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Sea ice scouring on the inner shelf of the southeastern Canadian Beaufort Sea

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Abstract

About 2200 ice scours were observed and analyzed over a distance of approximately 500 km on the inner shelf of the southeastern Canadian Beaufort Sea. Ice scours were divided into two types based on their morphology: multiple scours consisting of a series of parallel scours and ridges, and single scours. Single scours are the dominant type representing more than 85% of the total observations. The mean scour depth and width are 0.3 m and 11 m respectively, but scour depths of more than 2 m and a scour width up to 345 m were documented. The magnitude of ice scouring processes increases with water depth. In water depths less than 10 m, less than 25% of the seafloor surface is reworked by ice scours. This percentage increases significantly seaward of the 10 m isobath, being more than 75% in water depths in excess of 12 m. A break in the seabed slope at about 10 to 12 m water depth marks a boundary between a nearshore zone moderately influenced by ice processes and an outer zone affected by intense ice scouring. This morphological boundary could be due to intense erosion by the keels of pressure ice ridges at the inner edge of a zone of grounded ice ridges. Most of the observed ice scours appear to be reworked, especially in water depths of less than 10 m, and represent small-scale sediment sinks. Inshore of the 10 m isobath, scour reworking is believed to be mainly due to frequent bottom disturbance by wave orbital currents and mean near-bottom flows during the open water season. Scour orientations show that the dominant motion of ice during scouring events is east or west, which is subparallel to the bathymetric contours and coastline. Scour terminal push mounds, however, suggest a dominant east to southeast movement that may contribute to onshore sediment transport during ice push events.

1. Introduction

On arctic continental shelves, sea ice is a significant geologic agent affecting sedimentary processes and the morphology of the seafloor (Barnes and Reimnitz, 1974; Reimnitz and Barnes, 1974; Barnes et al., 1984; Shearer et al., 1986; Lewis and Blasco, 1990; Niedoroda, 1990; Rearic et al., 1990; Blasco et al., 1992). The interaction of dragging ice keels with the seafloor results in the formation of linear scours flanked by parallel ridges, the process of ice scouring leading to disruption of the seabed and sediment remobilization. Most ice scours are believed to form in winter when atmospheric and oceanic energy is absorbed by the ice canopy and transmitted to the seabed by grounded pressure ice ridges (Reimnitz et al., 1978; Barnes et al., 1984, 1987). A variety of terms have been used in the literature for describing the process of seabed disruption by ice keels and the resulting feature: i.e., *ice score* (Kovacs, 1972), *ice plough mark* (Belderson and Wilson, 1973), *ice scour* (Pelletier and Shearer, 1972; Lewis, 1977), and *ice gouge* (Reimnitz and Barnes, 1974; Barnes et al., 1984; Rearic et al., 1990). In this paper, we use the term *ice scouring* for the process of ice interaction with

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the seafloor, and *ice scour* for the seafloor furrow produced by ice motion on the bottom.

The sea ice cover on arctic shelves can be divided into at least three distinct zones, based on ice types, morphology and dynamics (Reimnitz et al., 1978). Near the coast, a relatively stable and flat ice cover, essentially composed of seasonal ice grown in place, forms the floating fast ice zone. This zone commonly contains pressure and shear ridges which form in early winter when new ice is still thin (Cooper, 1974; Shapiro and Barnes, 1989). A belt of grounded ice ridges formed by pressure and shear forces occurs at the seaward edge of the fast ice zone (Zubov, 1945; Kovacs and Mellor, 1974; Barnes et al., 1987). Stringer (1974) used the term "grounded fast ice" and Reimnitz et al. (1978) proposed the Russian term "stamukhi" for describing that zone characterized by large linear grounded ice ridges and hummock fields forming a transition between the floating fast ice zone inshore and the seasonal pack ice farther offshore. The most intense ice scouring occurs in that zone during the development and grounding of the pressure ridges during the first part of the winter (Barnes et al., 1984).

Observations on the inner shelf of the Canadian Beaufort Sea (Fig. 1) showed that the floating fast ice extends seaward to about the 12 m water depth contour (Arctec, 1987; Dickins, 1987). Discontinuous ice ridges, approximately parallel to the coast, are commonly grounded at the seaward margin of the floating fast ice zone where they act as anchor points during winter (Fig. 2). This zone is separated from the mobile polar pack ice by an active shear zone characterized by major ice ridges and variable amounts of open water (Marko, 1975; Dome et al., 1982). The most severe ice scouring on the Canadian Beaufort Shelf have been documented in that zone, in water depths between 20 and 30 m (Shearer et al., 1986; Lewis and Blasco, 1990; Hill et al., 1991), although ice may scour the seabed in deeper water (Blasco et al., 1992). Once grounded ice ridges have stabilized the fast ice zone, they constitute a partial obstacle for the onshore movement of drifting ice, thus restricting ice scouring in shallower water. Ice scouring is also possible within the floating fast ice zone, but it occurs during break-up and freeze-up when considerable ice may be present and in motion (Arctec, 1987; Shapiro and Barnes, 1989).

Several surveys have been carried out in the Canadian Beaufort Sea to document ice scours over the continental shelf (Pelletier and Shearer, 1972; Shearer and Blasco, 1975; Lewis, 1977; Hnatiuk and Brown, 1977; Shearer et al., 1986; Gilbert and Pedersen, 1987; Lewis and Blasco, 1990; Blasco et al., 1992). Most of these studies, however, were focused on ice scouring on the middle shelf, in water depths of more than 20 m, and the inner shelf has received less attention. There is very limited data available, at present, on ice scouring processes in water depths of less than 20 m in the Canadian Beaufort Sea, except for a few observations documented in studies concerning inner shelf/shoreface sedimentary processes (Hill et al., 1986; Hequette and Barnes, 1990). The aim of this paper is to (1) document the morphological characteristics of the ice scours, (2) examine the ice scouring regime, (3) and discuss the potential effects of ice scouring on sediment transport on the inner shelf of the southeastern Canadian Beaufort Sea, seaward of the Tuktoyaktuk Peninsula (Fig. 1).

2. Materials and methods

The data used in this study consist of bathymetry profiles, sonographs and seafloor sediment samples. Bathymetry was obtained using a 200 kHz echosounder with ± 10 cm precision. The sonographs were obtained with a 100 kHz and 500 kHz sidescan sonar system capable of resolving features of 10 cm relief. A precision range–range navigation system was used, providing accurate positioning to about 10 m. More than 500 km of acoustic profiles were obtained across the inner shelf to about 18 m water depth. The vessel trackline spacing varies from approximately 10 to 20 km (Fig. 1). The survey tracklines, sonographs and bathymetry profiles were divided into 1 km segments for analysis.

The frequency of ice scouring can be evaluated by repetitive surveys over several years (Barnes and Rearic, 1985; Shearer et al., 1986; Blasco et al.,

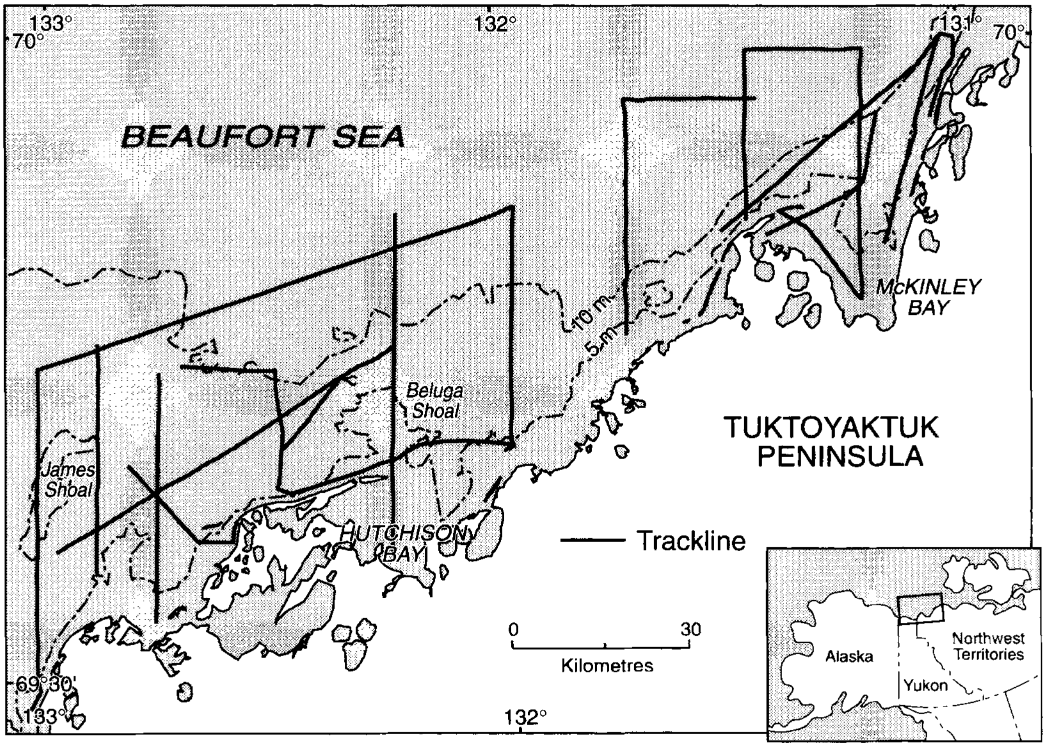

Fig. 1. Location map of the study area showing the sidescan sonar and echosounder tracklines.

