Temporal and Spatial Character of Newly Formed Ice Gouges in Eastern Harrison Bay, Alaska, 1978-1982

by

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INTRODUCTION

Interaction between the dynamic elements of wind, water, ice and seafloor sediment is recorded on the continental shelf of the Alaskan Beaufort Sea in the form of ice gouges. Gouging of the seafloor by ice keels causes a ridge and furrow microtopography with accompanying horizontal and vertical movement of the sediments (Barnes et al., 1984). Sea-ice forces are responsible for large volumns of sediment disruption and redistribution across the shelf (Barnes et al., 1984), while hydraulic forces from waves and currents further redistribute this sediment, in many cases filling depressions and smoothing the bottom (Barnes and Reimnitz, 1979; Reimnitz and Kempema, 1982).

The sea-ice canopy formed over the inner shelf in winter is broken by zones of ice ridging caused by shear and compressional forces between permanent rotating polar pack ice and seasonal stable shore fast ice (Hibler et al., 1974; Reimnitz et al., 1978; Stringer, 1978; Prichard, 1980). The formation of ice ridges causes ice blocks to be forced under the ice surface to form ice keels which may come into contact with the seafloor. When mobile ice keels in contact with the seafloor plow through the sediments ice gouges are formed (Figure 1).

Recurrence rates for ice gouging of the seafloor as well as the yearly size variation of the features is of major importance today due to petroleum development activities now taking place in the Alaskan Beaufort Sea (Oil and Gas Journal, 1983). Development plans are dependent upon knowledge of yearly gouge rates, depths, widths, and areal distributions in order to protect subsea pipelines from ice impact and bottom founded structures from excessive point source loads and stresses. Sea-ice also has a significant geologic effect on the seafloor through the destruction of sedimentary features such as bedding structure (Figure 2) and biological borings, the building and/or maintaining of shoals (Reimnitz and Kempema, 1984), the bulldozing of shelf sediment onto the beaches by ice ride-up (Barnes, 1982; Kovacs, 1983; Kovacs, 1984), the creation of sedimentary traps by the plowing of ice gouge furrows (Reimnitz and Kempema, 1982), and the transport of sediment by actual bulldozing and resuspension of sediment during ice gouging (Barnes and Rearic, in press). Data on yearly ice gouge characteristics is unfortunately very sparse and an increase in the understanding of this marine process will lead to greater knowledge about the environment of high latitude continental shelves and their hazards. The presence of sea ice and extreme low winter temperatures creates an environment that is affected by forces not usually found in low latitude marine environments. Ice contact with the seafloor, permafrost in the offshore sediments, the draining of the rivers in spring through holes in the ice canopy, and ice ride up and piling on the beaches are dynamic conditions unique to the high latitude environment.

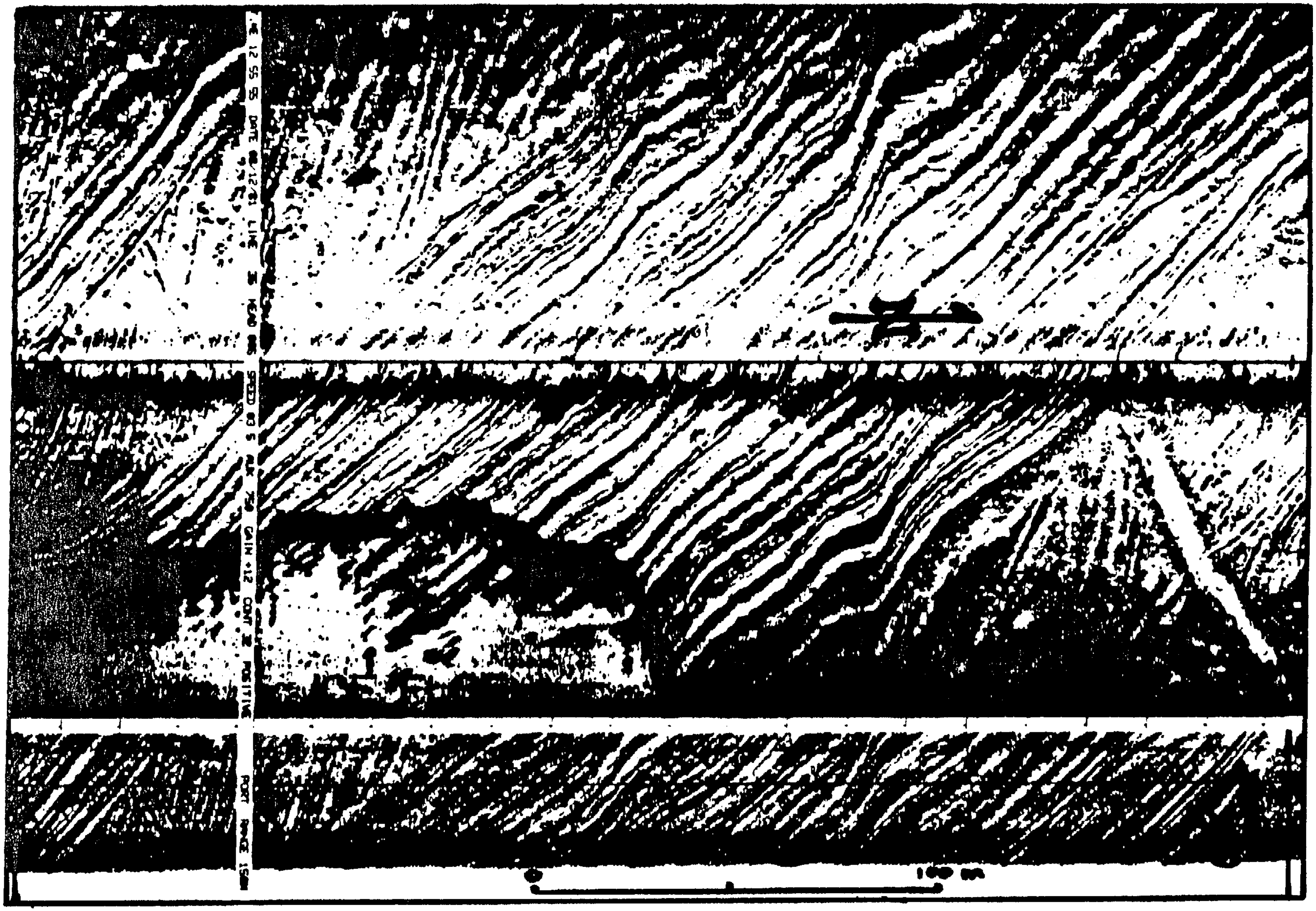


Figure 1, Sonograph record of a multiplet gouge east of Barter Island. Ice floe along bottom margin of record is grounded in about 25m of water. North is to the right and gouging taok place in a southeasterly onshore direction.

Figure 2. Sonograph record of an ice gouge produced in a ripple field. Note the destruction to the bedding. The gouge is about 5m wide and 20cm deep.

Ice gouges that are dated as less than one year old have been studied in the Alaskan Beaufort Sea and the results are presented here. The characteristics of these relatively newly formed ice gouges are presented and an interpretation aa to the significance of the information is discussed. In some cases the data speaks for itself by allowing the reader to observe variations in the characteristics over time and between shelf environments, while in other cases further interpretation of the data in the form of graphs, figures, and discussion inhances the importance of the study in relation to sedimentary processes now occuring in the Alaskan Beaufort Sea.

BACKGROUND

The influence exerted by sea-ice on high latitude and glacial seafloor sediments has been known for some time (Kindle, 1924; Carsola, 1954; Rex, 1955). Early studies centered on qualitative description of ice gouge features (Pelletier and Shearer, 1972; Kovacs and Mellor, 1974; Reimnitz and Barnes, 1974; Lewis, 1977a), while recent studies have attempted to quantify ice gouge characteristics (Toimil, 1979; Wahlgren, 1979a; Rearic et al., 1981; Thor and Nelson, 1981; Reimnitz et al., 1981; Barnes et al., 1984; Weeks et al., 1984). The above studies have centered on the total population of ice gouges of all ages existing on the seafloor at any one time.

The rate at which ice gouges are added annually to this record is not fully understood although studies to determine the ice gouge recurrence rate on the shelf have recently been reported (Lewis, 1977b; Reimnitz et al., 1977; Barnes et al., 1978; Pilkington and Marcellus, 1981; Weeks et al., 1983; Barnes and Rearic, in press). Assessing the rate of ice gouge reccurence is difficult. To determine recurrence rates in this study two tracklines were reoccupied on an yearly basis and the gouges less than one year old were measured. Comparing one years record to the next allows a good approximation of the gouges which are added to the seafloor over the previous year. This technique requires precision navigation and for optimum survey conditions, open water free of floating ice.

The first attempt to assess yearly ice gouging rates in the Alaskan Beaufort Sea was by Reimnitz et al. (1977). Preliminary rates were determined for the years 1972-1973. In a latter study estimates for the years 1975-1977 were calculated by Barnes et al. (1978). Gouge rate estimates from both of these studies agreed favorably with each other. They found that approximately 2% of the seafloor was gouged yearly in eastern Harrison Bay with a mean gouge depth of about 20 cm. Although they suggested that many gouges shallower than 20 cm existed, the resolution of their equipment precluded enumeration of the smallest gouges. Rapid infilling of the smallest gouges also increases the difficulty in recording these features. Another problem in these studies has been the lack of an extended data base in order to determine long term and regional variability in the ice gouge rates.

Environmental Setting

Harrison Bay is a large shallow embayment of the Alaskan Beaufort Sea coast (Figure 3). The embayment is influenced by outflow from the Colville River in the south which has created a delta in the southeast portion of the bay. Other characteristics of Harrison Bay include a barrier island system in the eastern part of the bay and sand and gravel shoals in the east and northern parts of the bay (Reimnitz and Maurer, 1978). The nothern extent of the bay is marked by shoals at a distance of 50 km from shore in 20 m of water. The shoals attain a height of about 10 m above the surrounding seafloor.

