

ATTACHMENT F

ICE GOUGING CHARACTERISTICS AND PROCESSES

by

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1. INTRODUCTION

over much of the Arctic Shelf, scouring of the seafloor by ice disrupts and modifies the seabed, affecting seabed sediments, ice **zonation**, and petroleum development activities. Scouring occurs where sea ice comes into contact with the seafloor to form ice gouges. As sediments are disrupted, atmospheric and oceanic energy is absorbed, ice movement is arrested, the ice canopy on the shelf is stabilized, and an areal ice zonation results. Development activities that place pipelines and subsea structures on the seafloor are affected by the plowing forces involved in ice scouring (Grantz et al., 1980).

Since 1972, we have recorded morphologic data of the ice-scoured continental shelf of the Alaskan Beaufort Sea using side-scan sonar and fathometers. The primary objective has been to assemble quantitative data on ice-gouge characteristics and processes and to analyze these data for trends. Initial comparison of seabed morphology and shelf-ice zonation suggested a relationship between ice gouging and sea ice ridges on the inner Beaufort Sea shelf (Reimnitz and Barnes, 1974). In this report we update earlier work, summarize new data regarding the character and variability of ice gouges on the Beaufort Sea shelf (Fig. 1), and discuss the gouging process, suggesting relationships to seabed morphology, sediments, and ice dynamics.

11. TERMINOLOGY

Terminology for features produced by ice interaction with the seafloor has not been standardized. Researchers have used one term to describe both a process and the resulting feature. Terms such as "ice plow mark" (Belderson and Wilson, 1973), "ice score" (Kovacs, 1972; Pilkington and Marcellus, 1981), "ice scour" (Pelletier and Shearer, 1972; Brooks, 1974; Lewis, 1977a,b), "ice-scour track" (Wahlgren, 1979; McLaren, 1982), and "ice gouge" (Reimnitz and Barnes, 1974; Thor and Nelson, 1981) have been used to describe a single feature. Accordingly, the processes were

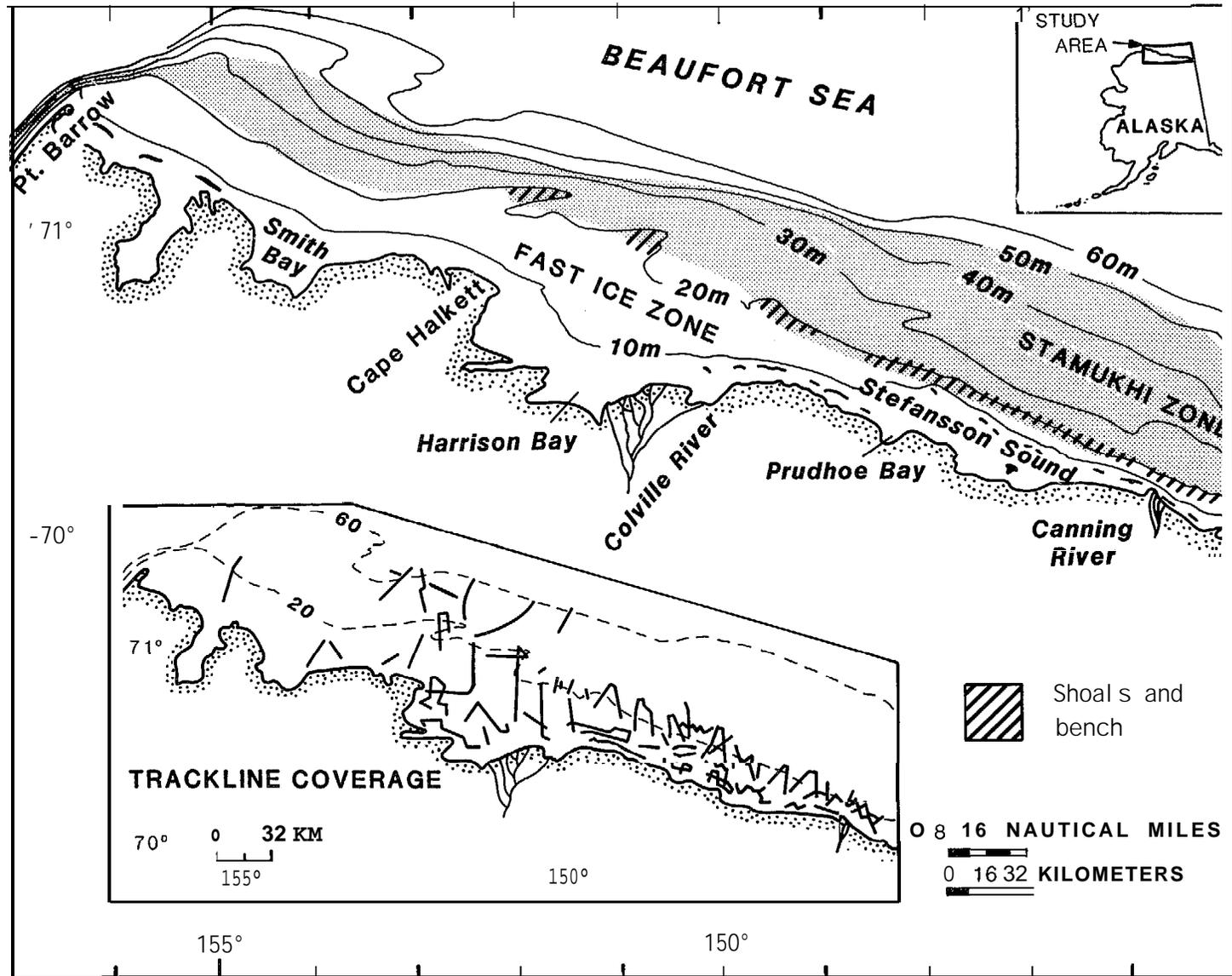


FIGURE 1. The shelf and coast of northern Alaska showing the bathymetry, ice regime, tracklines, and locations used in the text.

plowing, scoring, scouring, and gouging. A 1982 National Research Council of Canada workshop elected to use the term *ice scouring* for the processes of ice interaction with the seafloor. We use the term *ice gouging* interchangeably in this paper for the same processes to clearly separate ice scouring from hydraulic scouring. But only the term *ice gouge* is used here for the characteristic seafloor furrow and associated morphology caused by ice gouging. Each furrow is considered a separate gouge even when many gouges result from the same ice scouring event. We consider each gouge separately, as we are primarily interested in seafloor processes and secondarily in the events that caused them. The following terminology is used for the quantitative enumeration of an ice-gouged seafloor.

Gouge density - the density of all ice-produced sublinear features preserved on the seafloor. The measurement expresses the number of preserved gouges per square kilometer of seafloor by the normalizing of trackline data (Barnes *et al.*, 1978). Scour density or frequency as used by Lewis (1977a) and McLaren (1982) identifies and enumerates scouring events, each of which may have resulted in one or more gouges.

Gouge depth - the depth of a gouge measured vertically from the average level of the surrounding seafloor to the deepest point in the gouge (Fig. 2). Due to sedimentation and slumping, this depth is usually not equivalent to the original incision depth made by the ice. This value is similar to Lewis's (1977a) scour depth. Gouge depth is not to be confused with depth below sea level.

Gouge width - the width of a gouge measured horizontally at the average level of the surrounding seafloor (Fig. 2). This measurement does not include sediment ridges which commonly bound the gouges. Gouge width is equivalent to Lewis's (1977a) scour width.

Ridge height - the height of the ridge of sediments bounding a gouge, measured vertically from the averaged seafloor depth to the highest point on the ridge (Fig. 2). Lewis (1977a) used the term lateral embankment for the ridges bounding a "scour."

Gouge relief - the sum of gouge depth and ridge height.

Gouge orientation - the orientation of an ice gouge relative to true north (T). We report orientation as a vector between 180° and 360°. Using this convention, we imply a sense of motion, but recognize that gouging may occur in either of two directions (Reimnitz and Barnes, 1974). Considerable variation in the gouge orientations commonly made these observations subjective.

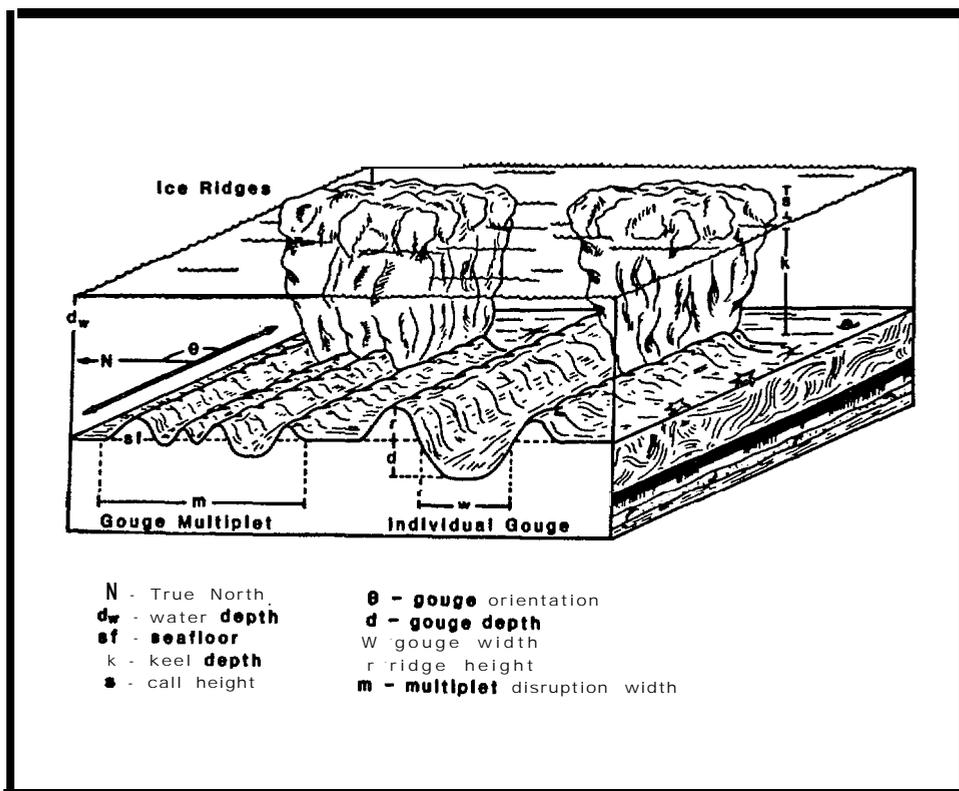


Figure 2. An idealized ice gouge and gouge multiplet, showing terms used to quantify the character of ice gouges.

Gouge intensity - a quantitative estimate of visible sediment disruption calculated as the product of gouge density, maximum gouge depth, and maximum gouge width. No units are assigned to this measure.

Gouge multiplet - A gouge multiplet is defined as two or more gouges, closely paralleling or overlapping one another, suggesting formation by a single multiple-keeled ice mass (Fig. 3). Lewis (1977b) called such features "multiple scour tracks" but did not clearly distinguish them from "ice scours," which are features that also may have multiple tracks. We consider each individual gouge within a gouge multiplet as a separate geologic feature created by a single ice event (Fig. 2).

Gouges per multiplet - the number of individual gouges making up a single gouge multiplet.

Multiplet disruption width - the width of seabed disrupted by a scouring event, measured normal to a multiplet incision and including the ridges on either side (Fig. 2). Disruption widths of individual gouges were not measured but are approximately 25% greater than the gouge width.