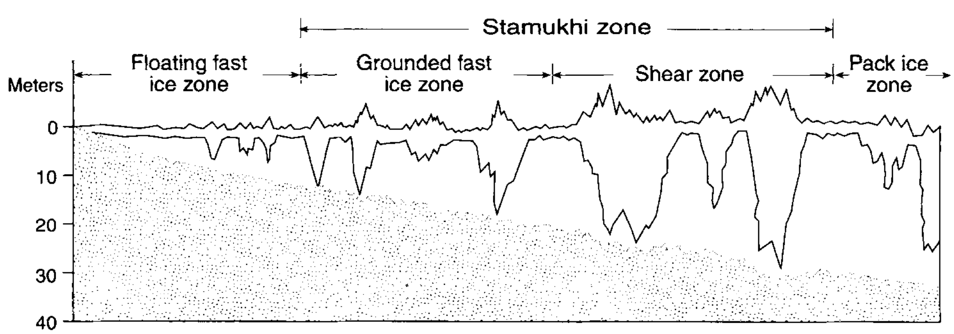

Fig. 2. Idealized sketch of the inner and middle shelf of the eastern Canadian Beaufort Sea showing ice zonation and terminology used in the text.

1992). The data used in this study were collected during one summer survey, so the frequency of ice scouring could not be determined. The spatial distribution of ice scours, and the analysis of their characteristics, can be used, however, to assess the importance of ice/seafloor interaction on the continental shelf. Severity of ice scouring processes is reflected in the size, shape and density of ice contacts with the bottom. For each scour observed, the scour depth and ridge height were measured relatively to the mean surface of the surrounding seafloor, using the 200 kHz echosounder records (Fig. 3). The maximum scour depth and maximum ridge height were also determined for each 1 km segment using the sonographs and fathograms. Scour width was measured on sonographs (Fig. 3).

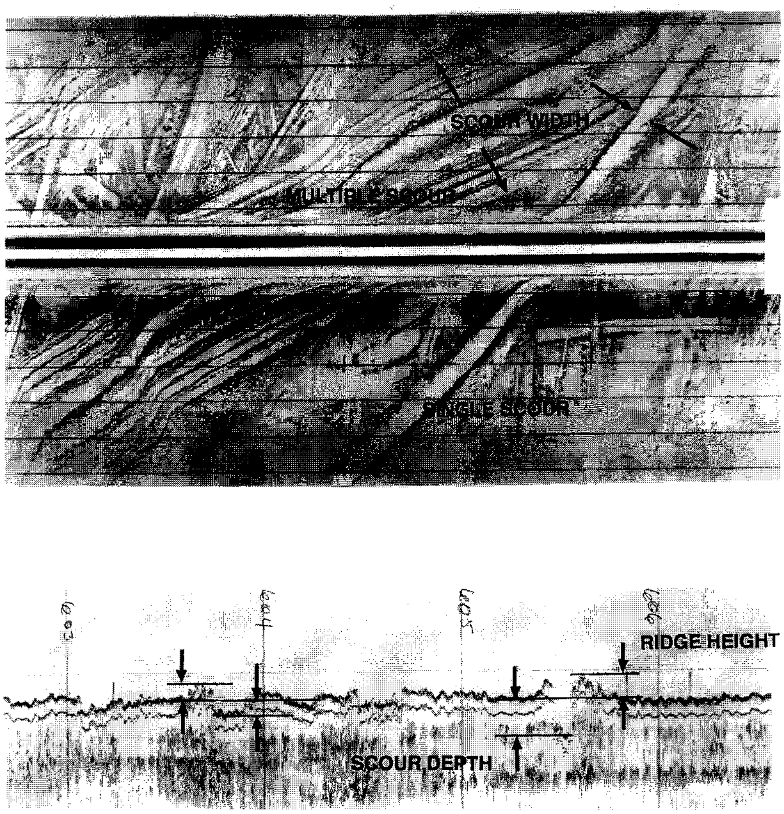

Fig. 3. Fathogram and sonograph showing single and multiple ice scours in 17.5 m water depth. The parameters measured to quantify ice scour characteristics are also shown.

Nearly 2200 ice scours have been observed and measured in this study.

The total number of ice scours was counted for each 1 kilometre segment in order to quantify the scouring density (number/km). Sonographs were also used to estimate the percentage of seafloor surface disturbed by sea ice scouring. This percentage was calculated as the proportion of surface area of seabed disturbed by ice scouring. 4 classes of seafloor disturbance were distinguished: <5%, 5–25%, 25–75%, >75%. The angular orientation of linear ice scours was determined on the sonographs as a bi-directional line relatively to the survey trackline (Fig. 4) and subsequently, relative to geographic north. When an ice scour was terminated by a push mound, the direction of the ice movement responsible for the generation of the scour could also be defined.

We differentiate non-reworked, moderately and strongly reworked scours (Fig. 5), this classification being based on the surface appearance of the scours on the sonographs and on their shape in cross-section on the fathograms. Non-reworked scours represent "fresh" ice scours that show little evidence of reworking by waves and currents. Moderately reworked scours refer to scours that underwent some reworking but whose shape is still clearly visible on both sonographs and fathograms. Strongly reworked scours are features that can still be distinguished on the sonographs but whose relief is greatly subdued or almost completely erased. This classification has no time-scale connotation, because an ice scour will be rapidly reworked by energetic hydraulic processes in shallow water compared to an ice scour formed in deeper water, all other things being equal.

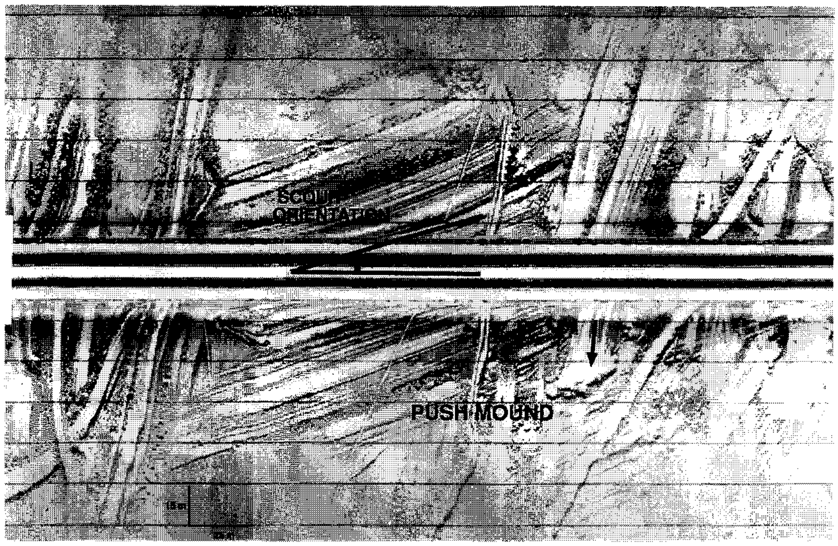

Fig. 4. Sonograph showing ice scours and a terminal push mound in 14.5 m water depth. When an ice scour is terminated by a push mound, the direction of ice movement can be determined.

