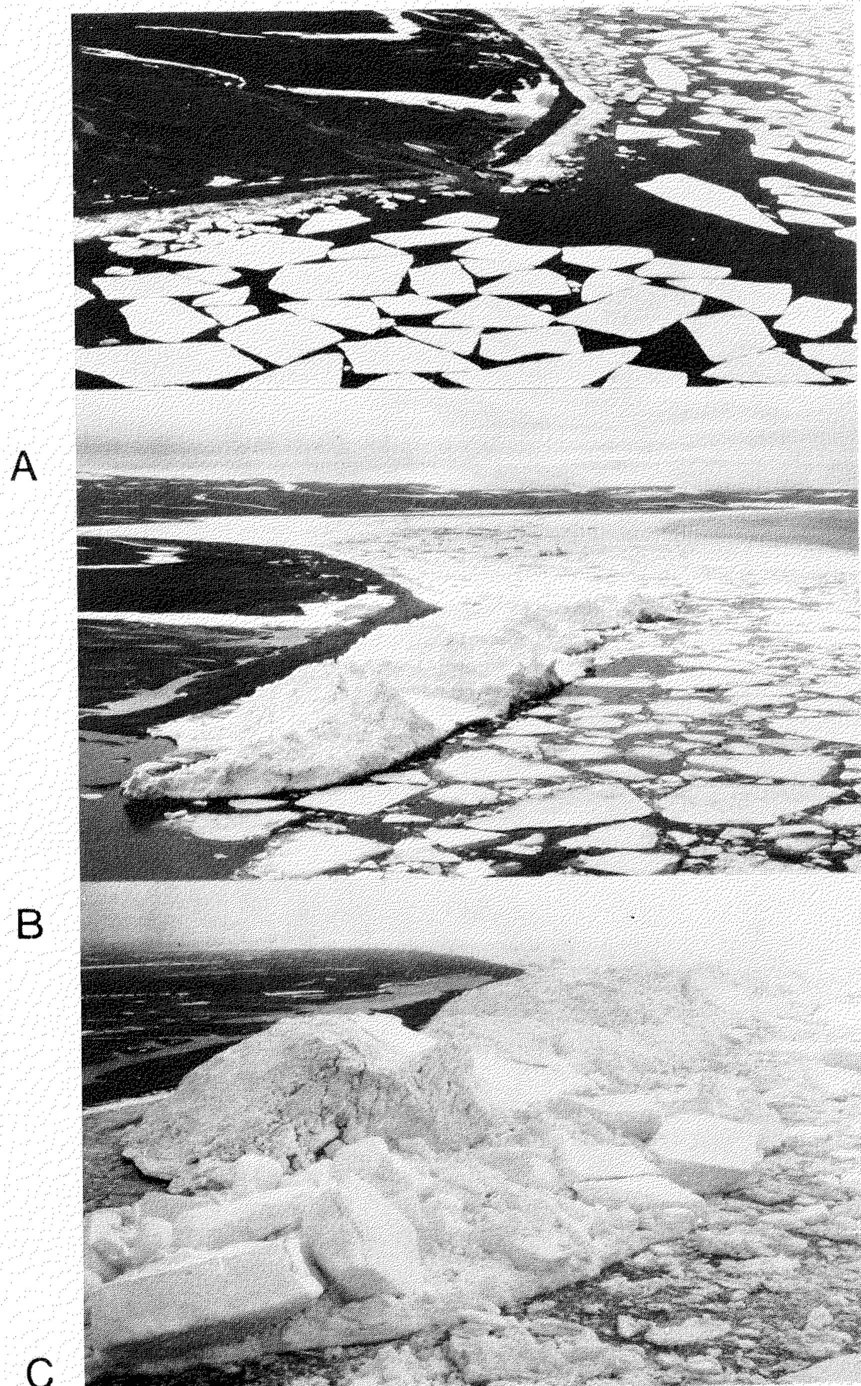


FIG. 8. Shore ice piling along 'Cape Fisher' during 1976: (a) ice conditions on July 10 just prior to ridging; (b) newly formed ice piles, 9 m high observed July 20; (c) grounded ice ridges at seaward edge of above ice piles, as observed August 30, 1976 (GSC photos 203216-G, 203216-K, 203216-H).