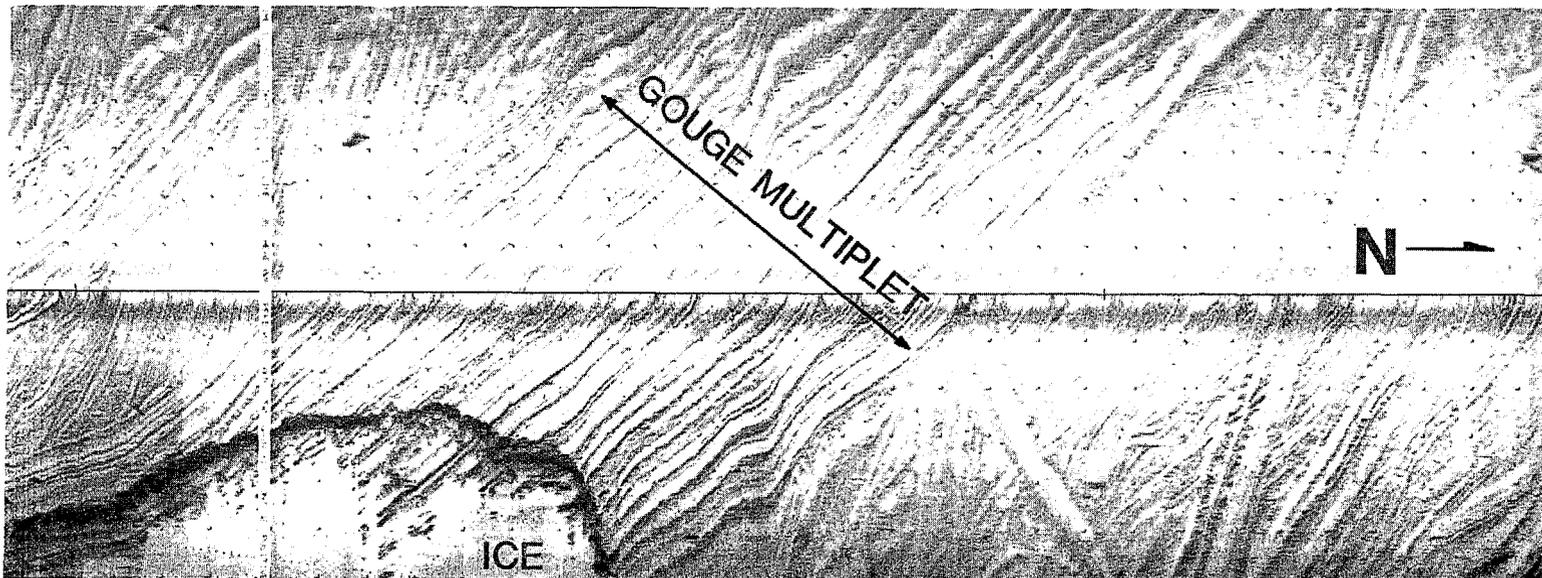


Figure 3. Sonograph record of a gouge multiplet from 25-m water depth east of Barter Island. Note ground ice floe along the margin of the record. This floe scoured the gouge multiplet in a (SE) direction.

Multiplet orientation - the orientation of a gouge multiplet relative to true north.

III. BACKGROUND

The Beaufort Sea shelf can be characterized as a narrow, shallow shelf, whose prominent features are broad shallows off major rivers (Dupre' and Thompson, 1979), sand and gravel island chains trending in echelon parallel to the coast, and a series of sand and gravel shoals in water 10 to 20 m Ueep (Fig. 1). The surficial sediments are characterized by textural variability over short lateral and vertical distances (Naidu and Mowatt, 1975; Barnes *et al.*, 1980a). In nearshore areas (water depths to 15 m), surficial sediments may be reworked to depths of tens of centimeters by episodic storm waves and currents (Barnes and Reimnitz, 1979). In water depths of 0 to 40 m or more, the seafloor is episodically reworked by ice. Thus, the seafloor is exposed to an interplay between hydrodynamic and ice-related processes (Barnes and Reimnitz, 1974).

A. Ice Regime

Temporal and spatial studies of ice zonation and the distribution of ice ridges and keels are critical to an understanding of the correlation between sea ice and the scouring events it causes. Regional ice ridge distributions and discussions of the ice regime have been presented by Reimnitz *et al.* (1978) and by Stringer (1978). The relation of ice ridge sail height to ice keel depth, primarily in the central part of the arctic ice pack, has been studied by Weeks *et al.* (1971), Hibler *et al.* (1972), Kovacs and Mellor (1974), and Wadhams (1975, 1980). However, ridging intensities and energy expenditures in ridge building are greatest on the edge of the polar pack, where it rubs against the coast (Hibler *et al.*, 1974; Reimnitz *et al.* 1978; Stringer, 1978; Pritchard, 1980). As Wadhams (1975, p. 44) notes: "the coastal areas of the Arctic, such as the Beaufort Sea, are probably the site of the deepest keels in the Arctic Ocean, since they have a combination of high ridge frequency and a preponderance of first year ridges of dense ice which results in deeper keels for the same ridge height.

The seasonal ice patterns change in the following general manner. As winter progresses, ice motion inside the barrier islands and in shallow water are small, while at the seaward boundary of the fast ice, repeated incursions of the polar pack cause ice ridging. Along this boundary, grounded first-year and multi-year ridges form a stamukhi zone (zone of grounded ice ridges) (Fig. 1). This zone forms in water depths of about 15-45 m, strung from promontory to promontory or from shoal to shoal along the inner shelf (Kovacs, 1978; Reimnitz *et al.*, 1978). In Harrison Bay, two stamukhi zones form (Reimnitz *et al.*, 1978;

Stringer, 1978). An inshore zone occurs near the 8 to 12 m isobaths. Further offshore, the major stamukhi zone is located along the 15 to 20 m isobaths and appears to be limited in shoreward extent by shoals in the northeast part of Harrison Bay and farther east. Additional ridges are commonly added to the stamukhi zone throughout winter, expanding the zone to 35 to 45 m water depths (Reimnitz *et al.*, 1978).

In spring (May and June), Arctic rivers flood the nearshore ice, hastening the onset of melting and deterioration of the fast-ice canopy, which is finally broken and dispersed by the wind. Grounded remnants of the stamukhi zone may persist through the summer open-water period. As sea ice melts and pack ice retreats during summer, the nearshore wave and current regimes intensify as more water surface is exposed to wind stress. Maximum open water generally occurs in September and early October and corresponds to the period of most intense storms (Reimnitz and Maurer, 1979).

B. Ice Scouring

Studies by Carsola (1954) and Rex (1955) were the first directed at seabed relief features related to ice scouring, although reports indicate that early arctic explorers had known scouring to occur (Kindle, 1924; Wahlgren, 1979). Studies during the early 1970's culminated in a series of descriptive papers on these features (Pelletier and Shearer, 1972; Kovacs and Mellor, 1974; Reimnitz and Barnes, 1974; Lewis, 1977a; and McLaren, 1981). Subsequent studies have concentrated on quantifying the processes and, in particular, have attempted to ascertain the annual rate of gouging (Lewis, 1977b; Reimnitz *et al.*, 1977; Barnes *et al.*, 1978; Toimil, 1978; Barnes and Reimnitz, 1979; Wahlgren, 1979; Thor and Nelson, 1981; Pilkington and Marcellus, 1981; Weeks *et al.*, this volume).

In a paper describing ice characteristics in relation to seabed gouging Kovacs and Mellor (1974) examined ice keel structure and the forces required and forces available from wind and momentum for gouging. They found that virtually all ice keels have enough strength for scouring. Enough wind energy was accumulated by the ice pack to easily cause gouging by an ice keel protruding from the pack. They found that when energy would be in the form of momentum of individual drifting floes driven by winds and currents, only short (tens of meters) and shallow (maximum about 60 cm) scour tracks would be created. Chari and Guha (1978) considered the gouging forces available from the movement of the massive icebergs of the east coast of Canada. When their data are extrapolated to the smaller ice masses of the Beaufort Sea, only shallow (less than 1 m deep) or short gouges would result from ice momentum alone. Thus the most intense gouging should be associated with ice keels driven by forces amassed from an encompassing ice pack.

In studies by Reimnitz and Barnes (1974) and Barnes and Reimnitz (1974), ice-gouge character was related to ice and sediment type. These authors noted that the bulk of the gouges were less than 1 m deep with a maximal depth of 5.5 m. Dominant gouge orientations were parallel to isobaths. They indicated that in water less than 20 m, lower gouge densities could reflect sediment reworked by waves and currents filling gouges rapidly. Other areas of low gouge density included shoals, lagoons and the lee of islands. Gouges in water deeper than 50 m were thought by Kovacs (1972) and Pelletier and Shearer (1972) to be relict since present ice keels are not that deep. However, Reimnitz and Barnes (1974) thought deep water gouges were possibly modern. They reasoned that ridge keels on the shelf may be deeper than in the deep sea, because here the highest concentrations of ridges occur. They also pointed out that average sedimentation rates are not applicable to gouge troughs, which serve as traps.

Lewis (1977b), in his landmark paper on Canadian ice scouring, indicated that the floor of the Canadian Beaufort Sea is saturated with gouges between 15 and 40 m water depths and that gouges are best preserved in cohesive silt and clay sediments. The less cohesive sand usually found inshore is seasonally reworked by waves and currents. Scouring also diminished in deeper water. Gouge depths averaged less than 1 m but ranged up to 7.6 m below the seafloor. Lewis was the first to note that the numbers of shallow and deep gouge depths followed an exponential distribution. He also suggested that the maximum water depth for modern gouging was the 50-m isobath as the deepest reported ice ridge keels are 47 m deep.

IV. METHODS

A. Data Collection

Data were gathered using a 105-kHz side-scanning sonar system and 12- and 200-kHz fathometers recording at 3 to 5 knots ship speed. Seafloor profile data were obtained almost exclusively with the 200-kHz recording fathometer, which has a resolution of approximately 10 cm in calm seas. The side-scan sonar was operated at slant ranges of 100 to 125 m, covering a swath of the seafloor up to 250 m wide. Many features were visible on the sonar that were not resolved by the fathometer, indicating that this system could resolve seabed features less than 10 cm high. Navigational accuracy varied according to the methods employed, which ranged from dead reckoning to the use of precision range-range systems. Estimated location errors range from a maximum of 1 km at distances greater than 20 km offshore to a few meters in nearshore surveys. A more complete discussion of equipment and techniques is given in Rearic *et al.* (1981).

The data presented in this report result from examination of more than 2000 km of trackline records and the observation and measurement of more than 100,000 ice gouges. Tracklines were selected to give continuous coverage of the Alaskan shelf from near shore to the shelf break at approximately 60 to 90 m depths and from Smith Bay to Camden Bay (Rearic *et al.*, 1981, and Fig. 1).