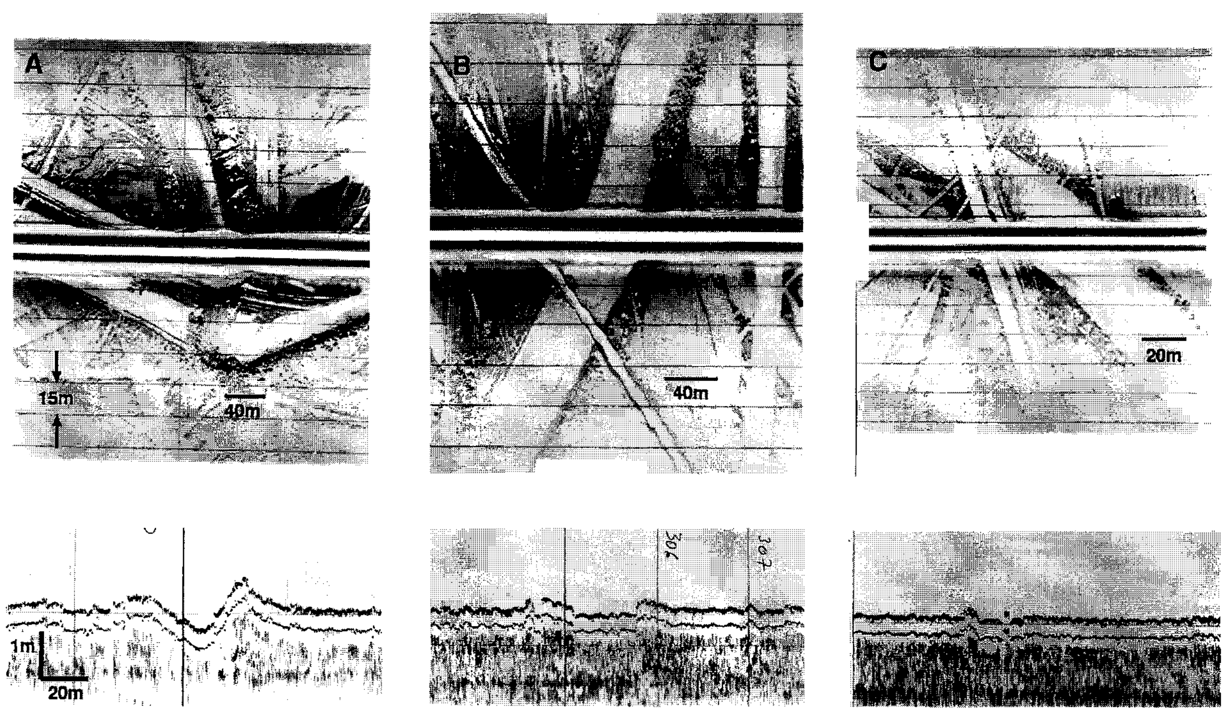

Fig. 5. Sonographs and fathograms showing examples of (A) non-reworked scours (15.0 m water depth), (B) moderately reworked scours (12.8 m water depth) and (C) strongly reworked scours (15.6 m water depth).

Therefore, this classification is an indication of the magnitude of the processes that effectively contributed to rework the ice scours.

3. Physical setting

The Canadian Beaufort Shelf is located in a large embayment between the Alaskan peninsula and the islands of the Canadian Arctic archipelago (Fig. 1). The eastern Beaufort shelf, east of the Mackenzie Delta, extends offshore to approximately 80 m water depth and is characterized by a very low gradient on the order of 1 : 2000. Several shallow shoals occur on the inner shelf, such as Beluga Shoal and James Shoal in the study area (Fig. 1).

Over most of the shelf a sequence of several hundred metres of Pleistocene outwash sand and marine mud is overlain by a variable thickness of Holocene marine deposits (Hequette and Hill, 1989; Blasco et al., 1990). The Holocene sediments essentially consist of interbedded sand and silt that were deposited under transgressive conditions (Hequette et al., 1995). The Holocene transgression in this region represented a relative sea-level rise of about 70 m (Hill et al., 1985). Landward of the 10 m isobath, bottom sediment generally consists of sands (Vilks et al., 1979), except for the embayments dominated by silts and silty-clays. In water depths of more than 10 m, the seafloor is covered by silty-clay sediments, mainly derived from the Mackenzie River (Harper and Penland, 1982; Hill et al., 1991). Sonographs and seafloor sediment samples were used for mapping bottom sediment distribution on the inner shelf in the study area (Fig. 6).

The Canadian Beaufort Sea is covered by sea ice for nearly 9 months of an average year (Fissel and Birch, 1984). The fast ice generally begins to form along the coast in October. During the freeze-up season, pressure and shear ridges develop at

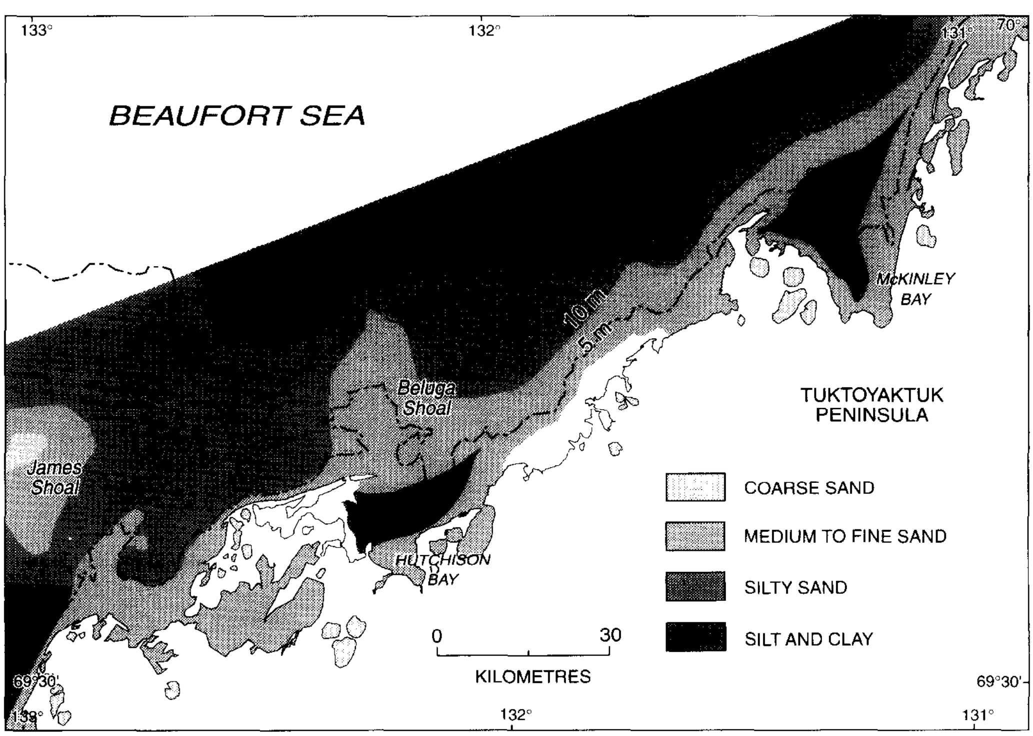

Fig. 6. Distribution of bottom sediment texture based on sonograph interpretation and seafloor sediment samples collected in this study.

the seaward edge of the fast ice zone which gradually grows seaward, reaching its maximum extent in December or January. The winter season is characterized by stable fast ice from January to July (Dome et al., 1982). The break-up season along the coast of the Tuktoyaktuk Peninsula usually occurs in early- to mid-July and corresponds to a rapid deterioration of the fast ice cover. During the open water season, wave energy is limited by the fetch-restricting pack-ice. Nearly 80% of the deep-water waves are less than 1 m high (Harper and Penland, 1982), and consequently the Canadian Beaufort Sea is considered a low to moderate wave-energy environment. During storms, significant wave heights are concentrated in the 1–2 m class, but can reach 4 to 5 m during the most severe events (Murray and Maes, 1986). The Canadian Beaufort Sea is microtidal with a spring tide range of 0.5 m.

4. Results

4.1. Morphological characteristics of ice scours

Two main types of ice scours were distinguished on the inner shelf, based on their morphology: single scours which consist of an individual linear furrow flanked by a ridge on each side, and multiple scours formed by a series of parallel scours and ridges generated during one scouring event (Fig. 3).

Single scours are the dominant type as they represent more than 85% of the total observations. Measurements of scour depth, ridge height and scour width show a large variability in the data. The width of single scours ranges generally from 2 to 8 m, but some scours can be more than 40 m wide (Fig. 7). Most of the scours of this type have a depth of less than 60 cm (Fig. 8). Although a maximum scour depth of 2.2 m deep was recorded (Table 1), single scours are rarely deeper than 1 m. The ridge heights show a similar frequency distribution, generally ranging from 20 to 50 cm (Fig. 8). The maximum ridge height observed was 1.8 m.