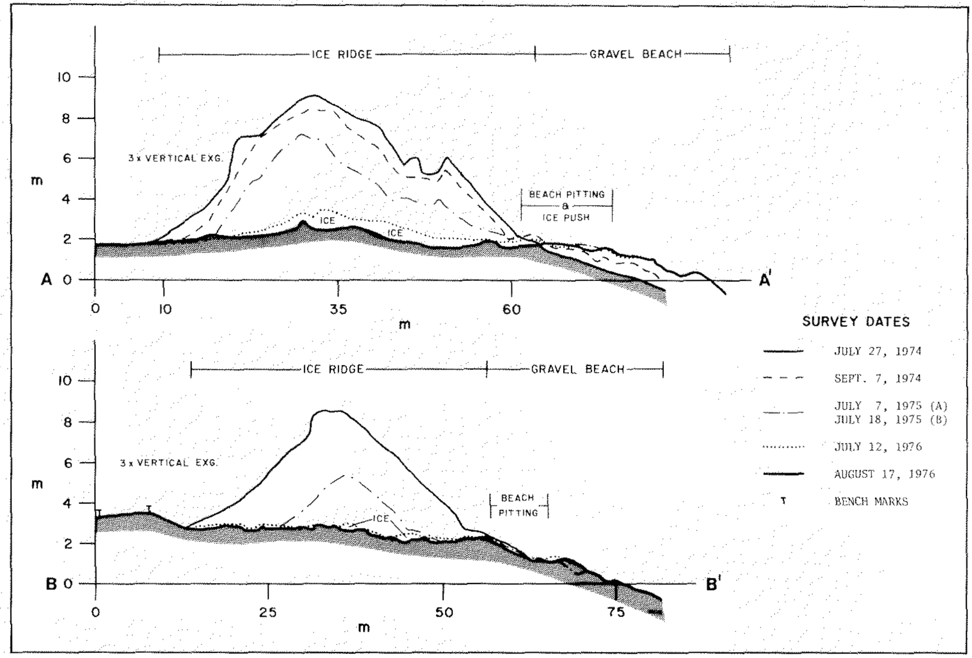


FIG. 9. Sequential cross-sectional profiles surveyed across the ice piles formed in 1973 at 'Cape Fisher' (see figure 6 for location of profiles).

The shape of the grounded ice ridges and shore ice piles was similar to a bulldozed pile of sand or gravel. The seaward slope of the grounded ice ridges and the ice piles at the shore's edge were often covered by a large ice floe which had been bent concave upward (Fig. 4A, B). If the large ice floe extended seaward of the bulk of the ice ridge, the flow was fractured by tidal oscillations or sheared away by other passing ice floes leaving a near vertical seaward edge (Fig. 4C, 8B). If the forces creating the grounded ice ridge stop temporarily and then resume, secondary ridges can be formed at the seaward edge of the first ridge.

The shore ice piles and the grounded ice ridges were both composed of pulverized ice and angular blocks of first year ice of 1 to 2 m thickness (Fig. 3B). Thicker ice blocks were also observed if multi-year ice was incorporated into the ridge during formation, particularly in the grounded ice ridges (Fig. 8C). The thickness of these ice blocks contrasts with the young thin ice in the ice piles described by other authors mentioned earlier. Newly formed ice ridges have a large proportion of inter-block voids. During the summer or melt season the ice blocks become rounded and the voids fill with refrozen melt of snow and ice and the overall relief becomes rounded and the ridge more solidified. The slope of newly formed shore ice piles averaged 37° and ranged from 24° to 62° . The last angle represents the shape of an ice pile which had been eroded and steepened by waves. A shore ice pile which had undergone one month's ablation had 28° to 40° slopes and even older ridges of

TABLE 1. Characteristics of Shore Ice Piles at 'Cape Fisher' (See Figure 6) as Measured on August 27, 1974.