R. *Data Analysis*

The trackline spacing on the inner shelf is approximately 10 km and the spacing on the outer shelf is approximately 25 km. The survey tracklines, monographs and fathograms were divided into 1-km segments for analysis. Monographs were used to measure gouge density, gouge width, orientation, and gouge multiplet characteristics. Gouge depths and ridge heights were measured from the fathograms. In each kilometer segment, the total number of gouges were counted and the dominant orientation estimated. This allowed us to normalize the gouge numbers to arrive at a gouge density by accounting for the angle at which the gouges were crossed (Barnes *et al.*, 1978). A distribution was prepared from the fathograms of gouge depths in 20-cm increments for each kilometer segment. Gouges less than 20 cm deep were entered as the difference between the number counted on the fathogram in the depth distribution and the number counted on the sonograph in determining gouge density. The maximum gouge depth, maximum width, and maximum ridge height were determined in each segment, as were the number and dominant orientation of multiples and the maximum number of gouges per multiplet. Maximum gouge relief was computed from maximum gouge depth and maximum ridge height which are not normally found on the same gouge in the segment.

Subjective judgment was required in interpreting the data because equipment malfunctions, weather, or natural randomness in gouge occurrence and orientation made the quality of the data variable. To "keep this judgment factor consistent, one of us (Rearic) examined and interpreted all records.

V. RESULTS

A. *Typical and Maximum Gouges*

1. *Individual gouges.* The "typical" gouge from our data, the one embodying the mean values of all parameters, occurs in water about 18 m deep, forms a furrow 56 cm deep with flanking ridges 47 cm high, and has a width of 7.8 m; it has a total relief of more than 1 m (Table I). In the vicinity of this gouge, the bottom is scoured to a density of 70 gouges per square kilometer with a dominant orientation of 273°. These gouge data represent an average or maximum values from 1-km-long trackline segments. The

wide scatter and variability of the data are shown by the standard deviations which, in many cases, are as large as the mean values (Table I).

TABLE I. Means and Extremes of Data on Gouges and Gouge Multiples (1972 to 1980 Data)

Parameter	Mean	Standard deviation	Range	Number of observations
Water depth (m)	18.0	14.4	1.2 - 125	2400
Gouge density (no. km ⁻²)	7.0	71.8	0 - 490	2191
Gouge orientation (O?)	273°	30.1		1917
<i>Individual gouges</i>				
Incision width (m)	7.78	7.96	0.5 - 67	2184
Incision depth (m) (A)	0.56	(2.65)	0.2 - 4	2179
Ridge height (m) (B)	0.47	0.49	0.2 - 5	2176
Gouge relief (m) (A+B)	1.02	1.09	0.2 - 8	2176
<i>Gouge multiples</i>				
Density (multiples km ⁻¹)	1.6	2.3	0 - 15	1842
No. of gouges multiplet ⁻¹	4.8	3.7	2 - 27	884
Disruption width (m)	28.4	21.4	2 - 150	884
Orientation (°T)	266°	40.6		884

The maximum values show that gouge densities reach almost 500 km⁻². Gouges up to 67 m wide and up to 4 m deep¹ and flanking ridges as much as 5 m high have been measured. Maximum relief of a single gouge has been measured at 8 m.

2. *Gouge Multiplets.* Gouge multiples occur an average of 1.6 times per kilometer of trackline, contain an average of almost 5 gouges per multiplet, and disrupt the seabed over a width of about 30 m (Table I). The average orientation of gouge multiples is nearly east-west (266°), less than 10° from the mean orientation of all gouges.

The maximal values for gouge multiples from our data show as many as 15 multiples per kilometer of trackline. These multiples contain up to 27 gouges with a seabed disruption width up to 150 m (Table I). Records taken in 1981 contain an even larger multiplet 2 2/5 m wide composed of 64 gouges (Reimnitz

¹ A single gouge 5.5 m deep was measured in water 39 m deep northwest of Cape Halkett. Poor fathometer records due to rough weather precluded enumeration of gouges on this 1-km segment except for this large one; therefore this gouge does not show in our routine statistics.

etal., 1982, and Fig. 3).

The volume of sediment excavated by gouging can be impressive (Fig. 4). A gouge couplet noted in outer Harrison Bay had a width of 78 m, total relief of 6.3 m, and a cross-sectional area of the incision estimated at 234 m².

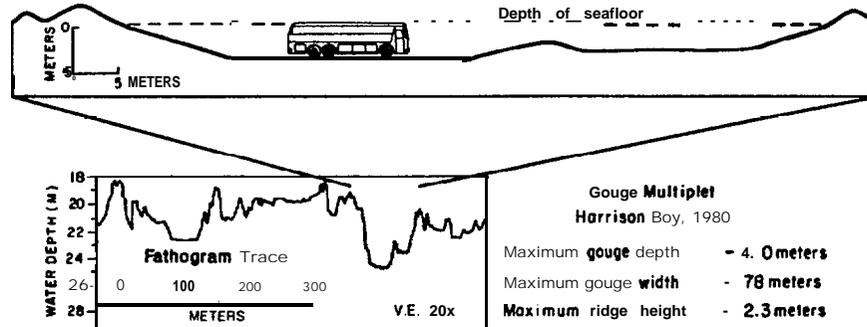


Figure 4. Major gouge couplet observed in outer Harrison Bay in 21-m water depth redrawn to remove vertical exaggeration. The total cross-sectional area of the incision cut by the double ice keels is approximately 234 m² (3 m by 78 m).

Multiples can be divided into two distinct classes. Multiples with more than 4 or 5 gouges rarely contain any deep ones and are commonly composed of gouges of nearly equal depth. These depths are usually less than 20 cm (Fig. 3). Multiples made up of fewer than 4 or 5 gouges may be shallow, but usually are more deeply and unevenly incised (Fig. 4).

B. Distribution of Data With Water Depth

1. *Individual Gouges.* Gouge parameters plotted as means against water depth create bell-shaped curves, with highest mean values of the parameters in 20 to 50 m water depths (Fig. 5).

Highest gouge densities are in water between 20 and 40 m deep, with mean values of more than 100 km⁻²; low gouge densities there are almost nonexistent. Trackline segments in these water depths always contained significant scouring. Lowest density values occur in water less than 5 m deep or more than 45 m deep (Fig. 5A). The maximum depths of gouges (Fig. 5B), maximum width (Fig. 5C), and maximum ridge height (Fig. 5D) follow a pattern similar to gouge density except that the deepest gouges occur in water 30-40 m deep. The peak maximum widths (Fig. 5C) occur in even deeper water (40-50 m). The figures show that the frequency

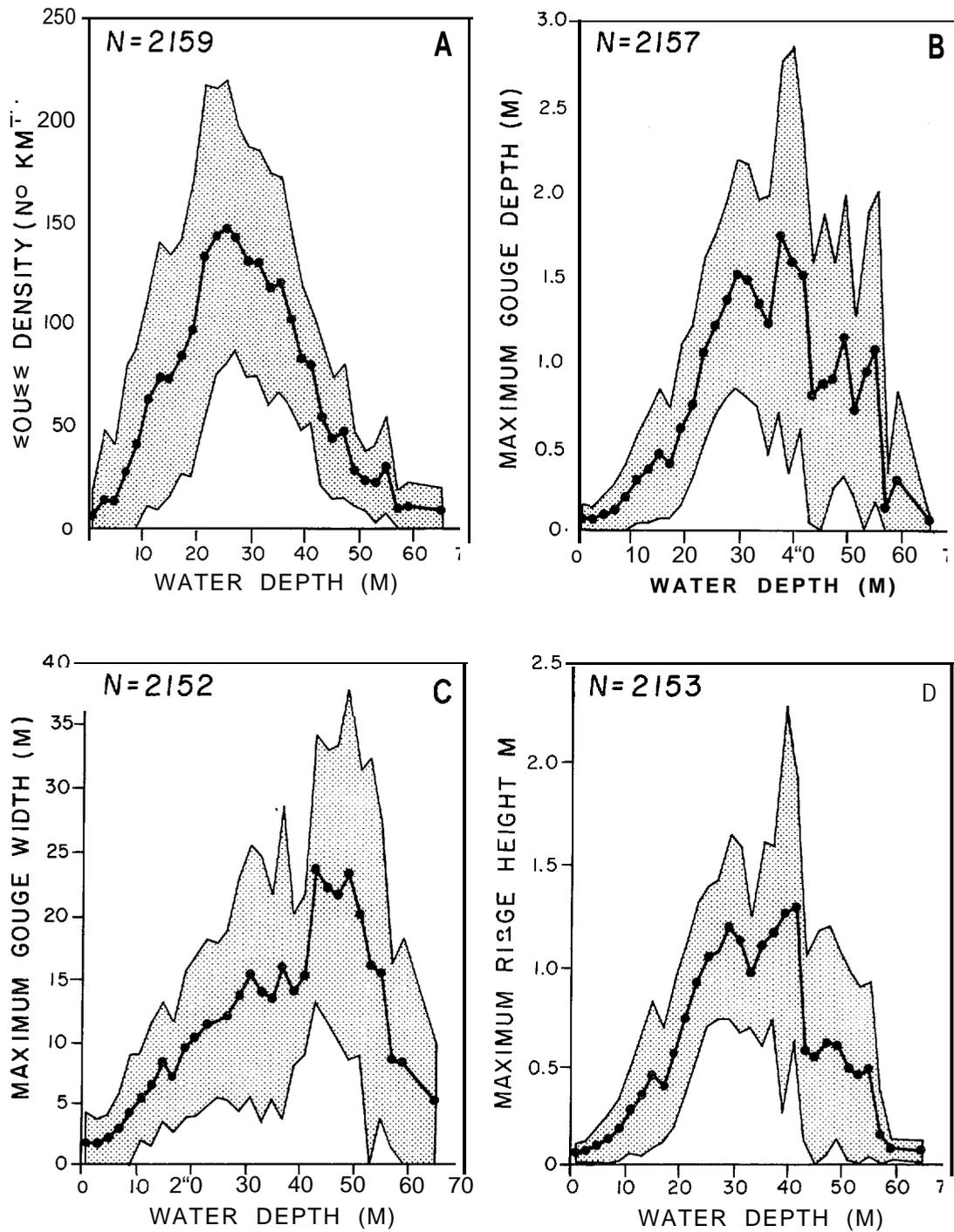


Figure 5. Mean gouge parameters measured in 1-km segments in 2-m depth increments. Standard deviation (shaded areas) is shown about the mean (connected dots). N refers to the number of observations in the distribution. Note the bell-shaped curves and the nickpoints in the data at 15-20-m depth. A) Gouge Density, B) Maximum depth, C) Maximum width, and D) Maximum ridge height.

of features associated with ice gouges diminishes abruptly in water deeper than about 40 m (Fig. 5). Another feature of the curves is a persistent nickpoint in the data at about 18 meters, and another at 30 to 40 m.

Gouge depths were enumerated in 20-cm increments. As not all gouges observed on the monographs (areal observations) were crossed by the fathometer (linear observations), the number of gouges reported as less than 20 cm deep should be anomalously high. The plot of these depth values is an exponential distribution from the shallowest gouges to gouges .25 m deep (Fig. b) and suggests that our approximation of the less-than-20-cm gouges is reasonable.

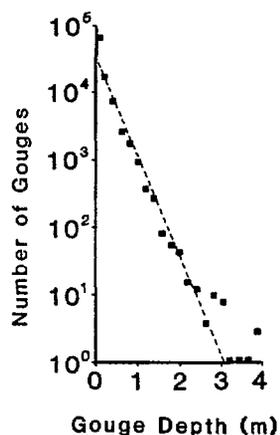


Figure 6. Total number of gouges observed versus their depth.