Multiple scours differ from single scours in several ways as the measurements of the same

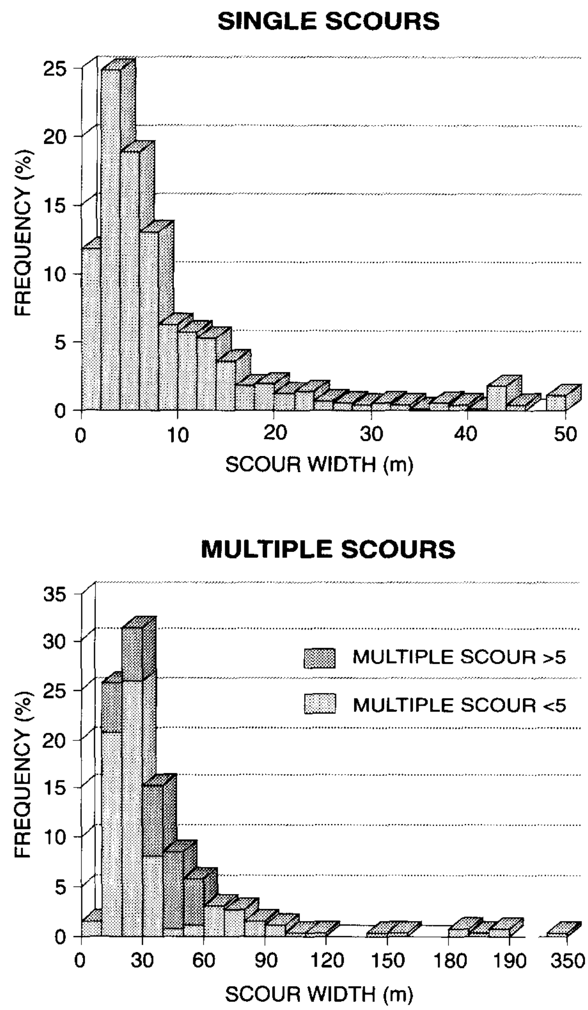

Fig. 7. Histograms of scour width for single and multiple scours.

morphologic parameters show. As expected, multiple scours are much wider, most of them being 10 to 40 m wide (Fig. 7). Based on the number of individual furrows within a multiple scour, two kinds of multiple scours were distinguished: scours formed of 5 parallel furrows or less, and scours of more than 5 furrows (up to 40 furrows). Multiple scours of less than 5 furrows have an average width of 14 m. The scours formed of more than 5 furrows are considerably wider (Fig. 7), averaging approximately 45 m. The widest multiple scour observed was 345 m wide.

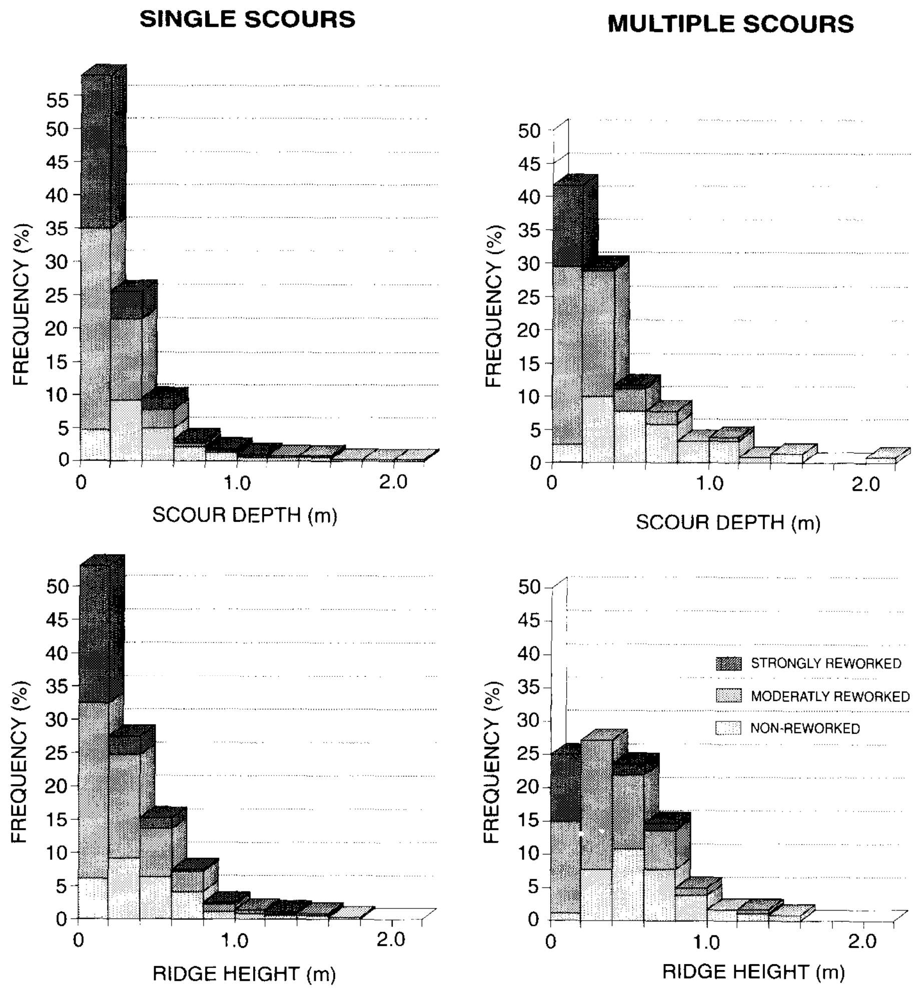

Fig. 8. Histograms of scour depth and ridge height for single and multiple scours.

Table 1
Variation in ice scour characteristics across the Canadian Beaufort Shelf (from Blasco et al., 1992, and this study)

	0–18 m (this study)	0–20 m (from Blasco et al., 1992)	20–40 m	>40 m
Mean scour depth	0.3 m	0.8 m	1.0 m	1.1 m
Maximum scour depth	2.2 m	3.0 m	5.0 m	6.0 m
Mean scour width	11 m	19 m	30 m	30 m
Maximum scour width	345 m	1375 m	1010 m	625 m
Orientation mode	98°	125°	116°	116°

Multiple scours generally show more relief than single scours, a slightly higher proportion of multiple scours reaching a depth of 50 cm or more compared to single scours (Fig. 8). Multiple scours are also characterized by a significantly higher ridge height compared to single scours. The ridge height of multiple scours is mainly in the range of 20 to 80 cm while the ridge height of single ridges rarely exceeds 60 cm.

The morphologic differences between single and multiple scours are more clearly distinguishable when non-reworked scours only are analyzed. Non-reworked scours represent virtually intact scours formed by ice action only, thus essentially reflecting ice/bottom interactions. Fig. 8 shows that the relief of both single and multiple scours is greater for non-reworked scours compared to the moderately reworked and strongly reworked scours. This is even clearer in the case of multiple scours that rarely show a maximum scour depth or a maximum ridge height of less than 20 cm for non-reworked scours while these values are common for reworked scours.

Assuming that most of the sediment bulldozed by an ice keel is extruded from the furrow with half of the debris deposited on either side, the expected ratio of ridge height versus scour depth would be of 1:2. According to our observations the ratio is closer to 1:1 (Fig. 9), showing that the ridge height is approximately equal to the scour depth. Barnes et al. (1984) found a similar ratio between ridge height and scour depth for scours less than 1 m deep on the Alaskan Beaufort shelf, a dimension corresponding to most of the ice scours analyzed in this study.