	(A) 1973 Ridges	(B) 1974 Ridges
Date of formation	July 24-27, 1973	July 29-31, 1974
Total volume	3600.6 m^3	594.2 m^3
Length alongshore	340 m	2 sections 156.8 m 36.5 m
Width of ice mounds	15 to 45 m	11 to 19 m
Maximum height above mean high tide level	7.89 m	4.9 m
Maximum distance inland from mean high tide level	60 m	1.9 m
Thickness of ice involved	1 to 2 m	1 to 2 m

one year's melt had slopes of 12° to 17° (Fig. 9). Unfortunately no slopes of grounded ice ridges were obtained. Slopes of new shore ice piles found on Somerset Island were greater than those of grounded pressure ridges found by Kovacs (1976) in the Beaufort Sea. He measured a 30° slope for a grounded multi-year shear ridge and 24° for a grounded first year pressure ridge. He did however observe a slope of 70° for a first-year shear ridge fragment floating in the pack ice.

Occurrence

Based on three years of observations, shore ice ridging occurred most frequently during summer, particularly just after sea ice breakup in Barrow Strait (Table 2). Ice ridging also occurred later in the season when large concentrations of sea ice were blown into Barrow Strait and onto the north Somerset coast by north to north-west winds. This contrasts to the Beaufort Sea examples where the grounded ice ridges normally occur in fall and winter. Along Somerset Island the largest grounded ice ridges and shore ice piles, both in number and magnitude, were built between July 10-13 in 1975 and 1976 as the tide rose to its highest level of the month (Table 3). Wind, as in the kinematic model for floating ridges (Parmerter and Coon, 1972), is assumed to be the main driving force in the movement of sea ice by interacting with the roughness features of the ice surface. In all examples when ice piling occurred, winds did not exceed 15 m/sec (33 mph) which suggests that strong winds are not required for the formation of ice ridges. Shore ice ridging was least frequent during years such as 1974, when lengthy periods of open water existed in Barrow Strait.

Duration

Grounded ice ridges and shore ice piles exist alongshore for a variable length of time (Table 2). The length of time a grounded ice ridge exists depends on: (1) ridge size and shape, (2) presence of large waves, (3) climatic conditions. Grounded ice ridges formed in the nearshore during 1974 and 1975 lasted 10 to 40 days but those formed in 1976 existed beyond the end of the field season, i.e., early September. This was because large concentrations of sea ice along the Somerset coast during August and September 1976

TABLE 2. Duration of Shore Ice Ridges.

LOCATION	DATE OF FORMATION	ICE RIDGES ERODED AWAY BY	TOTAL NO. OF DAYS (APPROX.)
C. FISHER			
(1) 15-60 m inland	July 24-27, 1973	Mid-August 1976	3 years
(2) Beach foreshore	July 29-30, 1974	Late Sept. 1974	45-60 days
(3) Beach nearshore	July 9-12, 1975	Late Aug. 1975	30-40 days
(4) Beach fast ice	July 12-13, 1976	Still present Sept. 1976	over 60 days
CUNNINGHAM	**SHOAL**		
(1) Nearshore	July 29-30, 1974	August 11	10-12 days
(2) "	July 9-12, 1975	Aug. 15-17, 1975	37-38 days
(3) "	July 12-13, 1976	Still present Sept. 1976	over 60 days
'RENNELL'	**BEACH**		
(1) Beach foreshore	July 9-12, 1975	Aug. 17, 1975 (eroded Aug. 8-11)	38 days
(2) " nearshore	July 12-13, 1976	Some by Aug. 2	21 days
(3) Beach foreshore	July 12-13, 1976	Present Sept. 1976	over 60 days

prevented the development of waves and their associated erosion of the ice ridges. Generally the greater the ridge size the longer it lasts, however the shape of the grounded ice ridge is important. For instance, the 30 m high ice ridge (Fig. 5) observed near Cape Rennell lasted less than 30 days because its small base and steep sides made it vulnerable to erosion by waves and pressure from passing ice floes. Waves undercut the ice ridges causing them to collapse and disappear very quickly. The summer climate of Somerset Island varies from year to year and the warmer summers of 1974 and 1975 had a greater effect on the melting of the ice ridges than during the cool summer of 1976 (Taylor, 1977).