The relationship between gouge depth and ridge height was examined. In taking the measurements, we noted that the maximum height and maximum depth in each segment *were* from different gouges and that ridges were normally asymmetric. Using the maximum ridge height and the maximum gouge depth in each 1-km segment, the mean maximum gouge relief (Fig. 7A) displayed the same bell-shaped curve as density, depth, width, and ridge height (Fig. 5). In an idealized gouge the ridges might be expected to be approximately half as high as the gouge is deep, with half of the debris piled on either side, or a ratio of about 1:2. The data, plotting maximum heights versus maximum depths (Fig. 7B), show that gouges up to 1 m deep are associate with ridges of equal height; a 1:1 ratio. The ratio of the mean values becomes closer to 1:3 for deeper gouges; that is, ridges are not as high as gouges are deep. This suggests that the material from incisions deeper than 1 m is distributed over a larger flanking area or compressed.

Dominant orientations of gouges plotted against water depth (Fig. 7C) show that in water more than 10 m deep the gouge trends

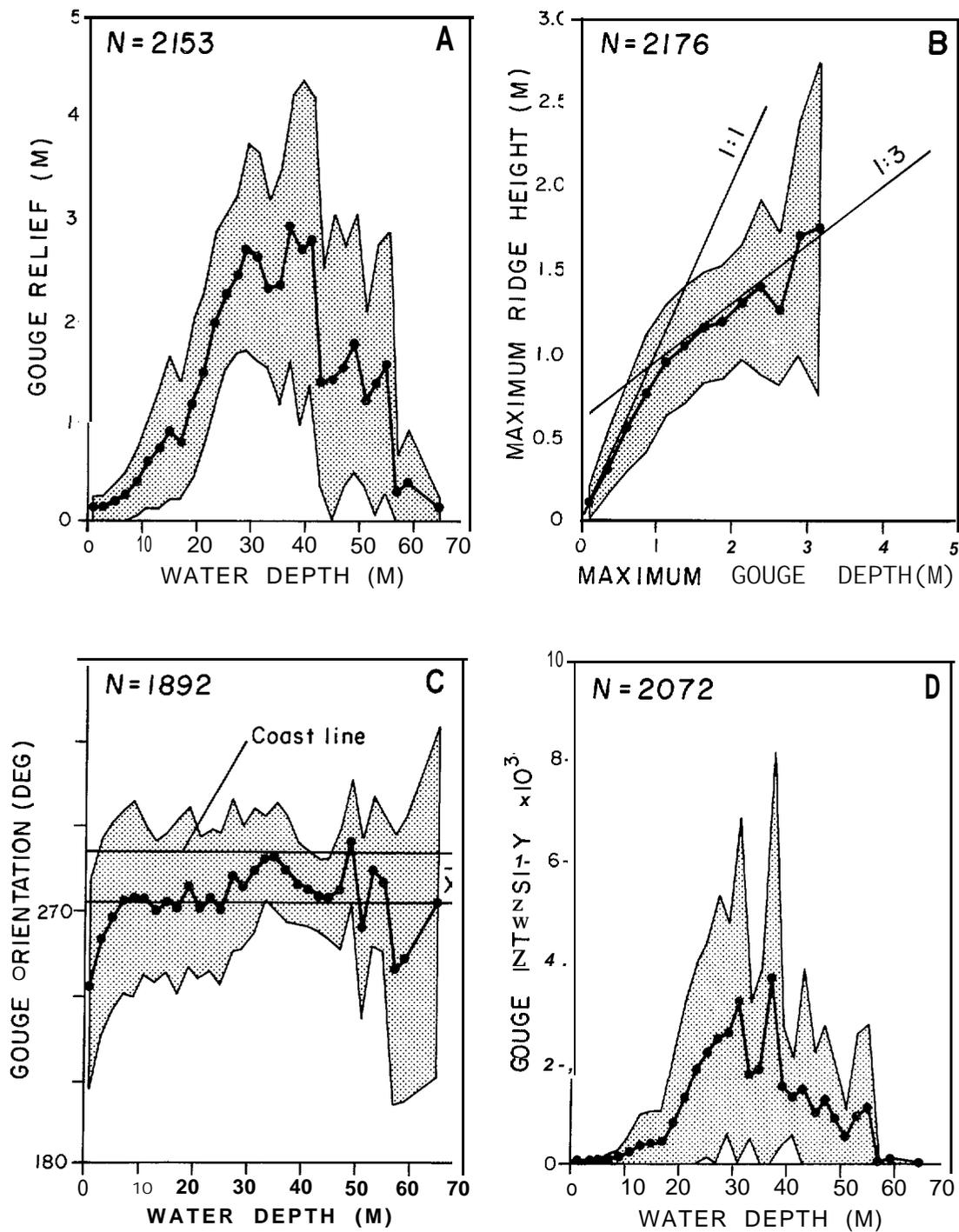


Figure 7. Mean parameters (connected dots) measured in 1-km segments (solid line) and standard deviation (shaded area) are shown. N refers to the number of observations in the distribution. A) Gouge relief versus water depth, B) ridge height versus depth, C) Gouge orientation versus water depth, and D) Gouge intensity versus water depth.

are generally within 20° of being parallel to the coastline orientation. In waters less than 10 m and more than 50 m deep the deviation from coast-parallel scouring increases to almost 50° onshore.

Multiplying three gouge parameters - maximum depth, maximum width, and density - approximates the volume of the sediments involved in scouring and may be the best measure of gouge intensity. The derivative graph of mean intensity versus water depth (Fig. 7D) emphasizes the similar bell-shaped character as seen in the individual components (Figs. 5A, B, and C). Gouge intensity increases with depth very slowly to water depths of 17 to 19 m, then increases rapidly to peak values in water depths of 30 to 40 m before decreasing to very low values in depths over 55 m (Fig. 7D). The scatter of values about the mean, expressed as the standard deviation, is commonly greater than the mean value (Fig. 7D). This may be due in part to the fact that the data composing this plot are maximum values and not mean values for each segment. Mean values for each segment could show less variation.

2. Gouge Multiplets. Multiplets are most abundant in water 25 to 35 m deep and are relatively uncommon in shallow water and in deeper parts of the shelf (Fig. 8A). The number of gouges per multiplet and the disruption widths increase to water depths of 25 to 35 m deep, then decrease as water depth continues increasing (Fig. 8B and C). Disruption widths triple from 10 m in water less than 10 m deep to more than 35 m in water depths greater than 25 m (Fig. 8C). Wide multiples are prevalent from 35 m to the seaward limit of the data set.

Gouge multiples are oriented slightly onshore from the trend of the coastline and isobaths (Fig. 8D and Table I). Multiples do not show the increasing onshore trend that was observed in the distribution of all gouge orientations inshore of the 20-m isobath (Figs. 7C and 8D).

3. Parameter Correlations

Although the measured gouge parameters share similar bell-shaped curves, correlation coefficients (Table II) show generally poor correlation between them. The low correlation value may be due to the slight positive and negative skewedness exhibited in the graphs of these parameters or to the fact that hydraulic reworking has reshaped many of the gouges since their inception. The low correlation could also indicate that the parameters are unrelated.

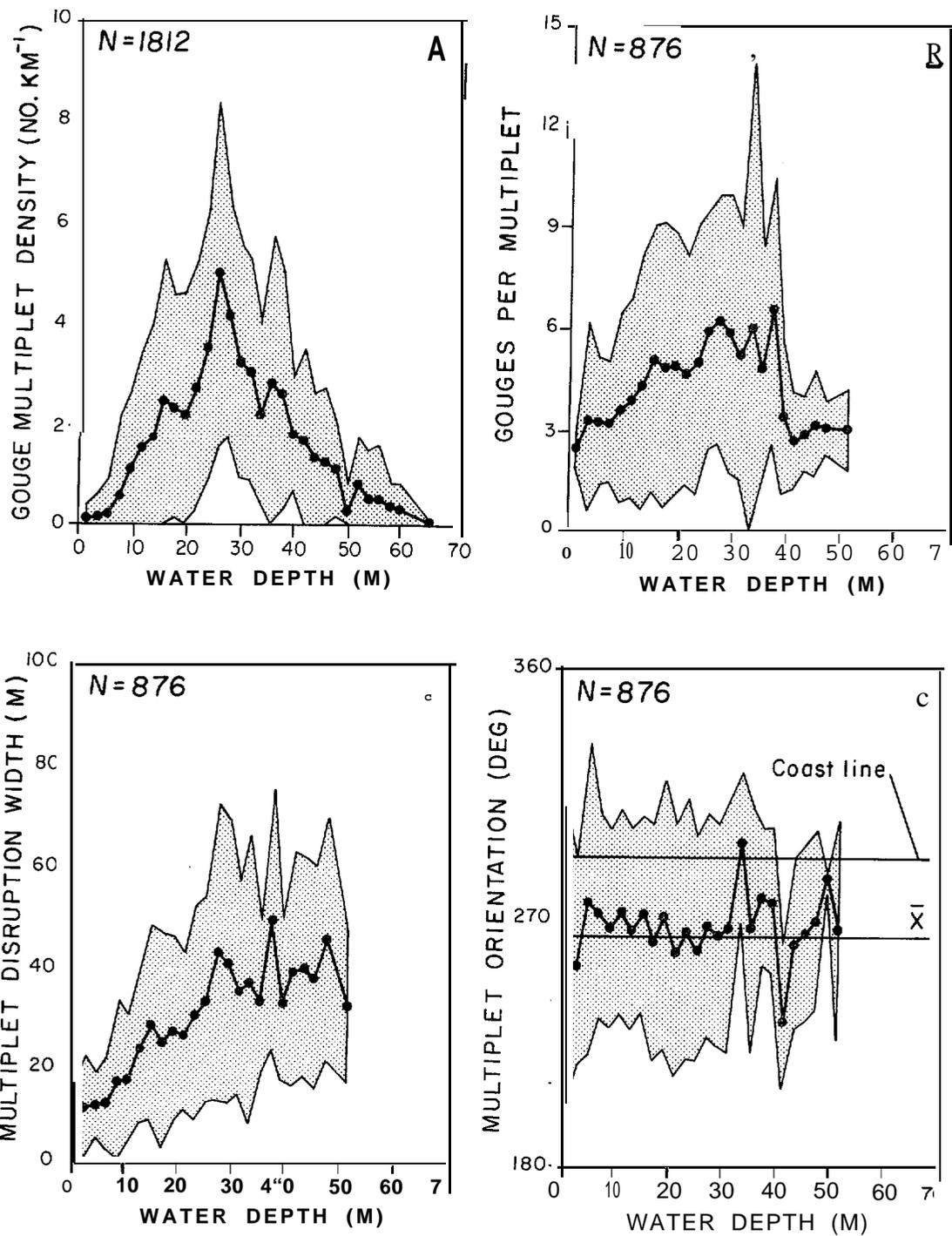


Figure 8. Mean gouge multiplet parameters versus water depth measured in 1-km sonograph segments and divided into 2-m depth increments. Mean value is shown by solid line, standard deviation by shaded area. N refers to the number of observations in the distribution. A) Gouge multiplet density, B) Gouges per multiplet, C) Multiplet disruption width, and D) gouge multiplet dominant orientation.