The analysis of the morphology of moderately reworked and strongly reworked scours provide some insights to the sedimentary processes that contribute to rework these features when affecting the inner shelf floor. When moderately reworked and strongly reworked ridges are considered, the ridge height/scour depth ratio is slightly higher,

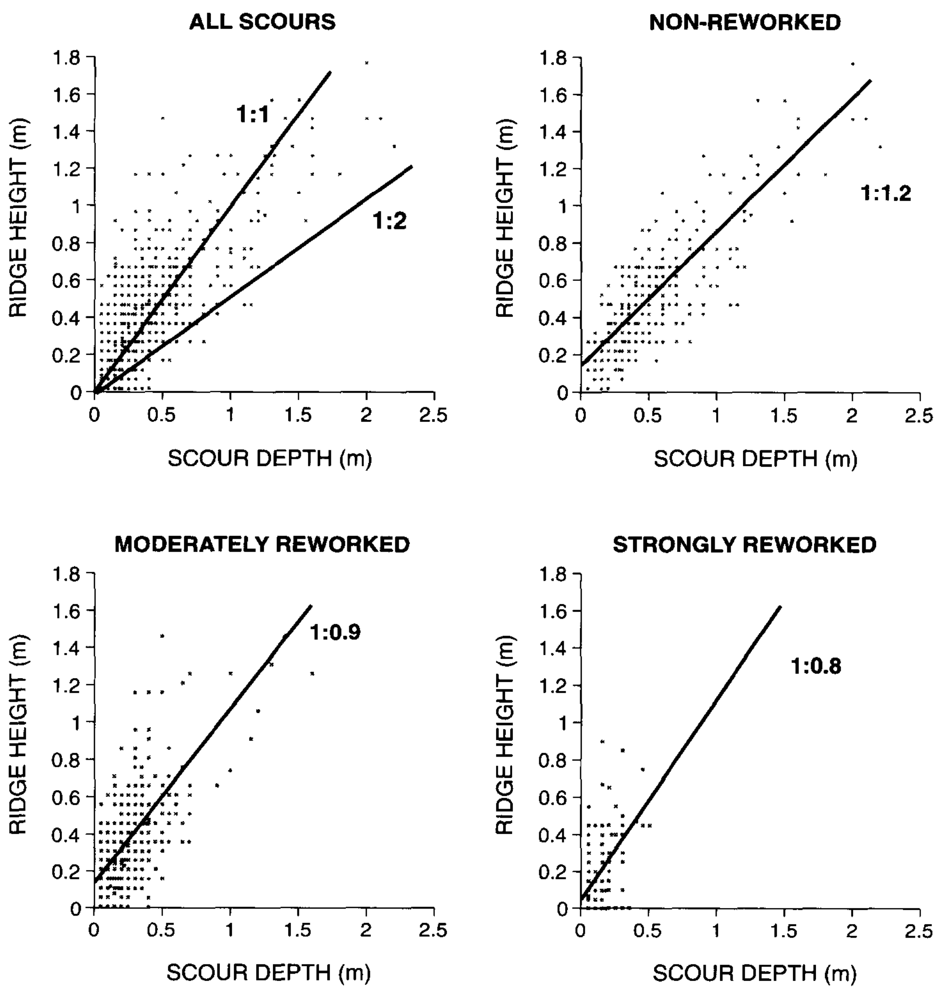

Fig. 9. Relationship between scour depth and adjacent ridge height.

averaging 1:0.9 and 1:0.8, respectively (Fig. 9). This suggests that the ice scours are mainly modified by sediment deposition in the troughs contributing to scour infilling while the ridges are partially preserved. Those numbers, however, do not reflect the variations with water depth, as in shallow depths, ridges are commonly flattened due to the action of currents.

In order to consider the effects of ice action only on the morphology of the ice scours, non-reworked scours were also analyzed separately. The analysis of non-reworked scours shows that the ratio is 1:1.2, so other processes are also required to explain this ratio as these scours were affected by limited sediment infilling. It is possible that the material piled in the flanking ridges occupies a larger volume due to a reduced compaction induced by ice bulldozing. In situ shear strength measurements on sediments in furrows and flanking ridges of ice scours in the Canadian Arctic Archipelago showed that ridge material is less compact than the material found in the trough (McLaren, 1982).

4.2. *Effects of bathymetry on ice scouring processes*

On the shoreface and inner shelf, the percentage of seabed disturbed by ice scouring increases with water depth (Fig. 10). The zone located between 10 to 12 m water depth seems to represent a transition zone between an outer area affected by more intense ice scouring and a shallower inner shelf–shoreface area characterized by limited ice action at the seabed. In water depths less than 10 m, less than 25% of the seafloor surface is generally reworked by ice scours, but this percentage increases significantly seaward of the 10 m isobath (Fig. 10). In water depths of 12 to 18 m, the sonographs show that more than 75% of the seabed is typically reworked by ice scours (see Figs. 3 and 4 for examples of severely disturbed seabed in 17.5 and 14.5 m water depths).

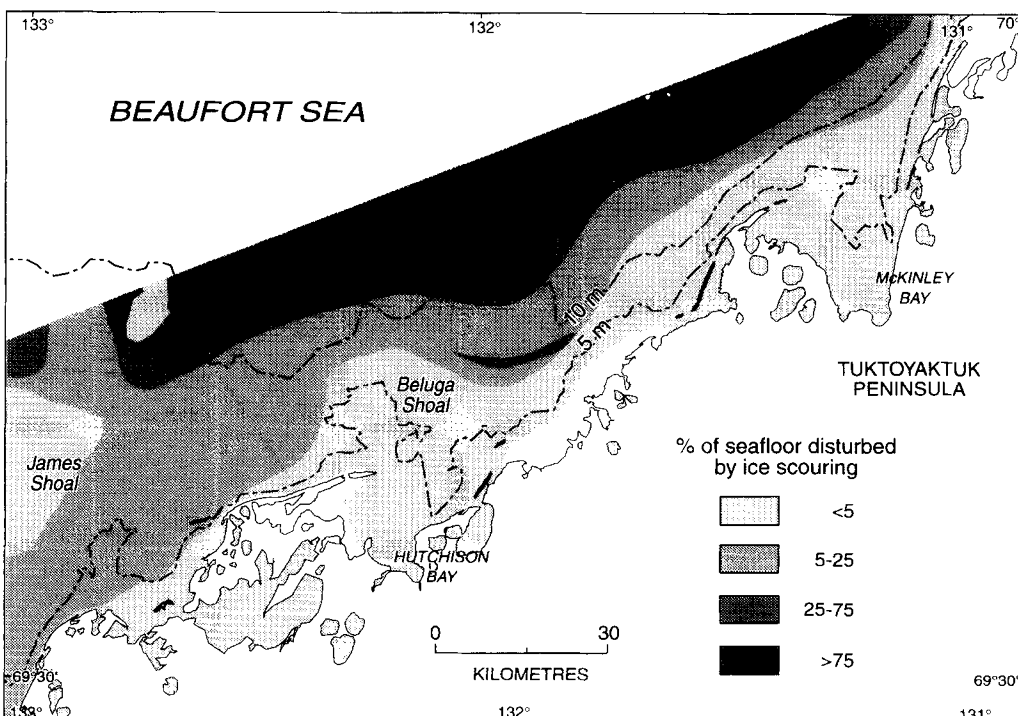

Fig. 10. Map showing the percentage of seabed disruption by ice scouring.

Scour dimensions also increase with increasing water depth (Fig. 11). Scours of all dimensions can be found in water depths of more than 10 m, the depth of individual furrows ranging from 0.2 to more than 1.5 m, but ice scours having a depth of more than 2 m occur only in water depths in excess of 14 m. Conversely, scour depth was always less than 1.0 m in water depths shallower than 10 m. Ridge height shows the same relationship with water depth. When single scours are analyzed, for example, a minimum water depth of 12 m is necessary for the generation of ridges higher than 1.5 m (Fig. 11). In comparison, ridge height is usually less than 0.5 m in water depths less than 10 m. The increase in scour dimensions with water depth is obvious when the maximum ridge height and maximum scour depth for each 1 km segment are plotted above cross-shelf profiles (Fig. 12). As shown on lines 12 and 46, maximum ridge heights and scour depths tend to increase with water depth (Fig. 12).

Scour density is also higher in deeper water. Profiles 12 and 46 (Fig. 12) show that the number of scours per kilometre increases significantly seaward. On profile 46, for example, scour density generally ranges from 20 to 40 scours km^{-1} in