The floor of the bay consists of patchy sand and mud deposits interspersed with layers of stiff silty clay which are highly consolidated and create resistant ledges in the troughs of some ice

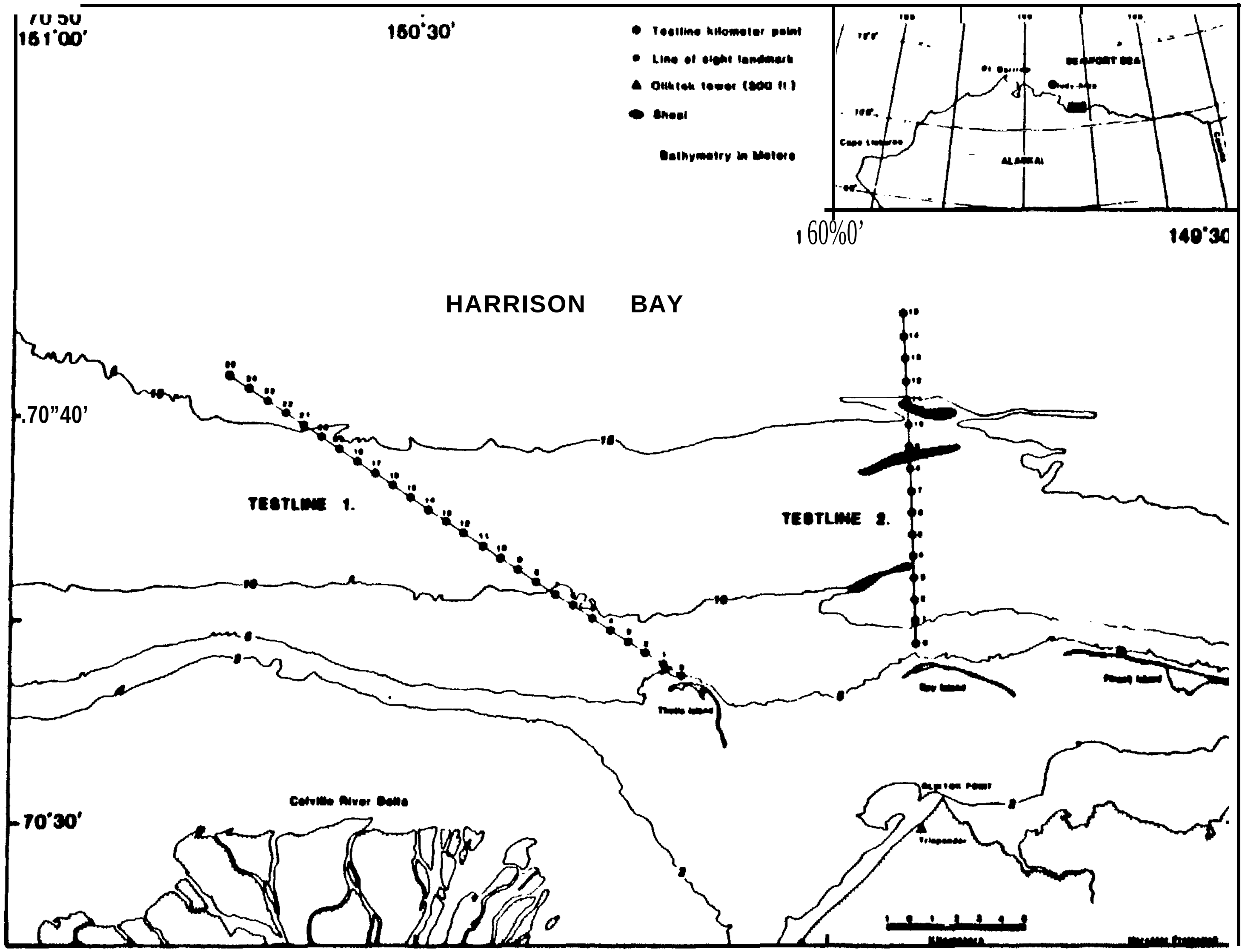


Figure 3. Location map of the study area. Note the location of the shoals along testline 2 and the lack of these features along **testline** 1. **Bathymetry is in meters.**

gouges (Reimnitz et al., 1980). Annual suspended sediment imput to the bay from the Colville River is about 5.8 millon metric tons and consists mostly of fine grained inorganic material erroded from river banks, mud bars and the thalweg of the river channels (Arnborg et al., 1967). During the time of greatest sediment transport, usually early June, the mouth of the Colville River and Harrison Bay are covered by ice. The sediment discharged at this time flows over the ice and is eventually either deposited on the bottom through holes erroded in the ice or is carried away on the ice during spring breakup by wind and current (Walker, 1974). Thus, sedimentation in this area is highly non-uniform and differs from deltaic processes of temperate climates.

Freeze up in Harrison Bay begins in late October or early November and is initiated by the formation of slush and frazil ice. As the sea-ice thickens a shore fast ice canopy is formed over the bay and the influence of hydraulic processes is minimized (Matthews, 1981). Ice motions within the ice canopy caused by wind and current create a zone of grounded ice ridges wherever the ice motion is met by resistance from the shore fast component of the canopy. In Harrison 13ay this ridge zone, termed the stamukhi zone, occurs in water depths of between 8 and 12 meters (Reimnitz et al., 1978; Stringer, 1978). Further seaward, in water depths of approximately 20 meters, another stamukhi zone occurs and is associated with the shoals of the northern boundary of the bay. Ice keels created during ice ridge formation are responsible for ice gouging throughout the winter. Isolated multi-year ice traped in the seasonal ice canopy during freeze up may also account for a significant amount of ice gouging (Barnes et al., 1984).

In May and June the Colville River thaws prior to the break up of the sea-ice canopy and floods the canopy with fresh water in the near shore areas. The flooding increases the rate of sea-ice break up and melting. Throughout the summer isolated ice remnants from the previous winter may remain grounded until the next winter freeze up. During the summer open water conditions allow wind forces to create waves and currents that may rework seafloor sediments (Reimnitz and Maurer, 1979). Shoal crests in particular are reworked yearly by these hydraulic processes (Reimnitz and Kempema, 1984). Summer ice conditions can vary and at times can be severe enough to affect navigation by causing excessive deviation from desired courses.

In the southeastern portion of the bay are two barrier islands from which the tracklines of this study initiate (Figure 3). The tracklines are here after termed testlines in that they have been reoccupied yearly with precision navigation techniques since 1972. Testline 1 extends from Thetis Island in a northwesterly direction and has been surveyed to a maximum length of 25 km and a maximum water depth of 16.5m when ice conditions have been favorable. The seafloor covered by testline 1 is relatively smooth with a gentle slope of approximately O.O5 degree. Testline 2 extends north from Spy Island and has been surveyed to a maximum length of 15 km and a maximum water depth of 18.5 m under favorable conditions. The seafloor covered by testline 2 has a slope about the same as testline 1, however, the seafloor here contains 3 successive 2 to 3 meter high shoals, trending east-west, subparallel to the bathymetric contours, in water depths of between 8 to 15 meters. Because of variable ice conditions from year to year the distances covered on the testlines varied yearly.

Study Objectives and Terminology

The objective of this study is intended to extend our understanding of gouge rate variability in both time and areal distribution and to compliment the previous studies of Reimnitz et al. (1977) and Barnes et al. (1978). The variability in gouge size and shape which occur yearly are an important part of this understanding (Figure 4). A thorough description of ice gouge terminology can be found in Barnes et al. (1984) and consists of essentially the following elements:

1) Gouge Event - The passing of a grounded ice keel, leaving one or more furrows, through the bottom sediments of any ice influenced body of water.

2) Gouge - Furrow left on the seafloor whether caused by a single or multiplet event.

3) Single Gouge - The furrow left on the seafloor after the passing of a grounded ice keel having only one projection contacting the bottom.

4) Multiplet - The furrows left on the seafloor after the passing of a grounded ice keel having two or more projections contacting the bottom.

5) Gouge Depth - The depth of a gouge measured vertically from the average level of the surrounding seafloor to the deepest point in the gouge. Only the deepest incision of a multiplet is measured.

6) Gouge Width - The width of a gouge measured horizontally at the average level of the surrounding seafloor. This measurement pertains only to single gouges and does not include the ridges of sediment often found bounding a gouge.

7) Ridge Height - The height of the ridge of sediment bounding a gouge measured vertically from the average level of the surrounding seafloor to the highest point on the ridge. The ridge sediments are primarily made up of material plowed from the corresponding gouge.

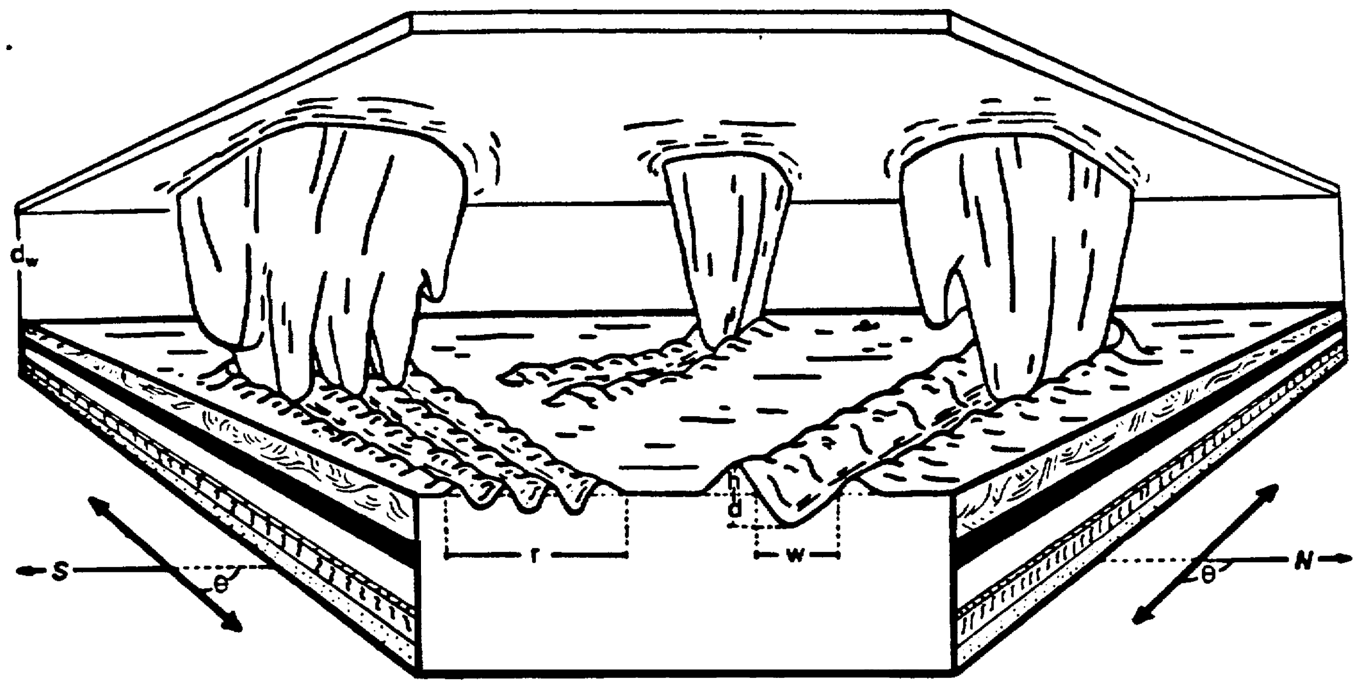
8) Gouge Orientation - The orientation of au ice gouge relative to true north. Orientations are reported as a vector between O and 180 degrees but do not imply a direction of movement for the ice keel which created the ice gouge.

9) Number of Incisions - The total number of ajoining furrows created by a multiplet event. In some calculations each furrow is treated as an individual gouge while in others the event itself is only considered.