Tone II. Pearson Correlation Coefficients^a

	<i>Gouge depth</i>	<i>Gouge Width</i>	<i>Ridge height</i>	<i>Gouge multiples</i>	<i>Gouges per multiplet</i>	<i>Multiplet disruption Width</i>
Gouge density	0.54	0.35	0.58	0.72	0.32	0.14
Gouge depth		0.56	0.84	0.57	0.14	0.27
		Gouge width	0.51	0.33	0.02	0.24
			Ridge height	0.59	0.14	0.25
				Gouge mutiplets	0.31	0.26
					Gouges per multiplet	0.70

^a*Values are statistically significant at the 0.05 level.*

Exceptions are the positive correlation between ridge height and gouge depth (0.84), between gouge density and the number of gouge multiples (0.72), and between the number of gouges per multiplet and the total disruption width of that event (0.70). These correlations suggest that (1) higher ridge heights are found in segments with deeper gouges, (2) high gouge densities are associated with areas of numerous gouge multiples, and (3) the widest sediment disruptions are from multiples containing many gouges.

c. Regional Distribution of Data

To provide an understanding of the regional distribution of ice keels contacting the shelf surface gouge densities, maximum gouge depths, gouge relief, gouge intensities, and gouge multiples were contoured. In this effort the data had to be treated as if all records were of equal quality and that data were synoptic. However, where tracklines from different years crossed each other, there were commonly disparities in the data because the records were of uneven quality and the non-synoptic data represent various stages of scouring and reworking by waves and currents. As a result subjective compromises were made to accomplish the contouring.

Highest densities of gouges are found in the stamukhi zone, in water 20 to 30 m deep. Gouge densities are lowest inshore and at the seaward edges of our data in zones paralleling the general trend of the coast (Fig. 9). Low densities also appear in the lee of the islands and to the southwest of the offshore shoals. The central portion of Harrison Bay also has relatively low gouge densities.

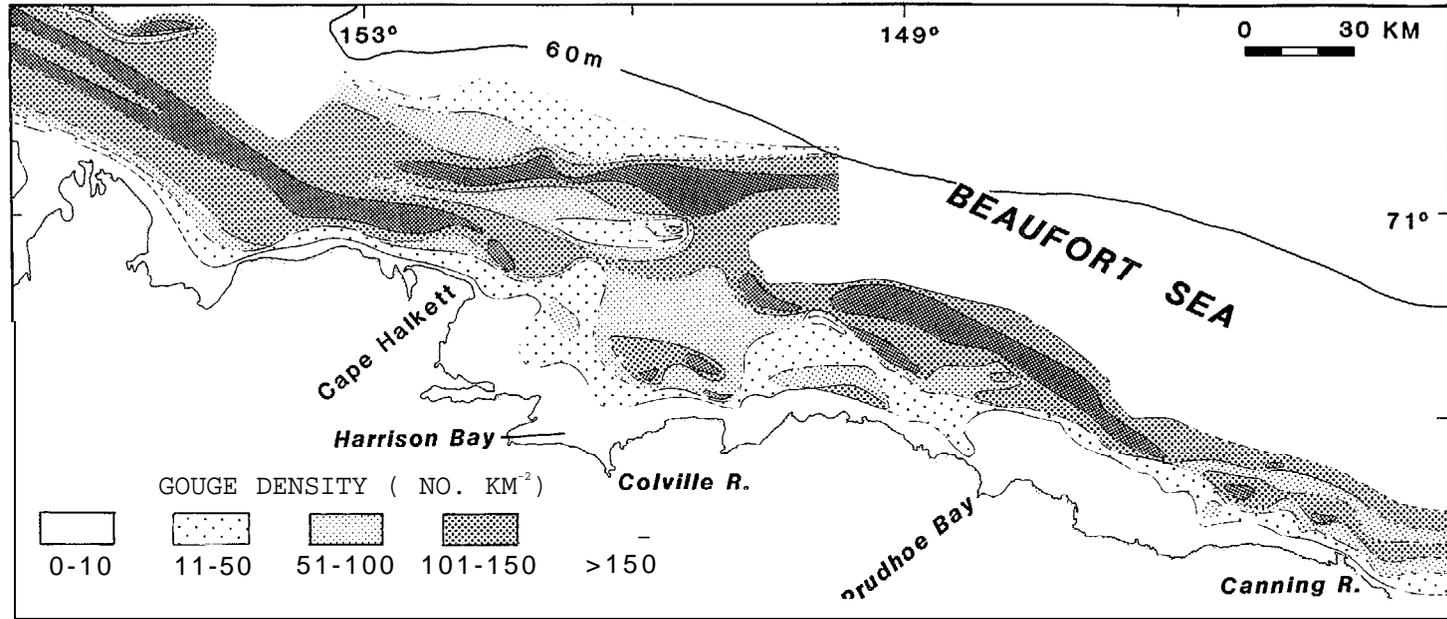


FIGURE 9. Regional distribution of gouge densities observed in 1-km segments. See Fig. 1 for distribution of tracklines used.

Gouge depths are greatest in a zone parallel to the isobaths in water depths between 20 and 40 m (Fig. 10), in deeper water than the corresponding values of high gouge densities. Lower gouge depths are associated with central Harrison Bay east of Cape Halkett and in the vicinity of shoals.

Gouge relief in excess of 2 m is common in a band of varying width that extends across the central part of the shelf (Fig. 11). Gouge relief is generally less than 1 m in the coastal embayments and inside the coastal island chains. Other areas of low gouge relief occur in the central part of Harrison Bay and at the seaward limit of our data.

Gouge intensities are greatest in a band of varying width on the central shelf and in an inshore area off the Colville River (Fig. 12). Low values occur within the coastal embayments, inside the coastal island chains, and at isolated locations in the central portion of Harrison Bay, as well as at the seaward limit of the area studied.

The regional distribution of gouge multiples is patchy. Multiplet densities are highest in the vicinity of the 20-m isobath, particularly off the Prudhoe Bay area (Fig. 13). Low multiplet densities are present in the central part of Harrison Bay. Occasional multiples occur inside the islands or in the shallow portions of the coastal embayments.

In the analysis of regional gouge orientation variability the shelf was divided into 26 regions. The boundaries of each of these regions encompass what we judge to be uniform settings in terms of bathymetry and ice zonation. The dominant orientations within these regions were plotted as rose diagrams (Fig. 14). The orientation of gouges between the 20- and 40-m contours is essentially coast-parallel but slightly onshore. The dominance of isobath-parallel orientations also holds in the shallow water of Stefansson Sound and the shallow area off the Colville River delta. A slight counterclockwise rotation of orientations is observed nearshore. This rotation is most pronounced just seaward of the islands, and along sections of the open coast, southeast of Cape Halkett.

D. Distribution of Ice Ridges

Compressional and shearing forces in the ice pack commonly cause failure of the ice sheet and piling of ice blocks. The result is an ice ridge, composed of a submerged keel which isostatically supports a subaerial sail (Fig. 2). As it is difficult to measure keel depth, efforts have been made to determine the relationship between depth geometry and the more readily measured ridge sail height (weeks *et al.*, 1971; Kovacs and Mellor, 1974; Kovacs and Sodhi, 1980; Wadhams, 1980; Tucker and

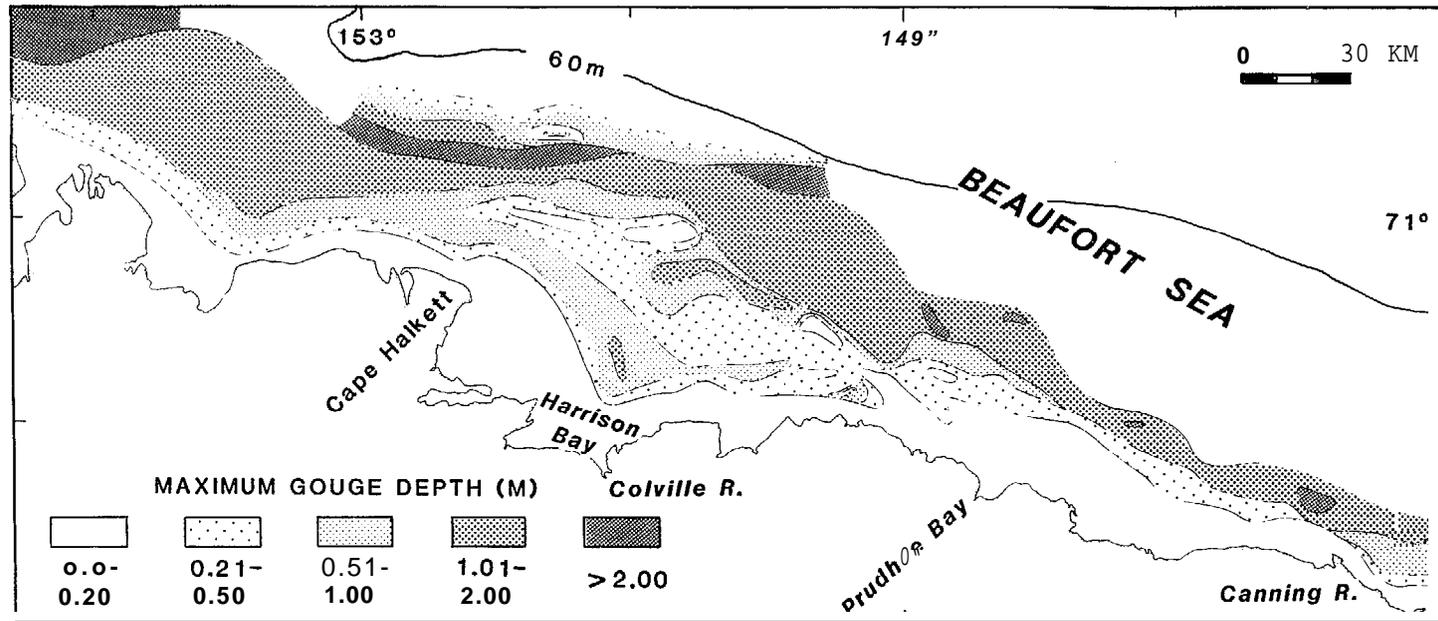


FIGURE 10. Regional distribution of maximum gouge depths observed in 1-km segments on the shelf. See Fig. 1 for distribution of tracklines used.