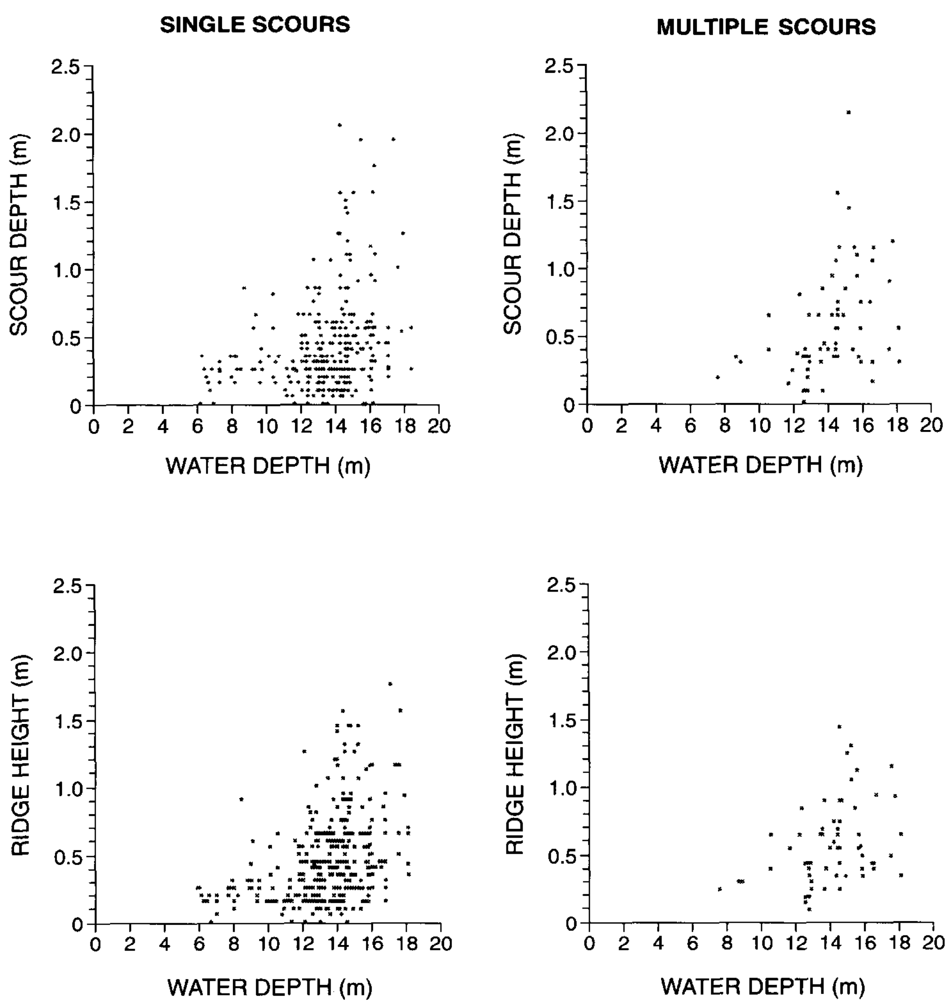

Fig. 11. Scour depth and ridge height as a function of water depth for single and multiple scours.

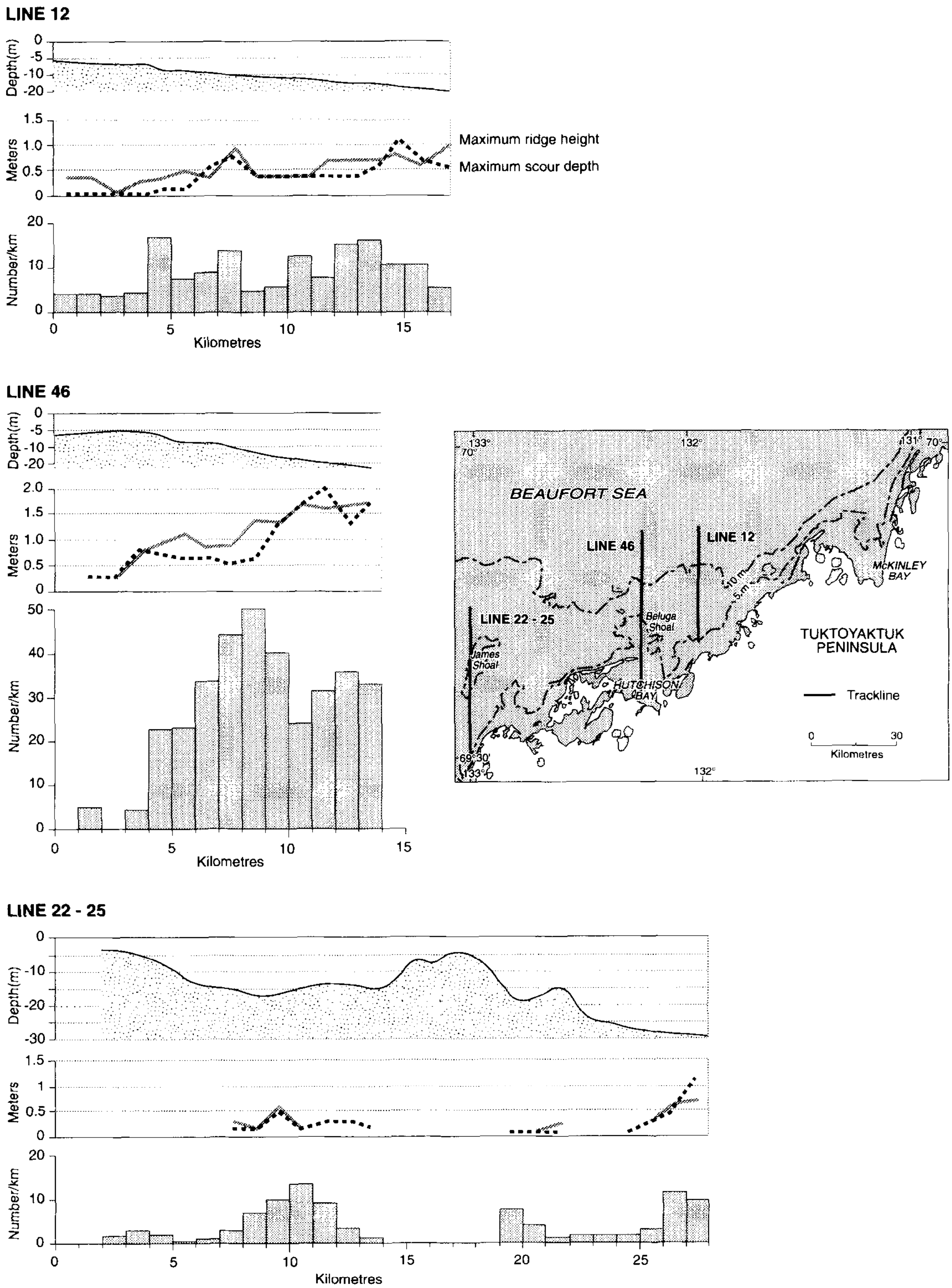

Fig. 12. Selected tracklines across the inner shelf showing the relationship between bathymetry, scour density, maximum scour depth and maximum ridge height per 1 km segment.

water depths of more than 10 m, while in less than 10 m water depth only a few scours were observed. The limit between the deeper, more intensely scoured seabed, and the shallower less disrupted seafloor seems to correspond to a major break in slope at about 10 to 12 m water depth (Fig. 12, lines 12 and 46). This geomorphic feature at the seabed, which occurs all along the inner shelf seaward of the Tuktoyaktuk Peninsula, also corresponds to a boundary in seabed sediment distribution between nearshore and shoreface sand and shelf mud (Fig. 6).

Several shallow shoals play also a role on the inner shelf ice scouring regime. These shoals that typically occur at a few metres below sea level show limited or no sign of ice scouring on their crest (Fig. 12, line 22–25). Over James Shoal, for example, less than 5% of the seabed is reworked by ice scours (Fig. 10). Once grounded ice ridges are formed offshore, they limit the development of ice ridges landward and tend to protect the shoals from ice scouring. The fact that ice scours were observed shoreward of the shoals, however, suggest that some scours are probably formed on the shoals but are rapidly reworked by intense near-bottom wave orbital currents at these shallow depths. The occurrence of megaripples on these shoals support this interpretation. Conversely, shoals on the inner shelf of the Alaskan Beaufort Sea are characterized by a significant increase in the number of ice scours on their crest compared to the surrounding areas (Reimnitz and Kempema, 1984; Rearic et al., 1990). The absence of ice scours on inner shelf–shoreface shoals in the southeastern Canadian Beaufort Sea is due to very rapid wave and current reworking in shallow water depths while the shoals of the Alaskan Beaufort Sea are located in water depths of more than 10 m where larger scours are generated and waves and currents are less intense.

4.3. *Ice scour orientations and directions*

Ice scour orientations and directions provide information on the direction of ice movements responsible for seabed scouring, and therefore on ice-induced sediment transport. It is important to note, however, that the direction of sediment bulldozing by an ice keel can only be determined by the observation of a scour terminal mound. Ice-scour orientations only indicate a trend of ice motion and cannot define the actual ice-scouring direction along that trend.

The scour orientations show that the dominant motion of ice during scouring events is east or west, which is subparallel to the bathymetric contours and the coastline (Fig. 13). The distribution of ice scour orientations is generally unimodal or bimodal in the shallower areas (<10 m water depths) while the distribution is more variable as water depth increases. Even in water depths of more than 10 m, the E–W component still represents a major proportion of the observations. Ice scour movement, as determined by terminal mounds of pushed sediment at the extremity of ice scours, indicated that ice keels primarily move obliquely onshore, ranging from south to east-southeast (Fig. 13). The east-southeast component is the major directional component and shows a good correlation with the total distribution of ice scour orientations. This suggests that ice motion on the inner shelf and shoreface is mainly directed to the east-southeast, obliquely to the general bathymetric contours.