The duration of shore ice piles apart from depending on size and climate, also varies with location and sediment cover. Shore ice piles formed within the reach of waves, i.e., at the edge of the icefoot or beach foreshore existed as many as 60 days but like the grounded ice ridges could be eroded much faster given any substantial wave action. For instance, the ice piles formed in

1975 at 'Rennell' beach (Fig. 3) were nearly completely destroyed after three days of moderate wave action (Table 2). In contrast the large ice piles which formed further inland at 'Cape Fisher' remained for three years (Fig. 7, 9). The ablation of the ice piles at 'Cape Fisher' was monitored over the three years using area change between cross-sectional profiles (Fig. 9). Ice melt was greatest in the first two years because of the larger surface area of the ridges and greater initial space between ice blocks. From July to September 1974, the rate of melting was 0.75 m^3 per day and from July 1974 to July 1975, the overall loss of ice was 85 to 94 m^3/m length of ice ridge. Differential ablation of the ice piles resulted because of the variable cover of sediment on the ice. Sediment thickness of over 10 cm appeared to protect the ice from melting. Nevertheless, except for a few isolated ice cored gravel mounds the 1973 ice ridges had disappeared by September 1976 (Fig. 7C).

Shore Ice Piling at 'Cape Fisher'

'Cape Fisher' is a flat low-lying river delta which extends out into Barrow Strait. From 1973 to 1976, four sets of ice piles occurred along the north and west shores. Two were built at the edge of the icefoot and two on land. The most extensive and longest lasting of all observed ice piles was formed 15 to 60 m inland along the northwest corner of the Cape (Fig. 6). These piles of ice were first observed during a flight along the coast on August 10, 1973. It is suggested based on climatic records from Resolute Bay and sea ice data that the ice piles occurred sometime between July 24-27, 1973 (Fig. 2). On July 24, 1973 an 8 km long ice floe (Fig. 2 - outlined by square) struck the western shore of 'Cape Fisher'. In July 1974 a parabolic shaped 'ice-pushed scar' delineated by a continuous line of small ice-pushed gravel ridges outlined the position of the finger of ice which was forced 185 m inland (Fig. 6). The movement of the ice across the beach was facilitated by the presence of an icefoot and the low relief of the backshore. Alestalo and Häikiö (1976) reported a similar ice thrust feature which was forced approximately 94 m inland from mean sea level, along the Gulf of Bothnia, Finland. At the same time that the unbroken finger of ice moved inland a portion of the larger ice floe was breaking and piling into ridges to either side. The ice piles were first surveyed in July 1974 when they extended to a height of 7.8 m (Fig. 9, Table 1). The original height of the 1973 ice ridges is estimated to have been at least 11 m. This height is based upon measurements of average vertical change in ice ridge surface from 1974 to 1975 which was 3.2 to 4.6 m.

At the same time shore ice ridging was occurring elsewhere along Somerset Island during 1974-1976, three shore ice piles occurred at 'Cape Fisher'. Each was more ephemeral than the 1973 ice piles, because of their proximity to the sea. Shore ice piling in July 1974 (Table 1) extended to a height of 4.9 m and by July 1975 only small ice cored gravel ridges and pits remained. On July 10-13, 1975 ice piled to a height of 10 m at the edge of the icefoot at the north end of the Cape. Only in a few localities did fingers of ice reach the beach, penetrating up to approximately 10 m inland. Once again on July 13, 1976, ice piled along the icefoot for a distance of 300 m, and to a height of 9 m (Fig. 8).

TABLE 3. Conditions During Shore Ice Ridge Formation 1974-1976.

Date/yr of shores ice piles	Prevailing wind direction		Mean and Max ( ) wind velocity (m/s)		Tidal Range (m)	Maximum height (m)	
	Cunningham	Resolute Bay	Cunningham	Resolute Bay	(Based on Resolute Bay)	grounded ice ridges	ice piles
1973 July 24-26	No data	WNW-NNW	No data	7(13)	0.5 to 1.6	no data	11
1974 July 29-31	W-NE	NW-N	6(8)	5(13)	0.5 to 1.7	5	9
1975 July 10-13	W-WNW	W-NNW	7(10)	7(15)	0.2 to 2.0	15	15
1976 July 12-13	WNW	NW-WNW	11(15)	7(12)	0.2 to 2.0	30	10

At 'Cape Fisher' winds in late August provided the momentum for the pressuring of sea ice into yet another series of ridges at the seaward edge of the July 1976 ice piles. These new grounded ice ridges were composed of very large multi-year ice blocks (Fig. 8C). The speed with which shore ice piles and grounded ice ridges were built was rapid. For example, in 1976 a grounded ice ridge 12 m high occurred at the edge of the 'Cunningham' shoal sometime between 7 and 11 p.m., less than 4 hours. Brunn and Johannsson (1971) also cite an example where a 5 to 6 m high ice pile occurred in half an hour.