10) Disruption Width - The total horizontal width of a gouge measured at the average level of the surrounding seafloor and including the ridges bounding the gouge. The disruption width of single gouges is estimated to be approximately 25% greater than the gouge width measurement. The width measurements of all multiples are reported as disruption widths.

11) Gouge Termination - The terminous of a gouge on the sonograph record. Generally associated with the terminous is a push moraine of sediment surrounding the final grounding area. The gouge termination is a reliable indicator of the true direction of ice keel movement.

12) Gouge Length - The length of a gouge or multiplet. This measurement is the most difficult to obtain because most gouges do not start and end on the sonograph records. For the purposes of this study all gouges which do not start and end on the sonograph record



d - Gouge Depth
w - Gouge Width
h - Ridge Height
r - Disruption Width
θ - Gouge Orientation
d_w - Water Depth

Figure 4. Idealized sketch of an ice gouge and gouge multiplet and the terms used to describe the characteristics measured in this study.

are considered to be in excess of 250 meters long (the width of the sonograph record) for the calculations in which they are used.

Methods of Data Collection

Two tracklines in Eastern Harrison Bay (figure 3), 50 km west of Prudhoe Bay, were resurveyed each year between 1977 and 1982 in order to determine the recurrence rate of ice gouging, ice gouge characteristics, and the resultant effects to the seafloor. Five years of data exist for testline 1 and four years of data for testline 2. The data analized in this study were collected from onboard the USGS research vessel Karluk. Data collection techniques involved the towing of a side scan sonar fish above the seafloor and recording the reflection returns on a wet paper recorder. The side scan sonar system presents a map view of the seafloor (Belderson et al., 1972) and the slant range (width of the record) was generally 125 m on either side of the ships track. Sonar coverage was accomplished using a model 259-3 EG & G side scan sonar recorder and a model 272 EG & G sonar fish with a 105 kHz pulse. Measurements of number of gouges, width, orientation, termination and length were made from the monographs (Figure 4). It is estimated that the maximum resolution of the monographs is 10 cm.

Bathymetry data were recorded on a high-resolution fathometer using a dry paper recording system. A Raytheon RTT- 1000 recording fathometer with a 200 kHz transducer allowed resolution of features as small as 15 cm under ideal conditions. Measurements from the fathograms included water depth, gouge depth, and ridge height (Figure 4).

Navigation of the tracklines was accomplished using a combination of trisponder ranges (acoustic pingers with an accuracy of about +-5 m), line of sight, and copies of previously recorded monographs for comparison with the copies being recorded at that time. This system under ideal conditions will give an accuracy of position to within 5 meters. In the worst cases ice in the path of the boat will cause detours in the testline direction which may cause a loss of coverage dependent on the size and amount of ice encountered. Poor weather and sea state as well as system failure may also degrade the record quality.

Testline 1 navigation consists of line of sight visuals between Oliktok tower and a hut (the only structure) on Thetis Island (Figure 3). The distance from Oliktok tower, on which the range trisponder is located, to the begining of the testline is 12557 meters. The testline is run on a course of 305 degrees true from this point. Deviation from the course can be noted by nonalignment of the tower and hut. The begining of testline 2 lies 7520 meters from Oliktok tower and 9670 meters from a trisponder located on Thetis Island. The testline is then run due true north from this location. Line of sight visuals between a day beacon on Spy Island and the tower on Olikok Point are also used to keep the trackline alignment accurate. On both testlines, photographs of testline monographs obtained in previous years were used to verify accuracy of trackline position by comparing bottom features with those previously recorded (Figure 5).

Methods of Data Analysis

The tracklines were plotted on navigation charts in the field each year. Navigation was initially divided into one kilometer segments beginning one kilometer from the barrier island coast and continuing in an offshore direction. The time for each kilometer way point was determined and these points located on the records by interpolation between time marks on the sonograph and fathogram records. The records were then compared to the preceding years recordings in order to determine new gouges and their characteristics. The measurements were recorded on data sheets and are included as an appendix to this study.

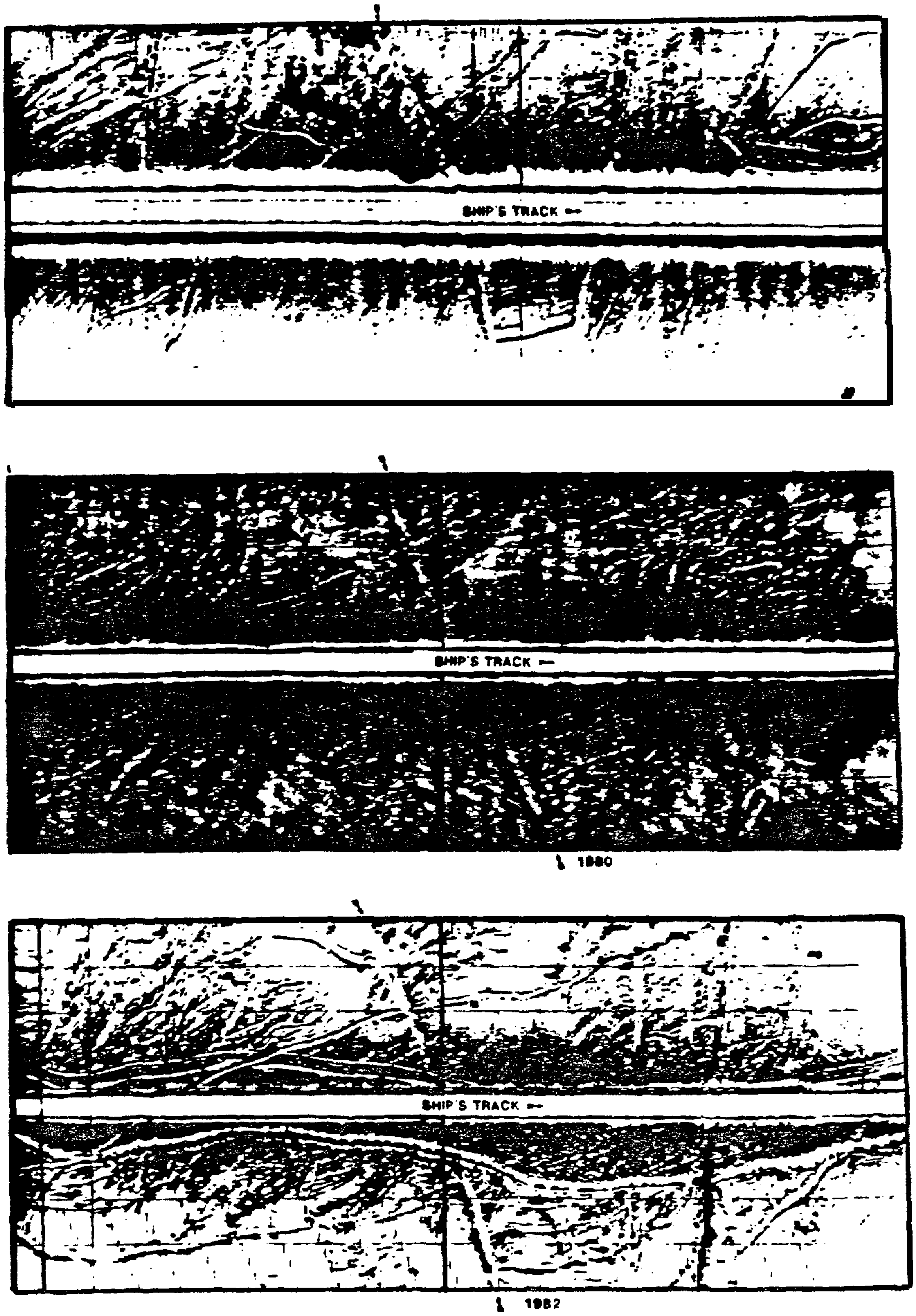


Figure 5. Thret **sonographs** of tbe same **areal** coverage from **testline 1** for the years 1976, **1980, and 1982**. A reference **gouge** created **in 1976 is** identified by the **arrows** on the monographs Note the **changes** to **the** seafloor over time as gouges are created and subsequently **infilled.**

RESULTS

The results of this study are based on the observation and measurement of 1292 ice gouges formed between 1977 and 1982. For the purposes of this study these gouges will be termed 'new' gouges. This is done in order to distinguish post 1977 gouges from gouges formed prior to 1977. The gouge characteristic measurements extracted from the records include depth, width, ridge height, length, orientation, and in the case of gouge multiples, the number of incisions created by a multiplet event and disruption width (Figure 4). The data are described by variations in the total new gouge occurance, yearly variations, and variation between tracklines.

Means and Maximums

All data from both testlines over all years were combined. The data are contained in the data sheets included as Appendix A and in Table I. One of the major observations noted from this study is the high variability in the number of gouges formed from year to year (Table 1). Although having differing seafloor morphologies, both areas averaged about 8-9 new gouges per 1 km segment per year over the course of this study. The number of gouges created over a years time did go as high as 64 in a 1 km segment on testline 1 and 44 on testline 2. However, the highly gouged segments were generally found in water depths greater than 10m.

Most gouges are shallow, 20 cm deep or less. Deep gouges occur only rarely and are relagated to the deeper water depths of the two areaa. Gouge depths ranged from a minimum of 10 cm to a maximum of 1.4 m. Segments containing the deepest gouges were in water depths greater than 10 m, much the same as occured with high gouge densities.

The formula for calculation of a distribution mean is dependent upon the type of distribution the data assumes when plotted. Most distribution means are calculated based upon the formula for the normal (Gaussian) distribution which is:

$$M = \frac{x_1 + x_2 + x_3 + \cdots x_n}{n}$$

where x is a particular value in the distribution and n is the number of x values in the distribution. When the means of the new gouge depths are calculated using the normal distribution formula, they are 16 cm for testline 1, 14 cm for testline 2, and 15 cm for the total study. These means are approximately 25% shallower than three found in previous studies in this same area (Reimnitz et al., 1977; Barnes et al., 1978). In these earlier studies those gouges less than 20 cm were not included in the calculation of mean gouge depth, which may partially account for the differences noted.

Because the gouge depth data from most ice gouge studies fits an exponential distribution (Barnes et al., 1984; Lewis, 1977a; Weeks et al., 1984) the formula which could be used for the

TESTLINE 1.