Single and multiple scours show a slightly different distribution of orientations (Fig. 14). Single scours are mainly oriented E–W (96°), but the orientations of multiple scours are predominantly NW–SE (115°). Based on the observed terminal mounds, one can assume that the ice motions responsible for the generation of the multiple scours were directed southeastward. This would indicate that the movement of multi-keel ice ridges is more strongly directed onshore compared to single ice keels. It is possible that the most prominent keel of a multi-keel ice ridge acts as a pivot during scouring when the keels advance in shallow water. As the keels move obliquely shoreward and upslope, more plowing resistance is met by the deeper-draft ice keel, resulting in an increasing onshore component of motion.

5. Discussion

A major proportion of the ice scours observed on the inner shelf of the southeastern Canadian

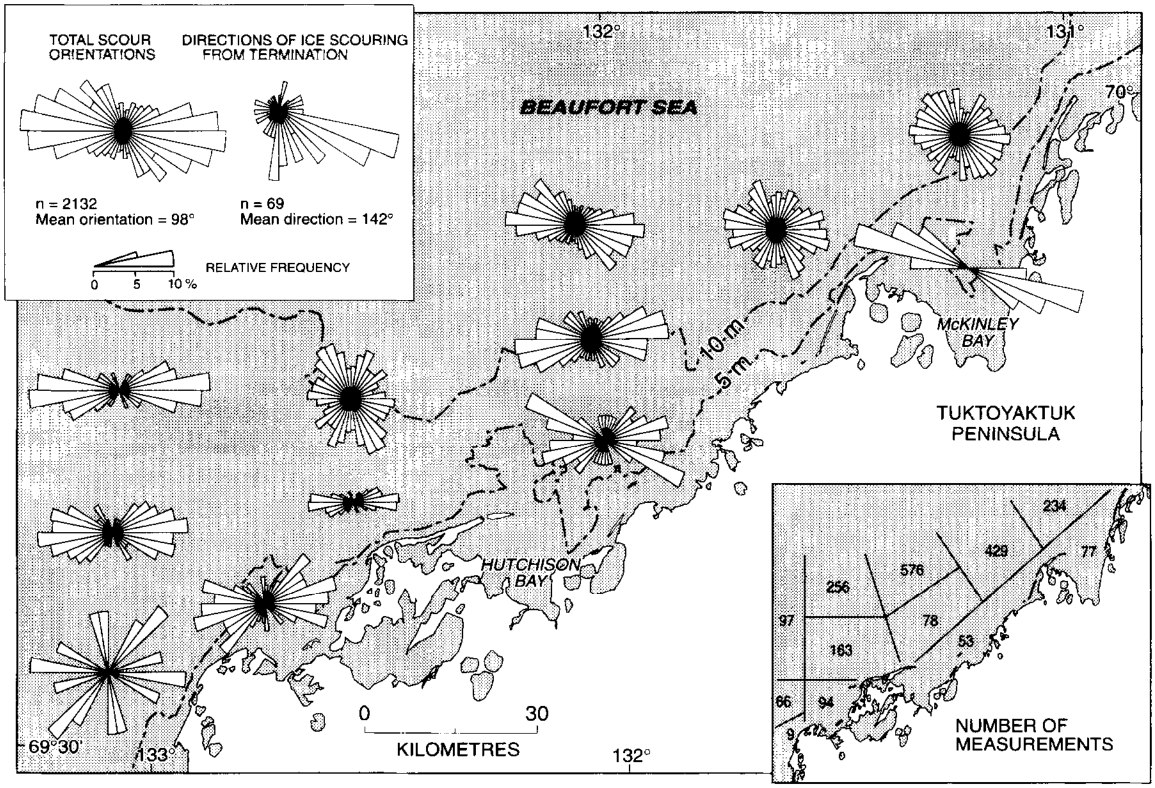

Fig. 13. Map showing rose diagrams of ice scour orientations (by sectors) and orientations and directions for total observations. Directions based on scour terminal push mounds.

Beaufort Sea occur at water depths of more than 10 m (Figs. 10 and 11). The seabed appears to be more often and more severely scoured by ice keels between 10 and 20 m water depths. The numerous and sometimes deep scours observed in that zone are probably due to the action of large pressure and shear ridges formed of first-year and multi-year ice that generally develop seaward of the floating fast ice zone (Fig. 15) (Reimnitz et al., 1978; Arctec, 1987). In comparison, the smaller first-year ice ridges of the floating fast ice zone would form less and shallower scours. A break in the seabed slope at about 10 to 12 m water depth (Fig. 12) marks a boundary between a nearshore zone moderately influenced by ice scouring and an outer zone where the seafloor is severely reworked by ice scours. It is possible that this morphological boundary could be due to more intense ice erosion seaward of the boundary compared to the adjacent shallower areas. Barnes et al. (1987) reported a break in slope on the inner shelf of the Alaskan Beaufort Sea at about 20 m depth which was ascribed to ice-related processes at the inner edge of the stamukhi zone. If the break in slope observed on the inner shelf of the Canadian Beaufort Sea has a similar origin, it would correspond to the inner edge of the grounded ice ridges of a stamukhi zone in the southeastern Beaufort Sea. Alternatively, the break in slope may be related to a former shoreline at a lower stand of sea level or even reflect antecedent pre-Holocene topography.

Most of the observed scours appear moderately reworked or strongly reworked (Fig. 8). This suggests that ice scours in this region are rapidly reworked and that they represent small-scale sediment sinks for the material in transit in the inner shelf/shoreface area. As suggested by Barnes and

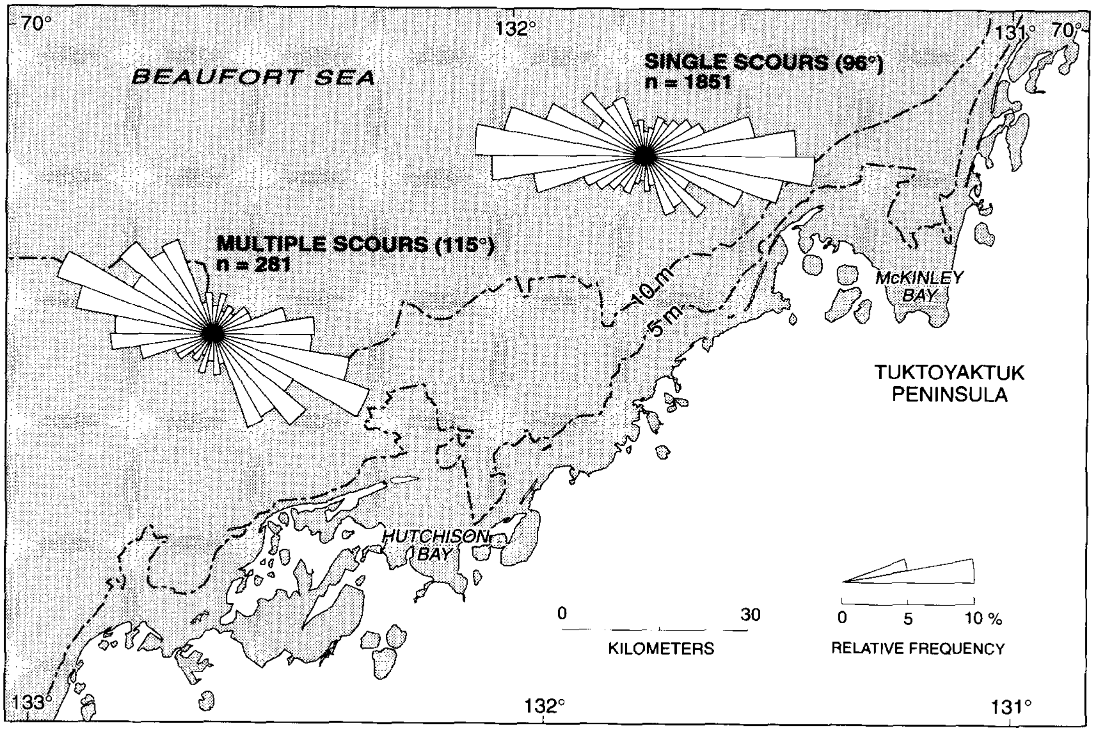

Fig. 14. Rose diagram of scour orientations for single and multiple scours.

Reimnitz (1979) and Barnes et al. (1984), the reworking and infilling of scours can be due to the vertical settling from suspension, to the lateral movement of material from bedload transport in response to near-bottom currents, and to the bulldozing action of ice keels. The respective importance of each of these processes seems to vary with water depth as shown by the morphology of the reworked ice scours.