Effects of Shore Ice Ridging on Beach and Nearshore Morphology

Surveys of the nearshore bottom were made in 1975 and 1976 soon after the formation of the grounded ice ridges along 'Rennell' beach and 'Cunningham' shoal. In both areas the bottom was composed of coarse gravel, cobbles and exposures of bedrock. The sea bed around these ice ridges, which were built in water depths of 3 to 5 m, showed an absence of sea ice scouring. Only at the base of the ice ridges were short, shallow — less than 1 m — depressions observed, probably the result of the rubble ice forced into the gravel sea bed during initial phases of ridge building. The apparent lack of disturbance to the nearshore bottom by sea ice as it is compressed into ridges may be a result of the following factors:
(1) the majority of ice blocks incorporated into the ridges are less than 2 m thick, therefore, do not extend to the sea bed;
(2) sea ice ridging over top of grounded sea ice only allows the upthrusting of subsequent ice sheets, therefore a substantial keel is not produced which would gouge the sea bed; (3) the hard coarse nature of the nearshore bottom also inhibits sea ice scouring.

The formation of grounded ice ridges in the nearshore also protects the adjacent shoreline from further sea ice pressure and from waves generated in Barrow Strait. Consequently, changes to beaches sheltered behind these ridges is minimal, for the period the ice ridges exist.

The effects of shore ice piling across the beach were examined in detail at 'Cape Fisher' and 'Rennell' beach. The most obvious effect was the scoring of the beach surface by ice blocks as they were forced landward (Fig. 6). The amount of interaction between ice and beach appeared to depend on the presence of shorefast ice and whether the ground was frozen and snow covered. The presence of shorefast ice enables the ice blocks to override the beach foreshore slope and a frozen or snow covered backshore facilitates the movement of ice further inland. At 'Cape Fisher' ice-pushed gravel ridges were common but few exceeded one metre high. The shore ice piles and ice-push features also disrupted the natural drainage of the land. The net effect to the land after the ice piles had melted was an irregular topography of ice-melt pits and gravel mounds, some ice cored (Fig. 6, 7C).

The effects to the beach and nearshore were surficial, however if inadequately designed shore installations or storage facilities had been located at the sites of ice piling, the effects could have been much greater. For instance it has been shown that sea ice can move at least 20 to 185 m inland

(Fig. 1) and in the process can gouge the landscape. Furthermore the shore ice ridges frequently contain large amounts of ice, the weight of which exerts a considerable vertical force on the ground.

CONCLUSIONS

Detailed field observations of the ice ridges provide basic information required to assess the interaction of sea ice with the northern shoreline of Somerset Island. It can be concluded that shore ice piling and grounded ice ridges can occur each summer particularly at some or all of the six designated areas. However, the magnitude and site of formation of the ice ridges differ from year to year within the six areas.

Grounded ice ridges extend to larger heights than shore ice piles; the former can attain maximum heights of 24 to 30 m whereas the latter only extend to heights of 15 m. Grounded ice ridges and shore ice piles formed within the reach of waves are ephemeral usually existing 10 to 60 days i.e. less than one open water season. In contrast shore ice piles formed further inland can remain for several years depending on their size and the climatic conditions.

The formation of grounded ice ridges and shore ice piles does not require abnormally strong forces, rather ridging can occur during moderate but sustained winds. In all recorded instances of ridge formation, the winds never exceed 15 m/sec (33 mph). It appears that the formation of shore ice ridges is rapid and that ice piles reach their greatest heights when tides are also attaining their maximum level.

Despite the large magnitude of the ice ridges their damage to the coastal environment is surficial. The coarse gravel and rock nearshore bottoms fringing northern Somerset Island, experience only minor disturbance from grounded ice ridges. Across the beaches a ridge and pit topography is left after the scoring by sea ice and the melting of the ice piles. Nevertheless it is suggested that storage depots and man-made structures should not be located on the north and west facing shores of capes of Somerset Island particularly along the six designated areas. 'Cape Fisher' which is less than a kilometre from the proposed pipeline route should especially be avoided. Sea ice can be thrust over 100 m inland across low lying beaches, a fact which is important in planning operations in the coastal zone.

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