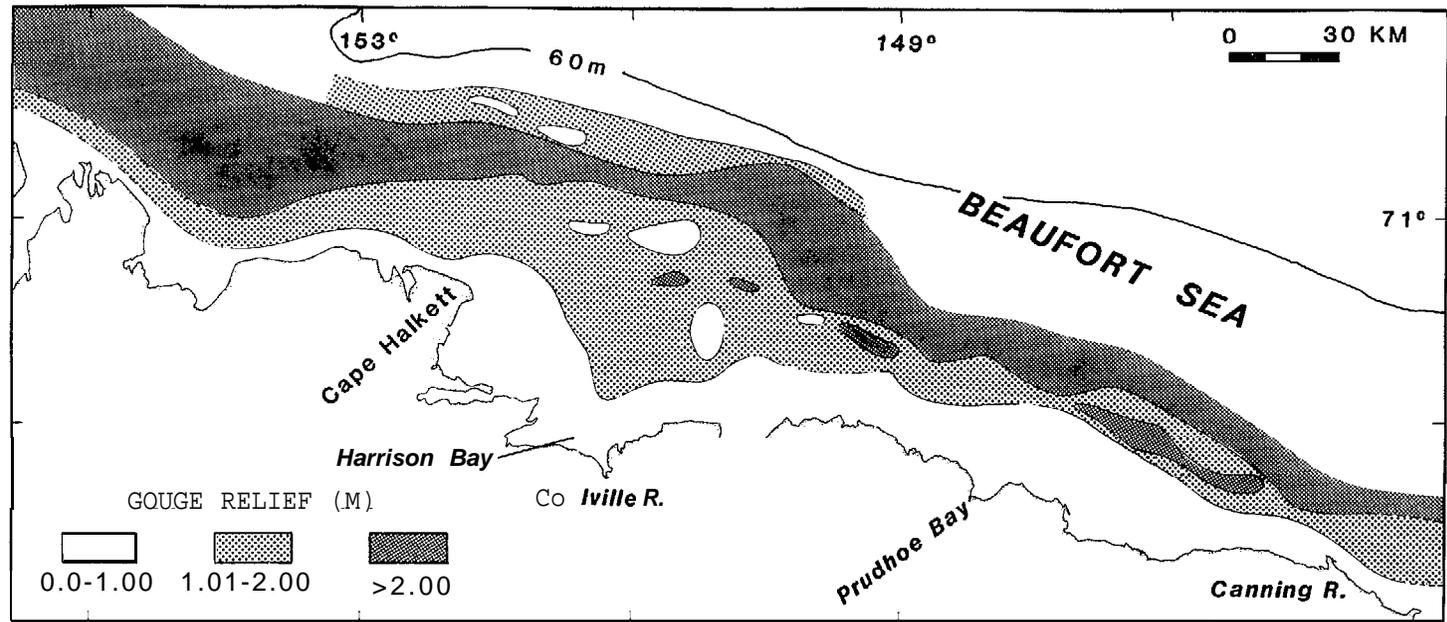


FIGURE 11. Regional distribution of gouge relief the sum of maximum gouge depth and maximum ridge height in each 1-km bathogram segment. See Fig. 1 for tracklines used.

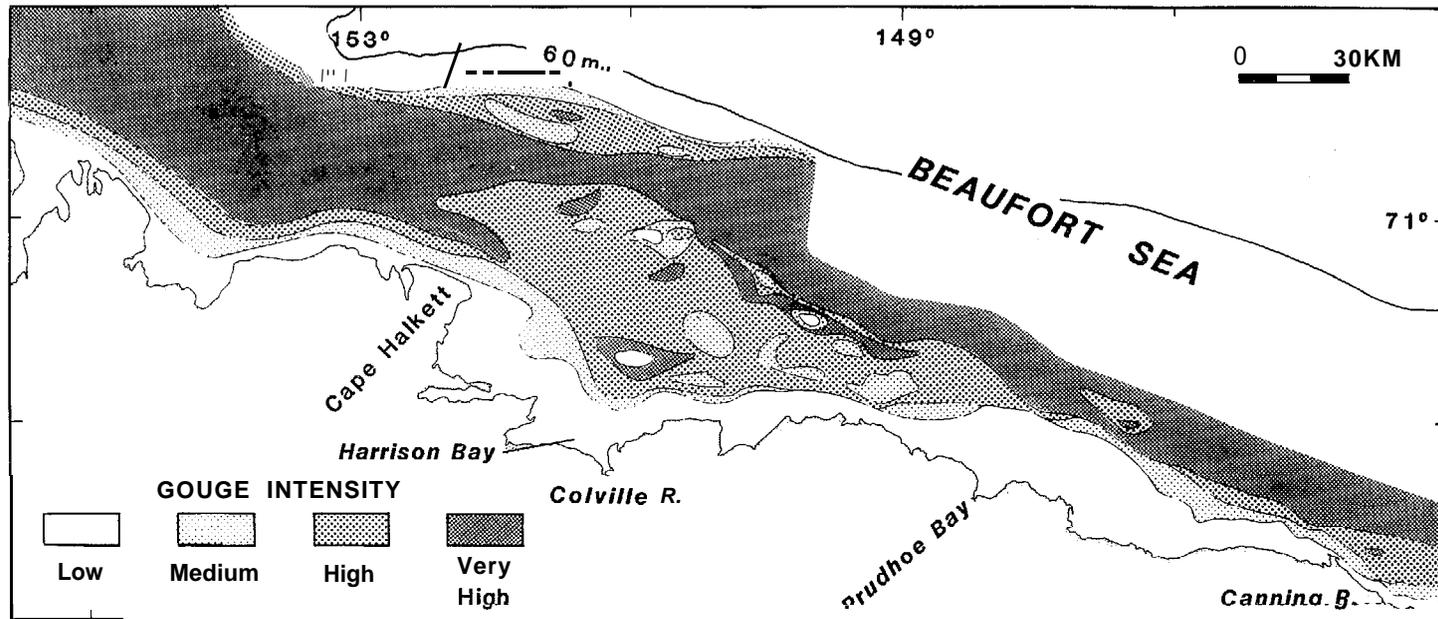


FIGURE 12. Regional distribution of gouge intensity (product of maximum gouge depth, maximum gouge width, and gouge density) in each 1-km segment. Compare this figure with Figure 16 (ice zonation and ice ridging). See Fig. 1 for tracklines used.

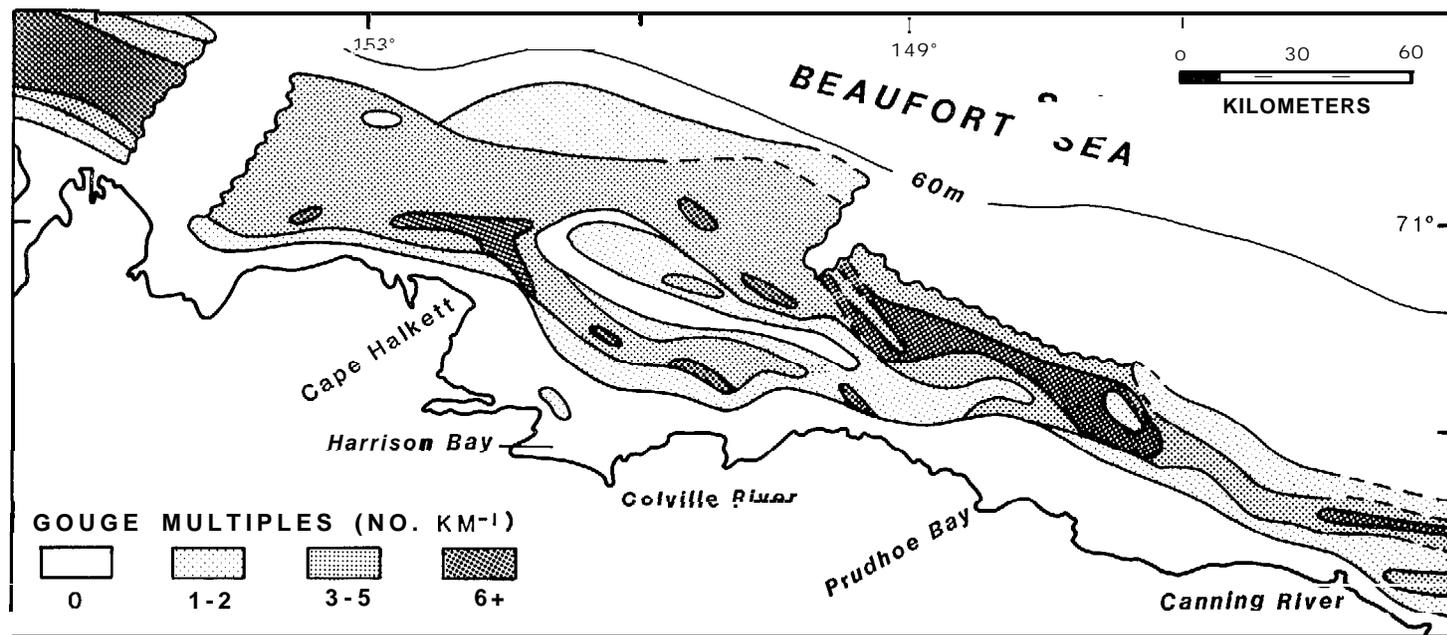


FIGURE 13. Regional distribution of number of multiples in each 1-km segment). See Fig. 1 for location of tracklines used.

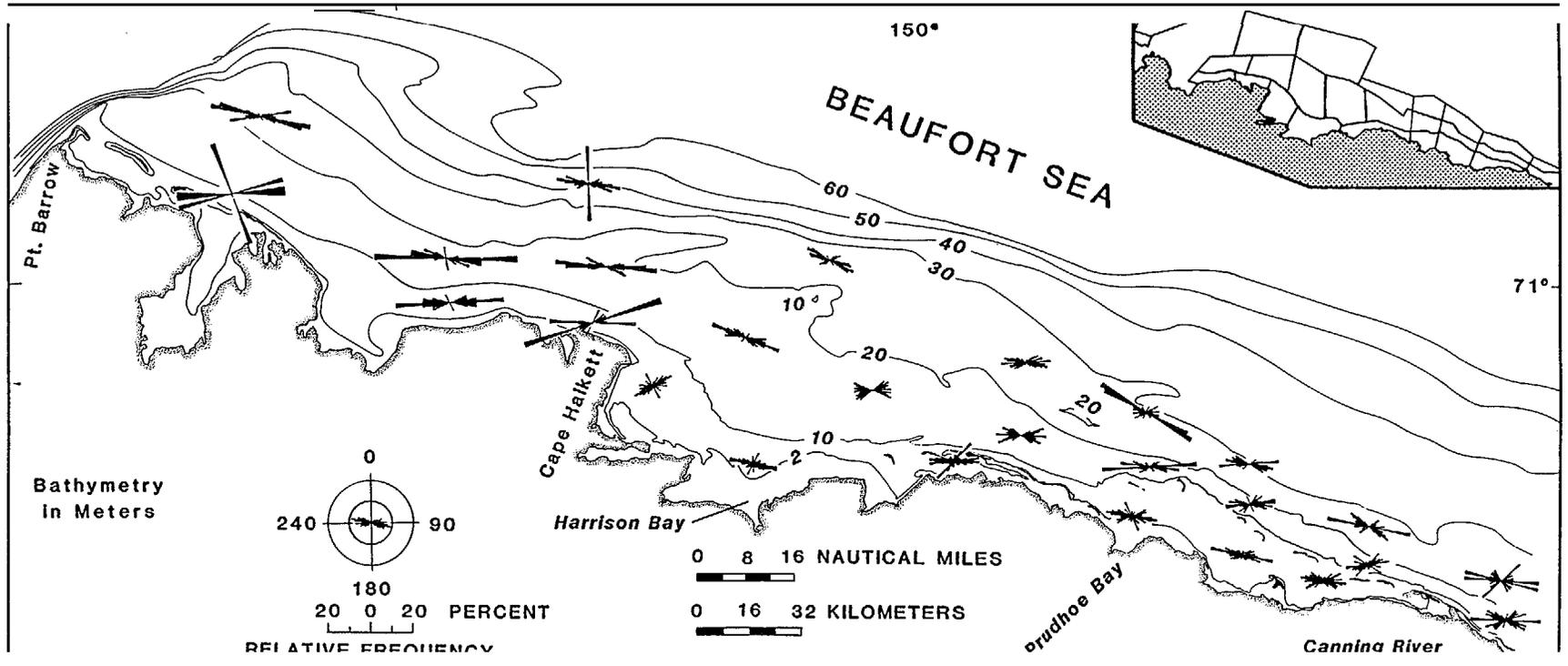


FIGURE 14. Dominant gouge orientations from 1-km sonograph segments shown as rose diagrams for 26 areas outlined in the upper righthand corner.