Kilometers	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25		
Water Depth (m)	4.9	5.8	8.3	8.5	9.6	10.1	10.0	10.4	10.9	11.5	12.0	12.4	12.8	13.1	13.6	13.8	14.2	14.6	14.9	15.1	15.2	15.5	15.4	16.0	16.5	16.7		
No. of Gouges																											Total	
1977-1978	0	2	6	0	0	6	0	0	1	18	5	4	15	21	18	8	6	0	0	0	0	10	4	5	0		127	
1978-1979	4	4	13	20	12	0	1	4	9	7	15	9	2	2	6	24	8	3	8	1	-	.	0				142	
1979-1980	.	.	16	30	k	64	51	14	10	5	2	8	0	1	3	40	4	-	13	13	0						278	
1980-1981	.	.	9	15	36	9	2	12	14	15	6	11	15	15	22	30	7	9									207	
1981-1982	1	0	2	8	10	7	1	2	20	20	6	6	1	1													91	
Max. Gouge Depth (m)																											Deepest	
1977-1978	0	.1	.1	0	0	.1	0	0	.3	.2	.1	.1	.1	.3	.2	.3	.5	0	0	-0	0	.5	.3	.3	0		.5	
1978-1979	.1	.1	.1	.1	.1	0	.1	.1	.1	.2	.4	.2	.1	.1	.1	.1	.2	.1	.2	.2	.	-	0				.4	
1979-1980	.	.	.1	.8	.1	.1	.1	.1	.1	.1	.4	.3	0	.1	.2	.4	.2	-	.3	.3	0						.4	
1980-1981	.	.	.3	.7	.4	.2	.1	.1	.3	.3	.6	.1	.6	.3	.2	.3	.3	.2									.7	
1981-1982	.1	0	.1	.1	.3	.1	.1	.2	.4	.1	.4	.2	1.0	.5													1.0	
Total Disruption Width (m)																											Total	% Dist.
1977-1978	0	18	20	0	0	9	0	0	4	70	3	29	102	92	46	60	37	0	0	0	0	49	24	46	0		609	2.4
1978-1979	8	8	42	59	45	0	3	25	50	24	60	25	6	5	23	101	30	12	33	4	-	-	0				563	2.7
1979-1980	-	-	71	123	14	174	214	31	43	33	31	62	0	10	27	146	21	0	82	82	0						1164	~~6.5~~ 6.1
1980-1981	-	-	30	70	58	36	8	64	62	96	71	51	74	62	105	113	35	40									975	6.1
1981-1982	1	0	10	31	31	29	4	5	58	62	25	42	22	28													348	2.5

Total No. of New Gouges: 845 Deepest New Gouge: 1.0m Total Disruption Width: 3659m Mean Annual Percent Disturbed: 4.0

TESTLINE 2.

Kilometers	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25		
Water Depth (m)	6.9	10.0	11.4	11.5	32.2	13.3	14.2	14.9	14.4	14.3	15.1	15.4	16.3	17.2	17.9	18.5												
No. of Gouges																											Total	
1977-1978	12	4	1	22	1	30	17	4	23	0	8	13	11	17	7												170	
1978-1979	0	1	25	44	12	1	0	0	20	0	9	0	1														113	
1979-1980	0	0	0	21	0	1	2	1	14	0	2	1	4														46	
1980-1981	2	5	2	25	7	6	2	0	Ib	7	7	Ib	19	8													118	
Max. Gouge Depth (m)																											Deepest	
1977-1978	.1	.1	.1	.1	.1	.2	.2	1	.1	0	.1	.2	.4	.7	.5												.7	
1978-1979	0	.1	.1	.2	.1	.1	0	0	.1	0	.2	0	.1														.2	
1979-1980	0	0	0	.2	0	.1	.1	.1	.2	0	.1	.1	.3														.3	
1980-1981	.1	.1	.1	.1	.1	.1	.1	0	.2	.4	.2	1.4	.3	.3													1.4	
Total Disruption Width (m)																											Total	% Dist.
1977-1978	72	19	3	97	9	134	65	20	50	0	44	58	56	139	60												826	5.5
1978-1979	0	4	97	149	30	3	0	0	53	0	18	0	4														358	2.8
1979-1980	0	0	0	82	0	3	15	3	48	0	4	1	15														171	1.3
1980-1981	11	13	5	121	21	14	4	0	64	28	49	88	88	34													540	3.9

Total No. of New Gouges: 447 Deepest New Gouge: 1.4m Total Disruption Width: 1895 Mean Annual Percent Disturbed: 3.4

Table 1. Condensed data **from Appendix A showing annual** variation **in gouge characteristics and distribution.**

calculation of the mean is as follows (Miller and Kahn, 1962):

$$E = \log_b \left(\frac{b^{x_1} + b^{x_2} + b^{x_3} + \cdots b^{x_n}}{n} \right)$$

b = log base = 10

When this formula is used to calculate the mean the average new gouge depth for testline 1, testline 2, and the total study is 18 cm. This value agrees more favorably with the new gouge depth mean (20 cm) determined from other studies of this area (Barnes et al., 1978).

The area of the seafloor disrupted can be considerable over short time spans. The total width of disruption over the course of this study was 5554 m over an average total trackline length of 34 km. This is an average of 37 m/km/year of disruption occuring in the two areas. As with the above gouge characteristics, the largest disruptions occured in water depths greater than 10 m. In 1980 a maximum of 214 m of disruption occured in a 1 km segment and was mostly due to scouring of the seafloor during 5 multiplet events. Single gouges are generally responsible for narrow disruptions in the study area.

Most gouges that were formed had no measureable sediment ridge associated with them. This is due in part to the resolution of the fathograms but also to the shallow depth of most gouges, allowing little sediment to be available to form the ridges. The ridges are also most susceptible to errosion by waves, currents and further ice gouging. The shallow water depths of the two areas subject the seafloor to wave and current reworking and, therefore, may also have an effect on the length of time a sediment ridge is in existance. Only 4 ridges of the 384 measured exceeded 50 cm. Mean ridge height was 14 cm with a maximum height of 90 cm.

Gouge length is the most difficult measurement to obtain and we, therefore, have the least data on this characteristic. Some new gouges begin or end off the record while most travel across the entire width of the record. Few gouges begin and end on the sonograph records and these are generally very shallow, narrow, and short. For these reasons, ranges and the mean for this characteristic have not been calculated.

Yearly Variations In New Gouge Characteristics

Although new ice gouge occurance is ubiquitous in the study area, both consistency and variation are noted between years and areas. New gouge frequency curves for testline 2 show a yearly consistency in the peaks of frequency which correlate with the areas and water depths of the shoals (Figure 6). Seaward of the outer most shoal the new gouge frequencies increase rapidly with increasing water depth. On testline 1 new gouge frequeny curves do not exhibit consistency in areal distribution other than a general increase in gouge frequency with an increase in water depth and a peak that shows up at 16m depth particularly in the years 1979 through 1981.

Total disruption width in a segment is a function of the number of gouges in that segment (Barnes et al., 1934) and, therefore, the total disruption width curves (Figure 7) reflect the same peaks in the data as the frequency curves (Figure 6). Disruption width curves of testline 1 data

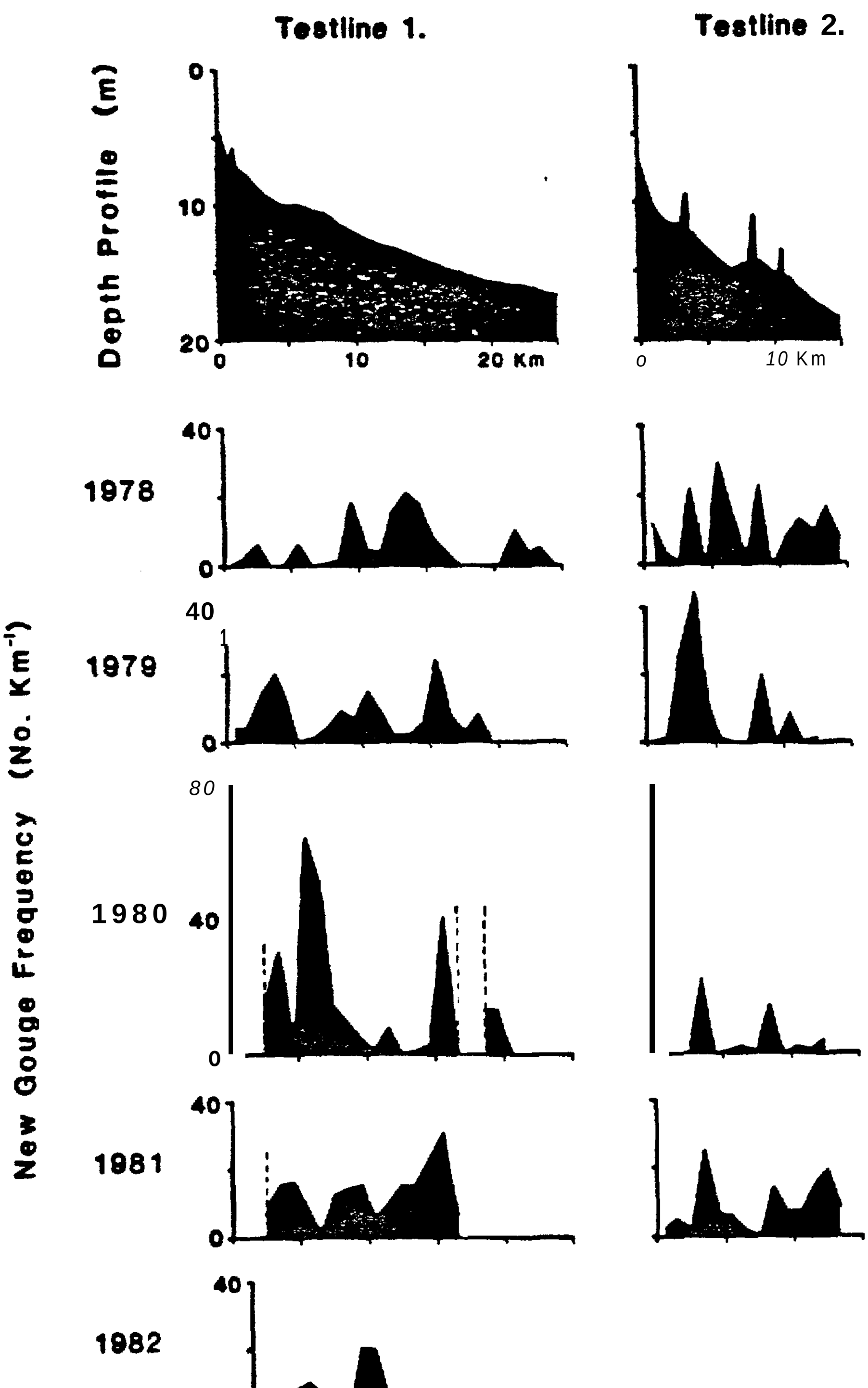


Figure 6. Graph of yearly gouge frequency along both testlines. Note the correspondance of the major peaks of the testline 2 graphs to the shoal locations on the depth profile. In 1978 high frequency gouging also took place between the inner two shoals. Gouge frequency along testline 1 is more variable in its location on the seafloor with very high frequencies often found in shallow water such as occured in 1980.