Ice scours generally show a different morphology whether they are located landward or offshore of the 10 m isobath. In deeper water, moderately reworked scours typically show a partially infilled furrow while the flanking ridges are often partially preserved (Fig. 15B). This scour morphology suggests that in such depths scour obliteration is dominated by the deposition of fine-grained sediment transported in suspension from the Mackenzie River and from sediment remobilized during scouring events. In shallower water, however, reworked scours are still visible on sonograph but are commonly very difficult or impossible to distinguish on echosounder records because they have vertical relief of less than 10 cm. The furrows are infilled with sediment and the ridges are largely or completely eroded (Fig. 15A). This shows that, in shallow water, the morphology of ice scours is not only modified by depositional processes, but also by near-bottom currents which rework and eventually erode the flanking ridges.

During the open water season, mean near-bottom currents and oscillatory flows associated with surface gravity waves represent significant sources of bottom sediment remobilization in water depths of less than 10 m (Hodgins et al., 1986; Hequette and Hill, 1993). According to a wave hindcast model and calculations of orbital threshold velocity, Harper and Penland (1982) concluded that, even between 10 and 20 m water depths, the seabed is disturbed by wave orbital currents up to 10% of the time. Due to more frequent bottom disturbance by wave orbital currents in shallow water, the preservation potential of ice scours is also less in shallow depths. In

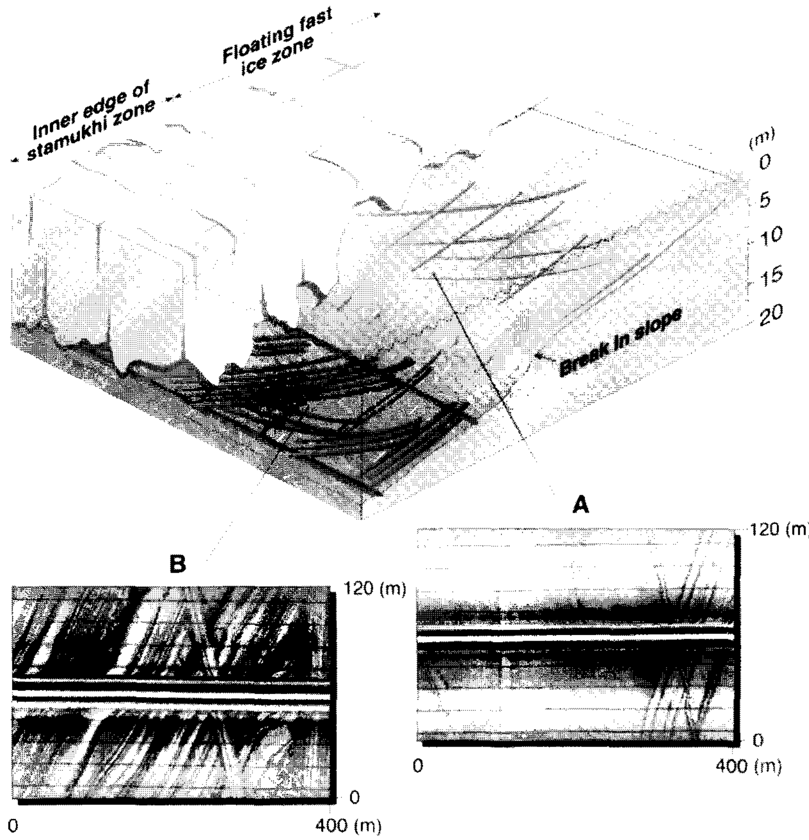

Fig. 15. Schematic block diagram of the inner shelf and nearshore zone in the southeastern Canadian Beaufort Sea, showing the cross-shelf zonation of ice scour processes at the seafloor based on sidescan sonar and echosounder records. Insets show typical examples of seabed: (A) seabed representative of the floating fast ice zone showing strongly reworked scours with infilled furrow and partially eroded ridges in 11 m water depth; (B) seabed representative of the inner edge of the stamukhi zone showing a high density of non-reworked and moderately reworked scours in 14.2 m water depth.

addition, sand which is not favorable to the preservation of ice scours (Reimnitz et al., 1978) dominates in the nearshore zone while seaward of the 10 m isobath the seafloor consists of finer grained, more cohesive, sediment (Fig. 6).

Ice scour orientations show that most scouring on the inner shelf of the southeastern Canadian Beaufort Sea has a bi-directional E–W trend which is oblique to the bathymetry (Fig. 13). Scour terminations, however, suggest that ice motion responsible for ice scouring mainly occurs unidirectionally eastward to southeastward, which correlates with the orientation data, but with a more pronounced southward or onshore component. These observations are in agreement with the results of Shapiro and Barnes (1989) and Rearic et al. (1990) who also found a strong onshore component of ice motion in the nearshore zone of Alaska, in water depths of less than 20 m.

As shown by wind data from Tuktoyaktuk, which are the most appropriate for application to the eastern Canadian Beaufort Sea (Fissel and Birch, 1984), the wind regime in the area is dominated by northwesterly storms, virtually all winds with speeds in excess of 40 km h^{-1} being from that direction (Harper and Penland, 1982). The frequency of occurrence and magnitude of northwesterly and westerly storms increase during the autumn and early winter months (Fissel and Birch, 1984). Our ice scour termination data suggest that early winter storms represent a significant forcing mechanism inducing eastward and southeastward ice motion during freeze-up while ice ridges develop. Based on scour terminations and storm wind directions, Rearic et al. (1990) also suggested that storms may be responsible for onshore ice scouring in shallow (<15 m) water depths of the Alaskan Beaufort Sea. Large ice movements leading to the formation of pressure ice ridges in the fast ice zone can occur as late as February under sustained storm winds (Spedding, 1983).

During ice scouring, bottom sediment is transported away from the scour by several processes. Fine-grained material may be placed in suspension by the dragging ice keel and transported by near-bottom currents intensified by the presence of the ice keel (Barnes et al., 1987). The transport directions of resuspended sediment may be extremely variable depending on the current direction at the time of scouring. When an ice keel scours the seabed, sediments of all grain sizes are bulldozed and extruded to the side, perpendicular to ice motion, forming a flanking ridge. Sediment is also transported in the direction of ice motion, forming a push mound at the termination of the scour when the ice keel ceases its movement. Scour terminations show that ice scouring is responsible for an onshore component of sediment transport through bulldozing of the seabed. This is consistent with several other studies suggesting that sea ice supplies shelf sediments to the coastal zone in high-latitude regions (Barnes, 1982; McLaren, 1982; Barnes et al., 1988; Shapiro and Barnes, 1989; Hequette and Barnes, 1990; Rearic et al., 1990; Reimnitz et al., 1990).

6. Conclusions

(1) Two types of ice scours can be distinguished based on their morphology: multiple scours formed by a series of parallel scours and ridges, and single scours which are the dominant type as they represent more than 85% of the total observations. Most ice scours have a depth of less than 60 cm, but a maximum scour depth of 2.2 m deep was observed.

(2) The percentage of seafloor disrupted by ice scouring increases with water depth. In water depths less than 10 m, less than 25% of the seafloor surface is reworked by ice scours, but this percentage increases significantly seaward of the 10 m isobath, being more than 75% in water depths in excess of 12 m. Scour dimensions also increase with increasing water depth, ice scours having a depth of more than 2 m occurred only in water depths of more than 14 m.

(3) A break in the seabed slope at about 10 to 12 m water depth marks a boundary between a nearshore zone moderately influenced by ice processes and an outer zone affected by intense ice scouring. It is possible that this morphological boundary could be due to more intense ice erosion at the inner edge of a stamukhi zone of grounded ice ridges.

(4) Most ice scours on the inner shelf of the southeastern Canadian Beaufort Sea are probably rapidly reworked and represent small-scale sediment sinks. Seaward of the 10 m isobath, reworked scours typically show a partially infilled furrow while the flanking ridges are often partially preserved, showing that scours are dominated by the deposition of suspended fine-grained sediment. In shallower water, reworked scours are infilled, but the ridges are largely or completely eroded due to the frequent bottom disturbance by wave orbital currents and mean near-bottom flows during the open water season.

(5) Scour orientations show that the dominant motion of ice during scouring events is east or west, which is subparallel to the bathymetric contours. Scour terminations, however, show that ice push events are primarily directed obliquely onshore, suggesting that ice scouring is a process contributing to onshore sediment transport.

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