Govoni, 1981). This work suggests a sail-to-keel ratio of about 1: 4.5 for first-year ice ridges (formed during the most recent winter) and 1:3.3 for multiyear ridges.

Laser profile studies of seasonal and areal distribution reveal considerable annual variation in ice ridges on the Beaufort Sea shelf (Tucker, this volume). Tucker *et al.* (1979) analyzed the distribution of ridge sails on three profiles across the shelf (Fig. 15): one off Barter Island, a second off Prudhoe Bay, and a third west of Cape Halkett. Ice 20 to 80 km from the coast over the central and outer portions of the shelf contained the highest number of ridges. These authors also suggested that grounded ice floes (stamukhi) stabilize ice inshore of about 20 km and limit ridging, and thus the development of sails. Further offshore, where no grounding occurs, weak first-year ice is subject to increased ridging (Fig. 15). The 1978 Prudhoe Bay profile reflects the fact that no multiyear ice was encountered on the inner 150 km of trackline; thus no core of multiyear stamukhi formed to protect the inner shelf, with the result that ridging extended up to the coast (Tucker and Govoni, 1981). This suggests that year-to-year variability in ice ridging depends upon the time of stamukhi zone development.

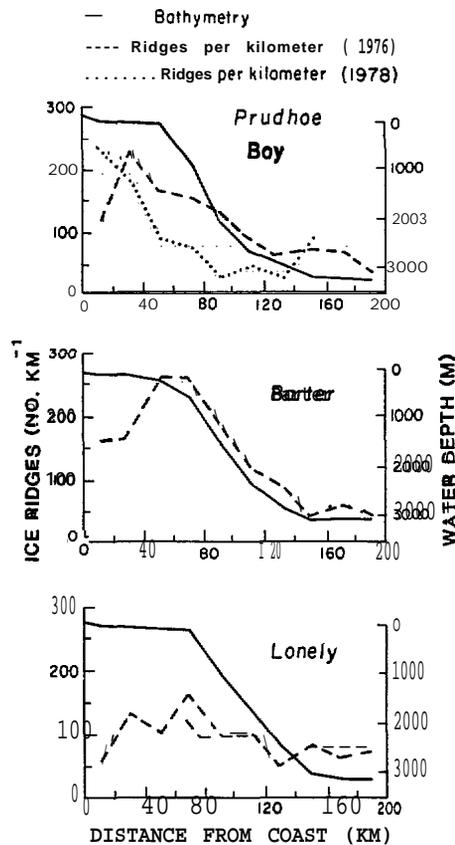


Figure 15. Number of ice ridges (sails) per km on three transects perpendicular to the coast compared to shelf depths on the same transect (modified after Tucker and others, 1979).

Stringer (1978) examined satellite imagery for the period from 1973 to 1977 to assess the distribution of ice sails. The 5-year composite map produced by this study smooths the considerable seasonal and year-to-year variability. We have overlaid a 5 km by 5 km grid onto the 5-year composite ridge map to quantify the density of ice ridges on the shelf. The result (Fig. 16) shows that densities are highest (more than 6 ridges per 25 km²) between the 20 and 50 m isobaths in the area between Prudhoe Bay and eastern Harrison Bay. Low ridge densities occur inshore, in central Harrison Bay, and in isolated areas on the outer shelf. The regional ice ridge abundance observed on satellite imagery also illustrates the increased occurrence of ridges in the stamukhi zone (Fig. 17).

VI. DISCUSSION

Those familiar with the literature recognize that this study of ice gouging on the Beaufort Sea Shelf and the relationship to ice regime are a quantification and reinforcement of earlier work presented with much sketchier data and older techniques (Reimnitz and Barnes, 1974; Lewis, 1977a). Several aspects deserve additional discussion. A useful tool for the study of sediment dynamics would be a measure of the severity of modern gouging. The trend of gouges are indications of the direction of ice motion during the plowing actions which has implications for the direction of sediment transport on the shelf. The break in gouge character at 15-20 m suggest a relationship between seafloor geologic character and ice zonation. Gouge multiples form a unique set of gouges which may be indicative of only certain ice conditions, which would indicate the character and location of these ice conditions on the shelf now and in the past tens to hundreds of years.

P. *Severity of Gouging*

The severity of ice gouging is a result of the recurrence rate and intensity of ice-seabed interaction. High gouge density values do not always indicate severe gouging but may reflect predominantly shallow, narrow, and infrequent scouring in an area with relatively little sediment movement. Conversely, areas with relatively low gouge densities may experience many large gouge events whose record in the form of gouges has been partially or completely erased by sedimentation or hydraulic reworking (Barnes and Reimnitz, 1979; Reimnitz and Kempema, this volume).

For determining actual gouge severity, either the spatial and temporal distribution of ice keels or temporal occurrence of new gouges is needed. Few data on gouge recurrence rates and the character of new gouges exist. There are no public data on the temporal distribution of keels, only a qualitative knowledge of ice sail distribution, and an even sketchier knowledge of the

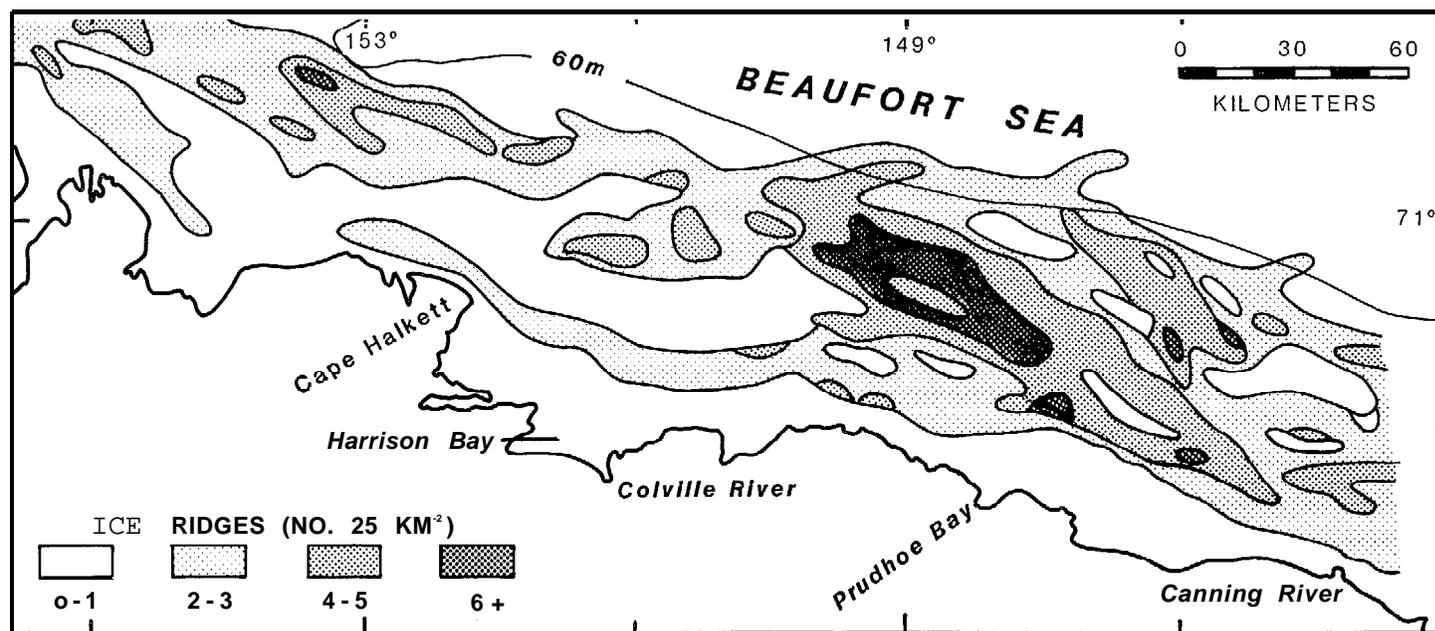


FIGURE 16. Density of ice ridges on the Beaufort Shelf (modified from Stringer, 1978). Compare with Figs. 9, 10, 11, 12, and 14.

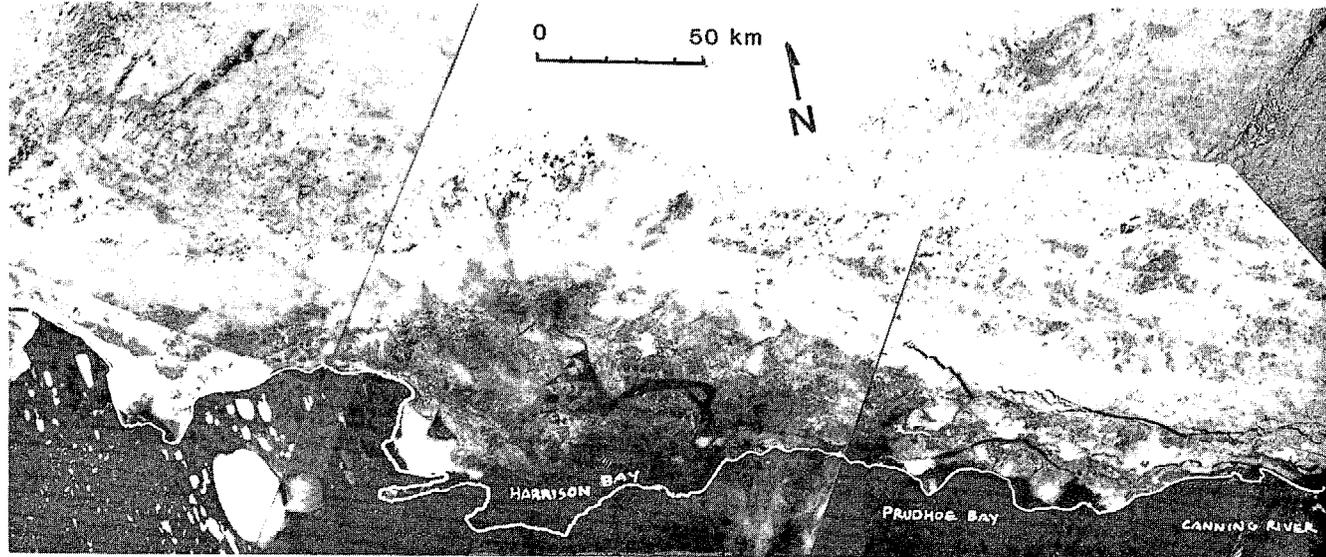


FIGURE 17. LANDSAT photomosaic of ice-covered Beaufort Shelf, showing areas of winter ice ridging. Dashed line is the 60 m contour and dotted line is the inner edge of the stamukhi zone. Imagery taken June, 1977.

quantitative relationship between sails and keels (Reimnitz *et al.*, 1978; Kovacs and Mellor, 1974; Tucker *et al.*, 1979; Wadhams, 1975). The rate of seabed reworking by ice as determined from repetitive surveys is limited to only a small part of the shelf, primarily inshore of the stamukhi zone, or to statistical considerations of gouge distribution (Lewis, 1977a,b; Barnes *et al.*, 1978; Wahlgren, 1979; Pilkington and Marcellus, 1981; Weeks *et al.*, this volume).