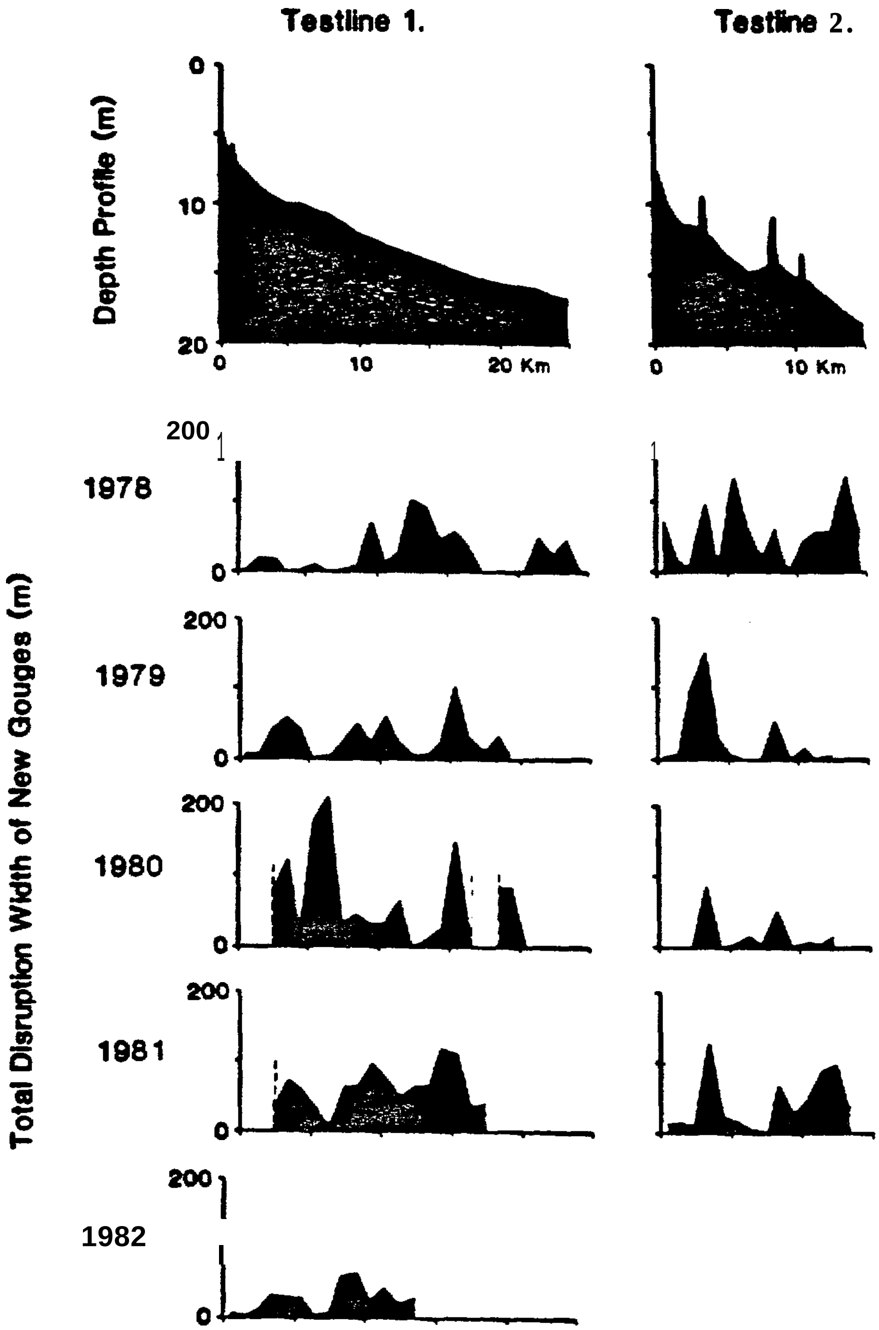


Figure 7. Graph of the total yearly disruption width in each 1km segment along both testlines. Note the similarity Of these graphs to three of gouge frequency. Peaks in the disruption values correspond to **the** *peaks* **of gouge frequency for** both testlines indicating a close relationship between the number of gouges created in a segment and tbe amount of the bottom disturbed by the passing of ice keels through the sediments.

show that disruptions in excess of 100 m/km/year occur in water depths as shallow as 8 m. Testline 2 disruption width curves show that disruptions in excess of 100 m/km/year generally occur on shoal crests or in water depths greater than 11 m. Relatively large disruptions can occur between the shoals as happened between 1977 and 1978 (Figure 7).

The maximum depth of new gouges was determined for each i km segment. On testline 1 maximum depths increase with increasing water depth and show a significant increase at a water depth of 10 m (Figure 8). On testline 2, the yearly consistency of the peaks in new gouge frequency are again noted in the curves of maximum gouge depth. However, although there are peaks inshore of the seaward most shoal of testline 2 these peaks are low values (20 cm or less) and the deepest gouges (>50 cm) occur offshore of the most seaward shoal in 15 m or more of water.

Maximum gouge depth and mean gouge depth for each 1 m water depth interval, averaged over the 5 and 4 years of data, demonstrate the effects of the shoals of testline 2 in controlling the depth of gouging (figures 9 and 10). On testline 1, both the maximum and mean values of gouge depth are greater than those of testline 2 for equivalent water depths. On testline 1, gouges as deep as 70 cm have occured in water depths as shallow as 8 m and gouge depth averages steadly increase towards deeper water. On testline 2, inshore of 15 m water depth, the deepest gouges found were consistently 20 cm or less and the mean gouge depth was approximately 10 cm. Seaward of 15 m water depth the mean gouge depths begin to approximate those of testline 1.

Frequency Distributions

Frequency distribution curves of the new gouge depths, widths and ridge heights (Figure 11) fit a negative exponential distribution (Benjamin and Cornell, 1970; Miller and Freund, 1977; Weeks et al., 1981). There are many more small gouges than there are large ones. In studies by Barnes et al. (1984), Barnes and Rearic (in press), and Weeks et al. (1984) the gouge depth distributions of the 'total' gouge population and the 'new' gouge population were also found to be a negative exponential (Figure 12), although gouge depth means were greater (56 cm and 19 cm) than in the present study (18 cm) due to differences in water depths and areas surveyed. Similar gouge distributions were calculated for gouge depths in the Canadian Beaufort Sea by Lewis (1977a,b) and Wahlgren (1979a,b). The deepest and widest gouges and highest ridges of this study do not fit the negative exponential distribution and in fact appear to occur more often than the distribution would call for. Examination of gouge frequency distributions from other studies shows a similar excess at the maximal end of the distributions.

The semilog plots of disruption width frequency vs. water depth and ridge height frequency vs. water depth (Figure 11) are similar in shape to the gouge depth frequency and suggest a negative exponential might also best describe the distribution of this data. Again, as with the gouge depths, the widest gouges and the highest ridges do not fit the distribution. It should be noted that part of this problem may be due to the short time over which the observations were made as it can be seen that there is only one observation for each width interval over 50 m (with the exception of two at 60 m) and each ridge height interval over 50 cm. Figure 11 suggests, therefore, that most gouges are shallow, narrow features having either a very small ridge of excavated material bordering the furrow or, as is often seen on the records, no disernable ridge at all. The most notable problem with attempting to relate the gouge characteristic frequency curves to a negative exponential distribution is the lack of fit in the high value range (gouges >80 cm deep and >50 m wide, and ridges >50 cm high).

Percent Of Seafloor Disrupted

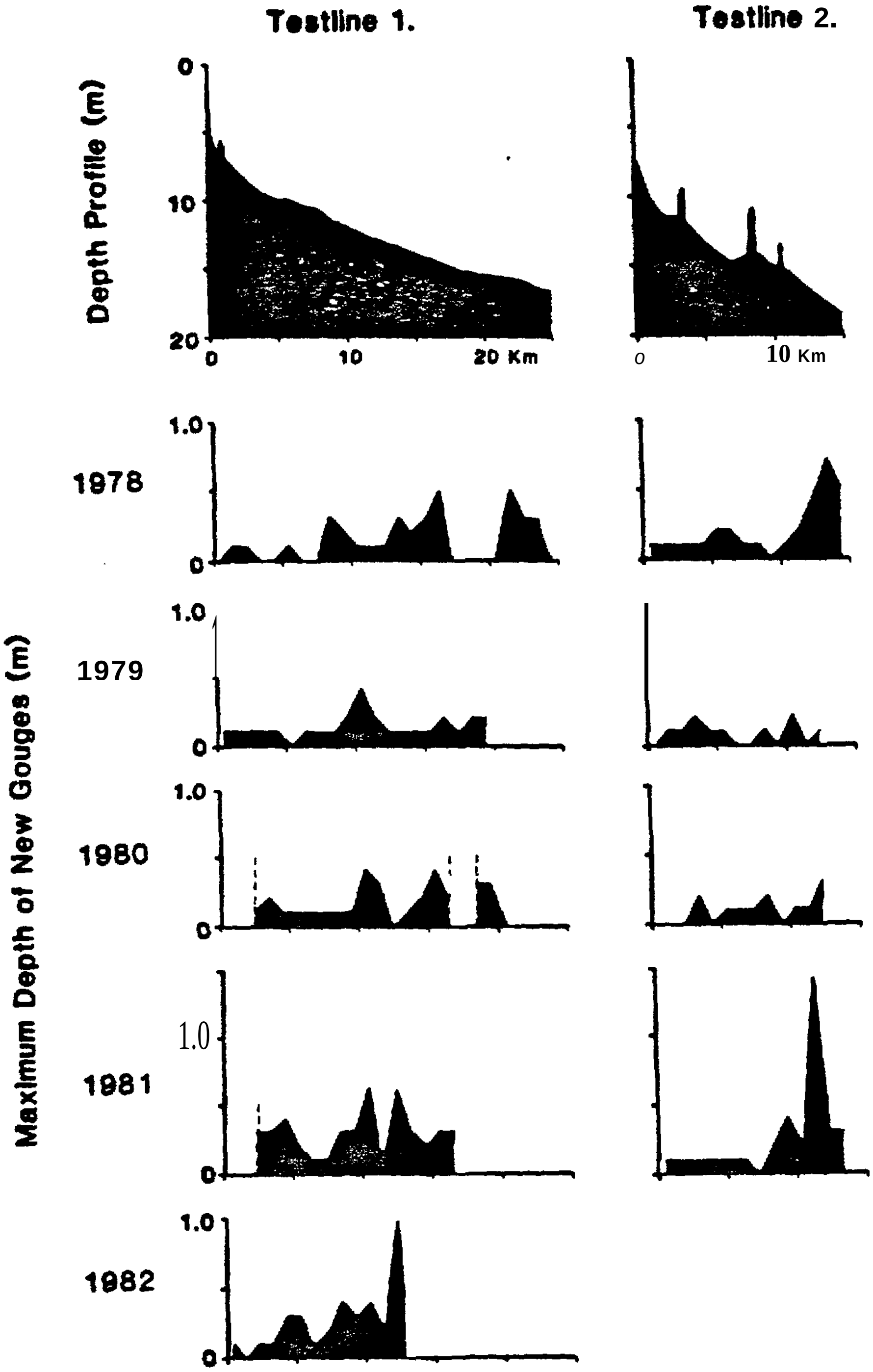


Figure 8. Graph of the deepest gouge in each 1km segment each year, Note that there is no **simularity to** the graphs of gouge frequency and disruption width. Deep gouges (> **50cm)** on **testline** 2 **are** restricted **to areas seaward of the** outer most shoal (water depths > **15m)** while on **testline** 1 **gouges of this depth can occur in water depths less than** 10m.