The most severe ice scouring should result with deeper, wider, and longer gouges and by this definition is approximated where gouge intensities are highest (Fig. 12). Our implications about gouge severity are therefore limited to a discussion of the general physical characteristics of gouge features and the overlying ice canopy.

The stamukhi zone is an area in which ice forces from the polar pack are expended, in part by building ice ridges (Thomas and Pritchard, 1980), but also on the seabed by disrupting sediments to form gouges. Reimnitz *et al.* (1978) showed that the most severe ice ridging occurs on the shelf. Sail height data (Tucker *et al.*, 1979) support this earlier concept (Fig. 15). The ice data also suggest that ridging and presumably grounding occur in this zone on a yearly basis (Stringer, 1978; Reimnitz and Kempema, this volume; Tucker *et al.*, 1979). Sediment cores from the stamukhi zone are turbated and lack horizontal laminations, while seaward and landward of the zone current-related laminations are common (Barnes and Reimnitz, 1974). This suggests frequent bottom reworking by ice in the stamukhi zone and also implies that all gouges could be modern features. Thus, we believe that seabed disruption is most severe where the stamukhi zone develops.

In Harrison Bay the relationship between ice regime and sea-floor processes is especially clear. The two zones of ice ridging near 10-m and 20-m water depths (Fig. 1b) correlate well with the highest gouge densities, maximum gouge depths, and highest gouge intensities as contoured in Figs. 9, 10, and 12.

In waters shallower than 10-15 m, the values of gouge intensity (Figs. 6d and 12) may not be true indicators of the rate of ice-seabed interaction. Here, hydraulic reworking of the seabed by waves and currents is frequent and the gouges represent fewer years of ice action (Barnes and Reimnitz, 1974, 1979). This interplay of ice and current is pronounced on shoal crests. The shoals are composed primarily of sand and gravel (Reimnitz and Maurer, 1979; Reimnitz and Kempema, this volume) on which gouges may readily fill through failure of the gouge ridges or through hydraulic reworking of sediments, either by storms or by intensified flow in the vicinity of grounded, or nearly grounded, ice keels.

Considering the ice regime alone, we would expect the number of ice gouge events in shallow water to increase while the depth and width of these events would decrease. Hibler *et al.* (1972) and Wadhams (1975, 1980) showed that the distribution of ice ridges and keels is exponential; thus, many more shallow keels are available to scour in shallow water than there are deep keels available in deep water. The depth and width of gouges in shallow water should reflect the smaller size of the keels, resulting in shallow, narrow gouges. Furthermore, shallow-water sediment may be able to resist gouging to a higher degree being coarser and more consolidated (Barnes and Reimnitz, 1974; Reimnitz *et al.*, 1980).

R. Ice Motion During Gouging

Inshore of the stamukhi zone (Fig. 1), ice motion in winter (and hence scouring) is restricted to tens of meters by the coast and the grounded ridges of the stamukhi zone. During the summer open-water period, this zone is often ice-free (Barry, 1979; Stringer, 1978). The most likely time for scouring within the fast ice zone is during spring breakup (June-July) and during fall freeze-up (October-November), when considerable ice may be present and in motion.

During formation of the stamukhi zone in winter, grounding and thus scouring occurs (Kovacs, 1976; Reimnitz *et al.*, 1978; Reimnitz and Kempema, this volume; Stringer, 1978). Once grounding has stabilized the zone (Reimnitz *et al.*, 1978; Kovacs 1976; Kovacs and Gow, 1976), the possibility of further scour to occur is limited. In waters beyond the stamukhi zone, ice ridges of sufficient draft are more rare although ice is present and in motion throughout most of the year (Hibler *et al.*, 1974; Kovacs and Mellor, 1974).

C. Direction of Ice Motion

The dominant ice motions along the Beaufort Sea coast in winter, when most scouring occurs, are from east to west (Campbell, 1965; Hibler *et al.*, 1974; Kovacs and Mellor, 1974; Reimnitz *et al.*, 1978). Thus, the dominant gouge orientation slightly oblique to isobaths indicates slightly onshore components of ice motion. This southwestward scouring action results in scour shadows in the lee of shoals inshore of the stamukhi zone.

When orientations are analyzed by water depth (Fig. 7C), the shallow inshore regions show orientations that are directed more onshore than in regions farther seaward. This onshore-turning also is characteristic for gouges and for ice movement in the Point Barrow area (Barnes, Shapiro, unpublished data) and for Harrison Bay (Rearic, unpublished data). We suggest that the long-term ice motion related to boundary stresses of the polar pack on the ice of the inner shelf may produce this pattern with shear (shore-parallel) motion more prevalent offshore and

compressional (onshore) motion more prevalent inshore.

P. *The 15-20 m Boundary*

Brooks (1974) was the first to note that a change occurs in ice gouge character in water 18 m deep. He reported that gouge density, width, and length decrease inshore of 18 m and held the opinion that the 18-m isobath marks the limit of the onshore motion of the deep draft ice-island fragments. These fragments were presumably responsible for the larger gouges seaward of 18 m.

The inshore edge of the stamukhi zone in many areas is associated with a change in geologic character near the 20-m isobath. This change is particularly pronounced from Prudhoe Bay to the Canning River. Cohesive but unconsolidated unstructured muddy gravel offshore abuts against overconsolidated layered muddy gravel inshore (Barnes and Reimnitz, 1974; Reimnitz and Barnes, 1974). Gouge depths are greater in the area of unconsolidated sediment due to its lower shear strength (Reimnitz *et al.*, 1980b). The sediment boundary is also associated with a bench or a shoal 2 to 4 m high (Reimnitz and Barnes, 1974; Barnes *et al.*, 1980b; Rearic and Barnes, 1980).

The boundary is also seen as a jog on graphs of mean values of ice-gouge characteristics (Fig. 5), including gouge multiples (Figs. 8A and 8C), in water 15 to 20 m deep. Gouge characteristics show increasing means with increasing water depth to depths of 35 to 45 m. This general trend in means is broken consistently in water depths of 15 to 20 m with one or two decreasing values before the continued increases toward deeper water.

Lower than expected values at 15 to 20 m depth may be due to resistance to gouging by the overconsolidated sediments that are common shoreward of this depth zone (Reimnitz *et al.*, 1980). Alternatively, hydraulic reworking of unconsolidated sediments on the numerous shoals associated with this depth zone (Fig. 1) may be responsible for reducing the mean values. The small bench or

shoal-like features (Barnes *et al.*, 1980b; Rearic and Barnes, 1980) and the large shoals, do provide shelter on the "down-drift side," where less scouring occurs. This sheltering, shown by a detailed study of Stamukhi Shoal (Reimnitz and Kempema, this volume) and discussed further below, is partially responsible for the anomaly in ice gouge parameters at the inner boundary of the stamukhi zone.

We are uncertain as to the origin of this geologic boundary and corresponding change in gouge character. However, either the inner edge of the Stamukhi zone is controlled by this boundary or the seasonally reforming stamukhi zone somehow is responsible for the geologic boundary. The overconsolidated sediments may be the result of freeze-thaw processes (Chamberlain *et al.*, 1978) during the Holocene transgression when sea level was lower or they may be caused by dynamic vertical, and perhaps more important, horizontal forces (Chari and Guha, 1978) associated with the intense ice-

seabed interaction at the inner edge of the stamukhi zone. McLaren (1982) documented higher sediment shear strengths in gouge troughs which he attributed to compaction during gouging.

F. Gouge Multiplets and First-Year Ice Ridges

As stated above, gouge multiples are divided into two types. The first type has commonly two, and always less than five gouges, and scours into the seabed to a depth of 50 cm or more (Fig. 4). The second type creates many incisions and is almost always unresolvable on the fathograms, which indicates that the gouge depths are less than 20 cm (Fig. 3).

The parallel tracks of multiples indicate single scour events. The uniformly shallow gouges cut into a horizontal shelf surface indicate scouring by adjoining ice keels that extend to the same depth below the sea surface. The formation of an ice ridge with multiple keels aligned as tines on a rake extending tens of meters laterally, all of about the same depth beneath the surface and creating gouge depths within as little as 20 cm of one another, is a highly improbable event. Yet we commonly observe gouge multiples that suggest this characteristic (Fig. 3).

We propose that gouge multiples are formed by ridge keels composed of first-year ice. This ice crumbled into piles of loose blocks, is shoved downward to conform to the seafloor over extensive areas. In order to gouge the bottom, the initially loose aggregate must be at least partially fused when its movement to another site takes place, otherwise short, interrupted, or irregular tracks would result, as blocks are rolled or dislodged from the keel. Instead, the tracks commonly are continuous, for hundreds of meters, as if made by a rake. A partial welding of the ice aggregate may occur during, or soon after ridge formation, because a heat sink from surface exposure to very cold temperatures is brought to the keels during ridge formation (Kovacs and Mellor, 1974). Seawater close to freezing point driven by oceanic circulation through such porous piles should result in rapid ice growth between the blocks. If such loosely bonded ridges were shoved into shallower water, its strength would be further increased by the resulting uplift (Kovacs and Mellor, 1974). The ability of first-year pressure ridges to gouge the bottom was observed in a study in Lake Erie (Bruce Graham, personal comm.). If the multiples under discussion really are formed by first year pressure ridges in the manner outlined, then they formed from ice tools made at the site. This means that multiples can form in depressions that seem to be protected from ice scouring by surrounding shallow sills such as lagoons.

Single gouges and multiples with few incisions are the deepest and widest gouges observed (Fig. 4). We believe that these features result from ice gouging by keels of multiyear ice ridges formed in deeper water. The multiple freezing seasons available for the welding of ice keels in a multiyear ridge makes for ice scouring tools more capable of forming deep gouges than newly formed first-year ridges (Kovacs and Mellor, 1974). The

gouging Of these deep features by multiyear ice ridges also implies that the keels of multiyear ridges are uneven in depth and gouge the bottom with only a few of their deepest keels.

VII. CONCLUSIONS

The most intense gouging on the Alaskan Beaufort Sea shelf is associated with the major ice ridging in the stamukhi zone. Gouge intensity is greatest in water between 15 and 45 m deep. The resultant gouges may be incised 4 m or more into the seafloor, have relief of 7 m or more, and saturate the seafloor with densities of more than 200 km⁻². Gouge orientations indicate an uphill scouring motion from east to west, principally parallel to shore. Gouging tends to decrease in intensity both inshore and seaward of the stamukhi zone. Gouge intensity inshore is less, even though ice-seabed impacts may be more frequent, because ice motion is less and the ice masses available to scour are small. The intensity of gouging is modified by non-ice-related factors such as shoals and seabed sedimentologic character, the increased rate of seabed impacts inshore, and increased rate of hydrodynamic reworking of the seabed in shallow water.

The inner edge of the stamukhi zone at 15 to 20 m is a geologic boundary marked by shoals, an abrupt decrease in the intensity of scouring, the presence of overconsolidated surficial sediments, and a change from offshore turbated to inshore beaded Holocene sediment.

Gouge multiples consisting of many shallow gouges are believed to be caused by the formation of first-year ice ridges whose keels are forced to conform to the seafloor over a wide swath during formation and indicate that first-year ridges can scour the seafloor.

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