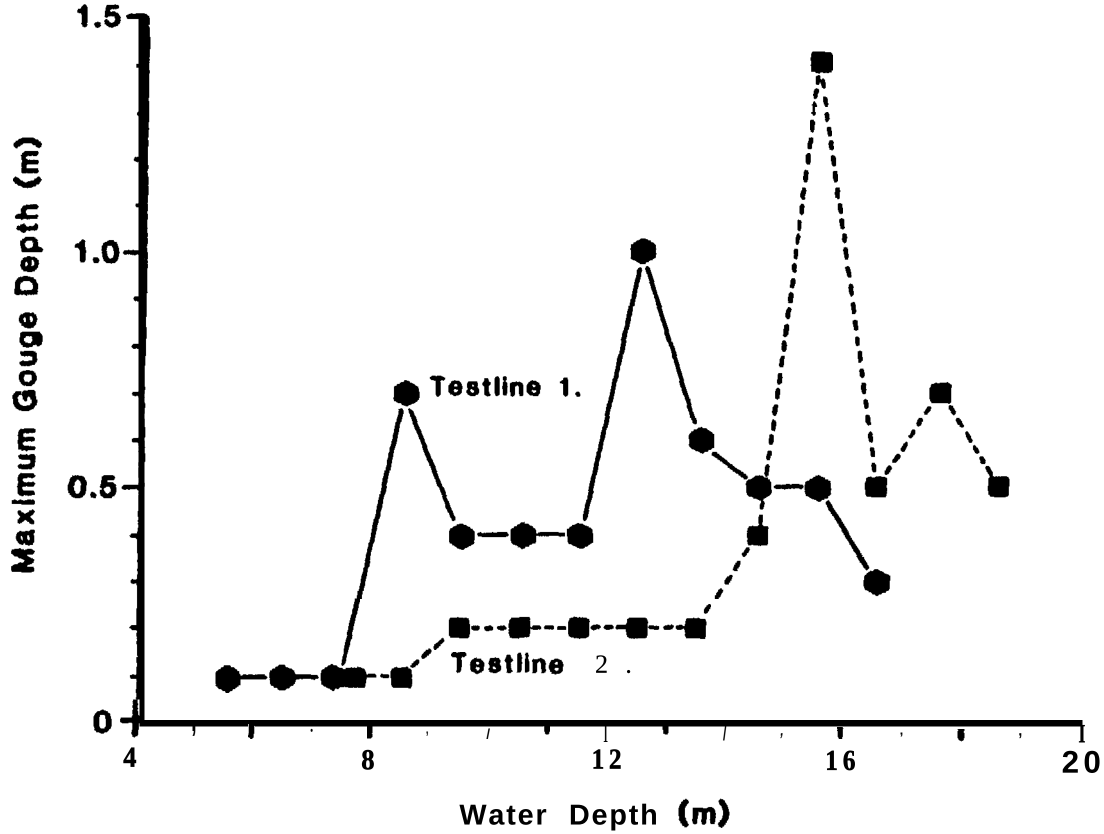


Figure 9. Graph of the deepest gouge found in each 1m water depth interval over the entire course of the study. Again, as in figure 8, deep gouges are restricted to the outer areas of **testline** 2. **Inshore of 15m water depth the deepest gouges found were consistently 20cm or less. On testline 1 deep gouging can occur in shallower water depths (note the 70cm deep gouge in only 8m of water).**

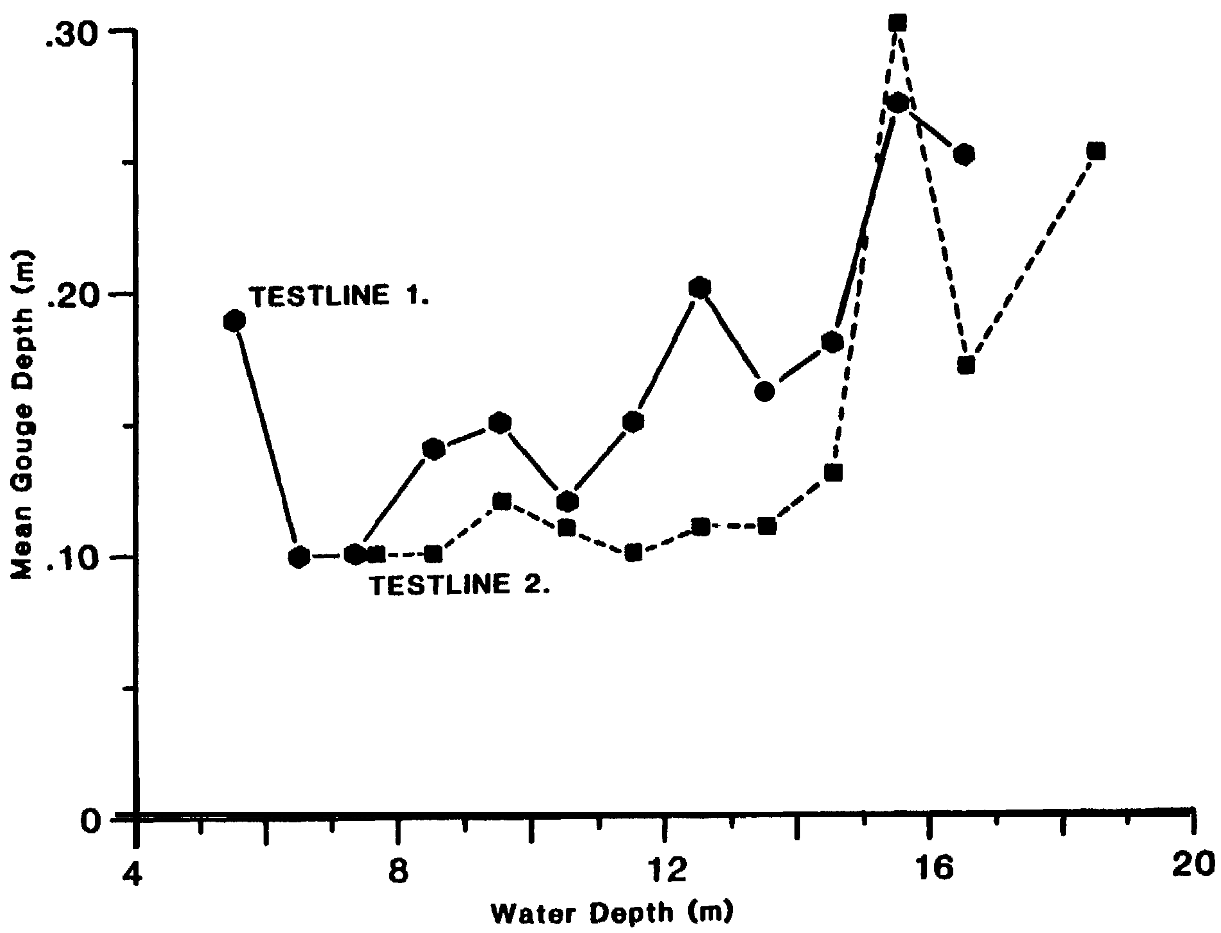


Figure 10. Graph of the mean gouge depth in each 1m water depth interval averaged over the entire course of the study. As with figures 8 and 9, mean gouge depths are very low (about 10cm) on testline 2 inshore of 15m water depth while on testline 1 the mean gouge depths are consistantly greater than those of testline 2 for equivalent water depths. In water greater than 15m deep average gouge depths are simular for both testlines.

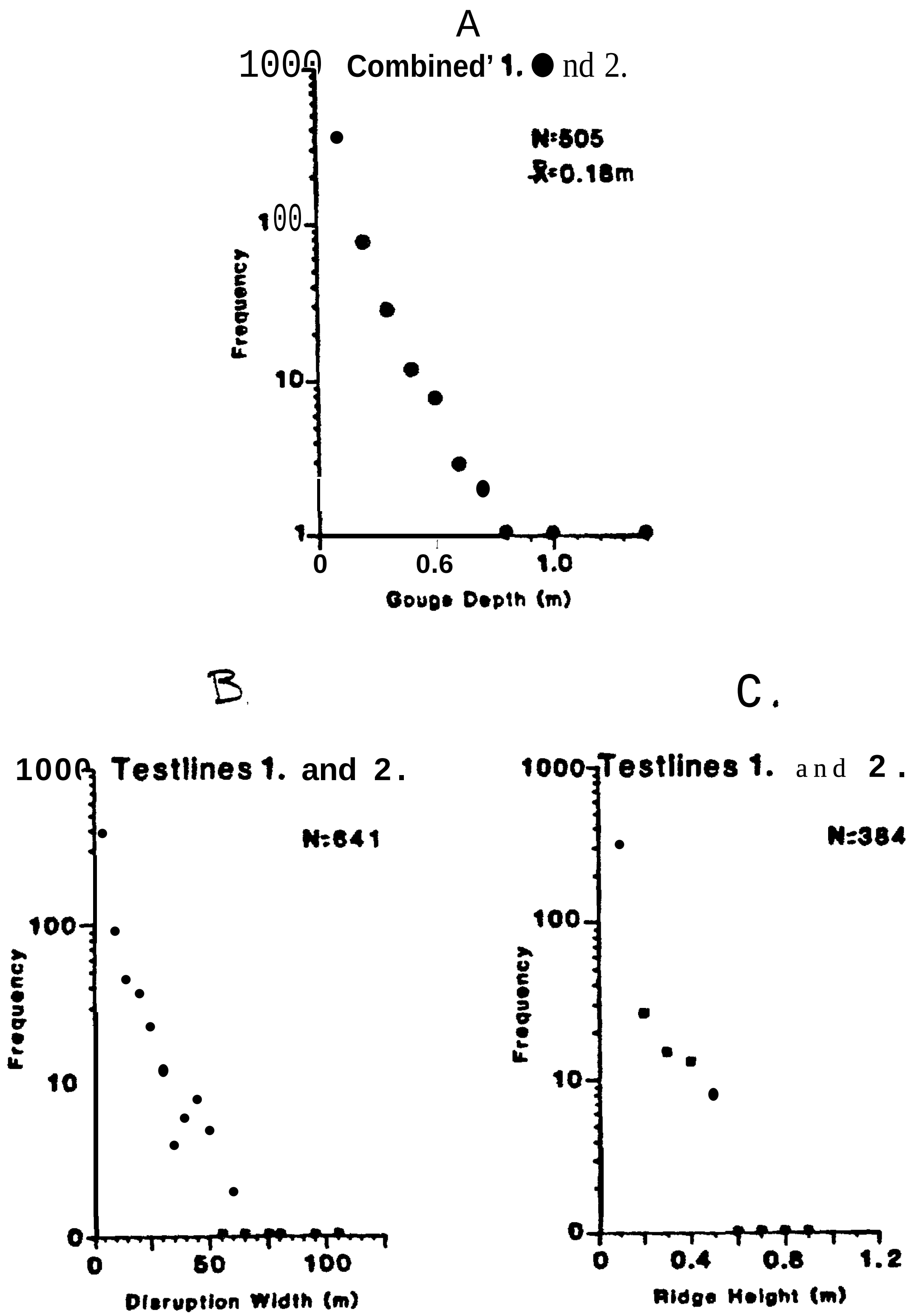


Figure 11. Frequency distributions plotted on similog paper for three gouge characteristics measured in this study; A) gouge depth, B) disruption width, and C) ridge height. Note that the characteristics fall on an approximate straight line indicating a negative exponential distribution. Of special interest are the large values of all three characteristics which do not fit the distribution. The reader is referred to the text for suggestions as to why the fit is so poor for the high end members of the distributions.

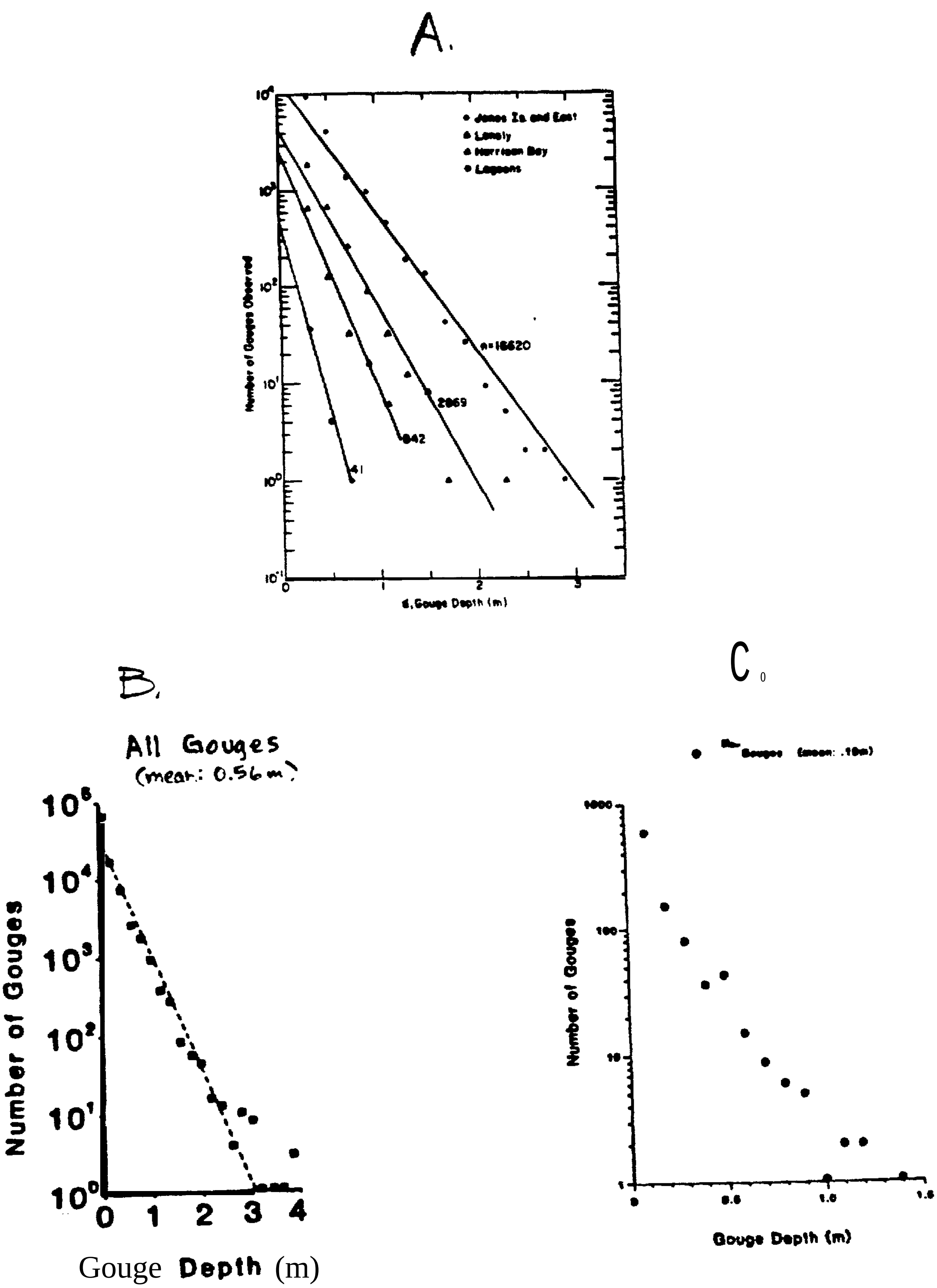


Figure 12. Gouge depth frequency distributions from the studies of A) Weeks et al. (1984), B) Barnes et al. (1984), and C) Barnes and Rearic (in press). Note that in all these studies, as with the present one, a negative exponential distribution ia indicated, The same problem exists in these studies as occured in the present with the high values failing to fit the distribution. See the text for possible explainations.

Seafloor disruption by ice gouging can be calculated as a percent of the trackline gouged in any one year. This is accomplished by adding up all the disruption widths (assuming that in the case of gouge width the disruption width is approximately 25% greater) over the length of the trackline and determining what percentage of the total trackline length was gouged.

The amount of seafloor disturbed each year was variable and ranged from a maximum of 6.1% to a minimum of 1.3%. The mean percent of seafloor disruption over the study period was 3.7% (Table II and Figure 13). Mean disruption was simular on both testlines when averaged over the length of the study even though their bottom morphologies are different. Data from Barnes et al. (1978) is included in the plot of Figure 13 as a reference for values calculated from earlier work, although they did not distinguish between disruption widths of multiples and single gouges. The new mean values that are calculated for seafloor disruption (3.9% and 3.4%) are almost double the 2% value found in the previous studies. Although seafloor disruption percentages exhibit a wide range of values the amount of disruption occuring most often (in 45% of the surveys) is in the 2-3% range (Table II).

Minimum Volume Of Sediment Disrupted

The above discussion was concerned with the area of the seafloor that is being gouged each year. However, It would also be of value to determine the volume of sediment involved in the disruption. This requires the incorporation of gouge depth and length in addition to width measurements. A minimum value for the mean volume of sediment disrupted annually (V) was calculated as follows (Table III). The mean annual gouge depth (X) and mean annual disruption width (Y) was calculated for one meter water depth intervals. The measured length of the gouges was used wherever possible to calculate mean length (Z). The remaining gouges on the sonograph record were assigned a length of >250 m (the width of the sonograph record). For this reason these values represent a minimum length (Table III). The mean values (X,Y,Z) for each one meter water depth interval were multiplied together (V = X x Y x Z) to give a minimum value of the volume of sediment disturbed within that depth interval.

The following results are calculated for a corridor 0.25 km wide extending through the water depth interval(s) being discussed. On testline 1 an increasing volume of sediment disruption corresponds to increasing water depths from 7 m water depth seaward (Figure 14). Approximately 2000 cubic meters of sediment were disrupted annually in 10 m of water and 7000 cubic meters of sediment in 15 m of water. The slope of this graph indicates that, starting in 10 m of water, for every 1 m increase in water depth there will be a corresponding increase of an additional 1000 cubic meters of disruption per year. If this correspondence holds true, at least to the inner edge of the stamukhi zone, we could expect about 12000 cubic meters of disturbed sediment per year in 20 m water depths. The stamukhi zone values will undoubtedly increase at a greater rate due to the greatly increased intensity of the ice gouge process in this zone (Reimnitz and Barnes, 1974; Barnes and Reimnitz, 1974; Barnes et al., 1984; Barnes and Rearic, in press). On testline 1, in water depths of between 7 and 15 m (a trackline length of about 17 km) a total of about 25000 cubic meters of sediment will be disrupted yearly. The area of the corridor in which this occurs is approximately 4.25 square kilometers. This gives a disruption value of 5800 cubic meters of sediment disturbed per square kilometer.

The shoal dominated profile of testline 2, inshore of 15 m water depth, is disrupted annually on the shoal creasts and on their seaward slopes at a rate of about 2000 cubic meters per year in each 1 m water depth interval while in the lee of the shoals volumes on the order of 200-300 cubic meters of sediment are disturbed yearly. Seaward of the shoals in water 15 m or more deep the disruption volumes increase rapidly with increasing water depth and begin to approximate the slope of the testline 1 graph. In water depths between 7 and 15 m on testline 2 (a trackline length of about 10 km) about 7500 cubic meters of sediment will be disrupted yearly. The area of the corridor in which this occurs is approximately 2.5 square kilometers. This gives a disruption

Testline	Year	Total Disruption width (m)	Testline Length x 1000m)	Percent Seafloor Disrupted
z.	1978	609	25	2.4
2.	1978	826	15	5*5
1.	1979	563	21	2.7
2.	19?9	358	13	2.8
1.	1980	1164	18	6.5 /
2.	1980	170	13	1.3
1.	1981	975	16	6.1
2.	1981	540	14	3*9
1.	1982	348	14	2.5
			Means	
1.	5 yrs.	732	18.8	3.9
2.	4 yrs.	474	13.8	3.4

Table II. Annual variations in seafloor disruption for eastern Harrison Bay.

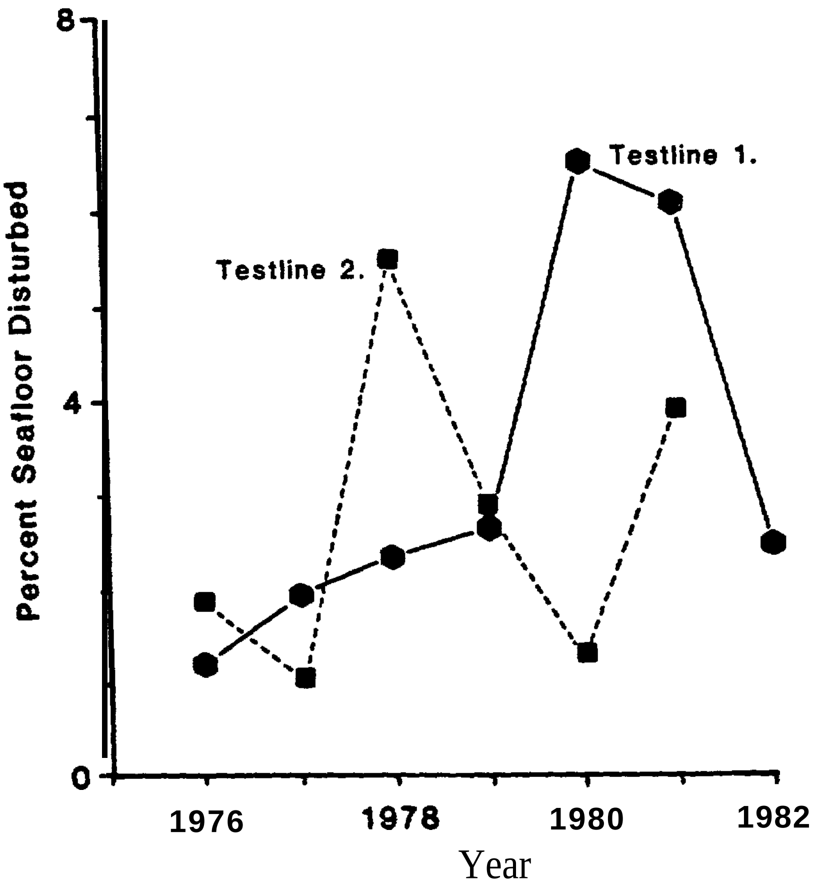


Figure 13. Graph of the percent of the seafloor disturbed each year on each testline. For comparison, the 1976 and 1977 values of Barnes et al. (1978) are included. Seafloor disruption is seen to vary yearly between about 1 and 6 percent on the testlines. Note the apparent inverse relationship between the two testlines in yearly percent disturbed.

Water Depth (m)	TESTLINE 1. X (depth) (m)	Y (width) (m)	Z (length) (m)	V (volume) (m^3)	TESTLINE 2. X (depth) (m)	Y (width) (m)	Z (length) (m)	V (volume) (m^3)
5-6	.19	4	46	35.0				
6-7	.10	2	76	15.2				
7-8	.10	14	>110	> 154.0	.10	15	>250	> 375.0
8-9	,14	49	> 204	>1399.4	.10	9	>250	> 225.0
9-1o	.15	61.	>209	>1912.4	.12	79	>180	>1706.4
10-11	,12	118	>181	>2563.0	.11	26	>142	> 406.1
11-12	,15	87	>233	>3040 .7	.10	70	>245	>1715.0
12-13	.20	101	> 217	>4383.4	.11	11	>229	> 277.1
13-14	.16	133	>231	>4915.7	.11	27	>216	> 641.5
14-15	.18	164	> 236	>6966.7	.13	78	>214	>2170.0
15-16					.30	21	>250	>1575.0
16-17					.17	59	>240	>2407.2
17-18					.20	102	>241	> 4916.4

Table III. Volume of disrupted sediment by 1 m water depth intervals averaged over the course of this study.

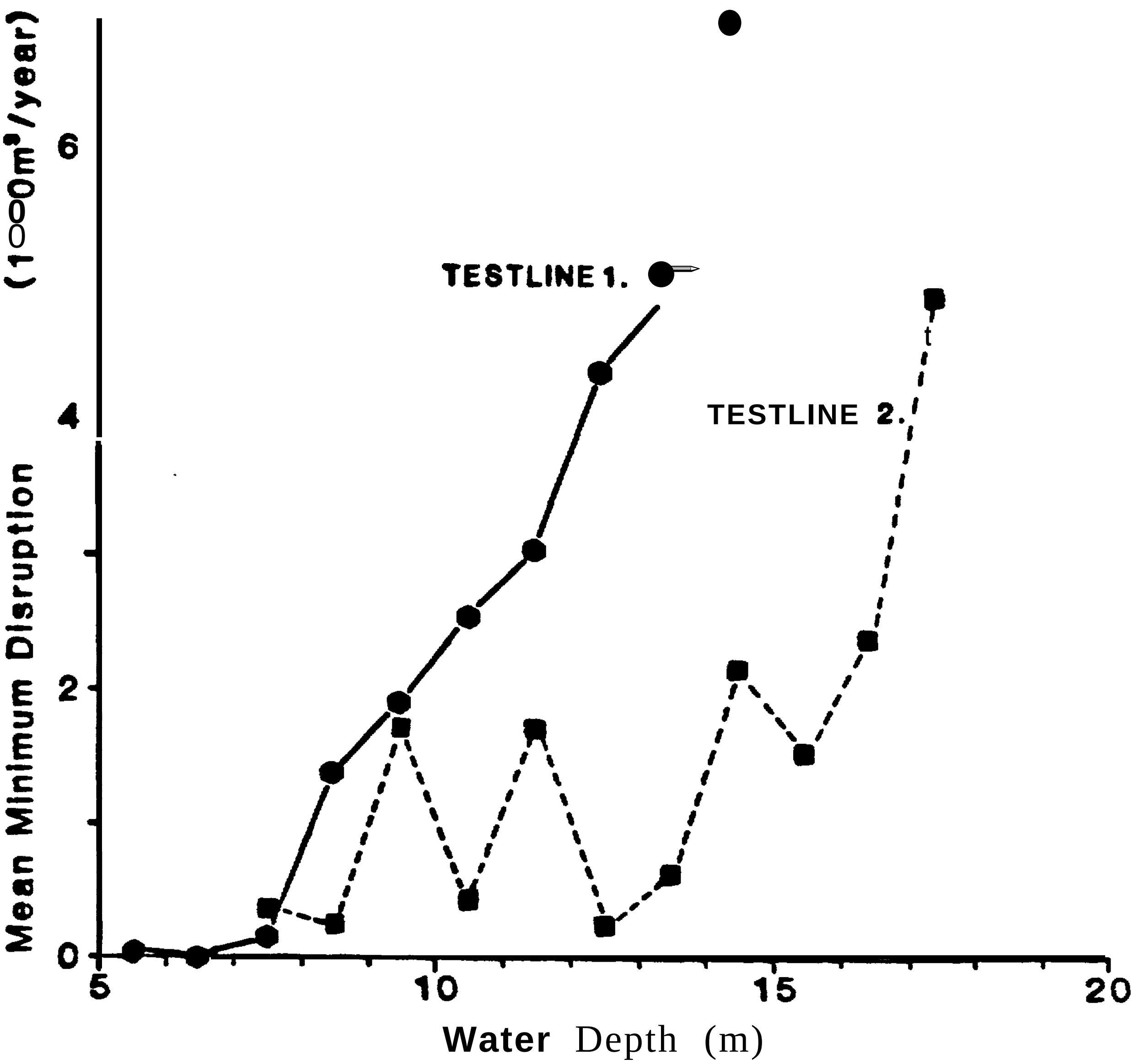


Figure 14. Graph of the average minimum volume of sediment disturbed each year on the test-lines in each 1m water depth interval. The influence of the shoals is again noted, as with gouge depth, in that values inshore of 15m water depth are relatively low on testline 2. Testline 1 demonstrates a consistant increase in disruption volume between 7 and 14m water depth of about 10CK) cubic meters per 1m of water depth increase.

value of 3000 cubic meters per square kilometer. Of this volume 75% (5500 cubic meters) will occur in the vacinity of the shoals. An additional 7500 cubic meters is disrupted between water depths of 15 m and 18 m (a corridor length of about 5 km). This gives a disruption value of 6000 cubic meters per square kilometer, similar to the value determined for testline 1 in shallower water depths. On testline 2, in water depths of 17 m, 5000 cubic meters of bottom sediments can be disrupted annually while on testline 1 this volume can be disrupted in water depths as shallow as 13 m.

New Gouge/Old Gouge Ratios

The number of new gouges in relation to the total gouge population at the time of survey could be important as a tool for determining relative infilling rates and length of gouge life span on the seafloor. If we compare two areas having equal yearly disruption rates from gouging and we determine that the new gouge to total gouge ratio is higher at one site than at the other then it could imply that infilling occurs at a higher rate at this site.

All the gouges observed on the monographs were counted and the percent of new gouges of this total was calculated (Table IV). Because of differences in record quality between years the number of new gouges when added to the previous years total did not equal the current years total as might be expected. The same problem was also noted in a study by Barnes et al. (1978). Ideally, on a yearly basis, this should not affect the ratio values because the quality of the records will equally affect both old and new gouge resolution.

On testline 1 new gouges make up 8.6% to 21.1% of the total number of gouges observed. On testline 2, 49.1% to 76.6% of the total gouge population was new. New gouges on testline 1 averaged 14.8% of the total and on testline 2 averaged 59.4%. Apparently, infilling of the older gouges on testline 2 is occuring at a greater rate than on testline 1 particularly since the average rate of new gouge production on testline 2 (3.4%) is not as great as that of testline 1 (3.9%).

New Gouge Orientations and Terminations

The orientation of an ice gouge depicts a track along which ice motion occured. After delineating the track we can determine the probable direction of approach and estimate what areas of the shelf may be more susceptible to ice gouges and which areas, such as the lee of shoals, may offer protection from gouging ice keels.

Orientations were taken on all new gouges and plotted as rose diagrams {Figure 15}. The orientation to the ships track was measured and then the orientation to true north was calculated by correcting for the ships course. Multiplet orientations were counted as only one occurance of that orientation, and as such, the diagrams are a record of the orientation of ice motion during ice gouging events.

On testline 1 the orientations of new ice gouges are essentially east-west and subparrellel to the bathymetry contours. Previous studies of other areas of the shelf have documented the parellel orientation of ice gouges to bathymetry contours when unaffected by seafloor morphology or other factors (Barnes et al. 1984). Testline 2 orientations are generally northwest-southeast and more variable than those of testline 1. This is possibly due to the influence of the shoals deflecting the motion of the ice canopy during winter and interfering with the normal flow of the sea-ice regime.

Gouge orientations tell us that the ice motion was along a particular track but do not give us actual direction of motion. Gouge terminations indicate the direction the ice keel was traveling during its disruption of the seafloor.

Testline	Year	Total Number of Gouges	Total Number of New Gouges	Percent New Gouges
1.	1978	1484	127	8.6
2.	1978	346	170	49.1
1.	19?9	886 "	152	17.2
2.	1979	167	113	67.7
1.	1980	1551	278	17.9
2.	1980	85	46	54.1
1.	1981	979	207	21.1
2.	1981	154	118	76.6
1.	1982	894	91	10.2
		MEANS		
1.	all	1.159	171	14.8
2.	all	188	112	59.6

Table IV. Percent new gouges of the total gouge record observed on the seafloor in eastern Harrison Bay. We would expect the sum of the new gouges and **the previous years total gouges to ● qual this years total gouge count; however, because of infilling** of older gouges, record quality, and deviation from **course this** is rarely the **case**. Barnes et al. **(1978)** noted **the** same problem in their studies of this area.

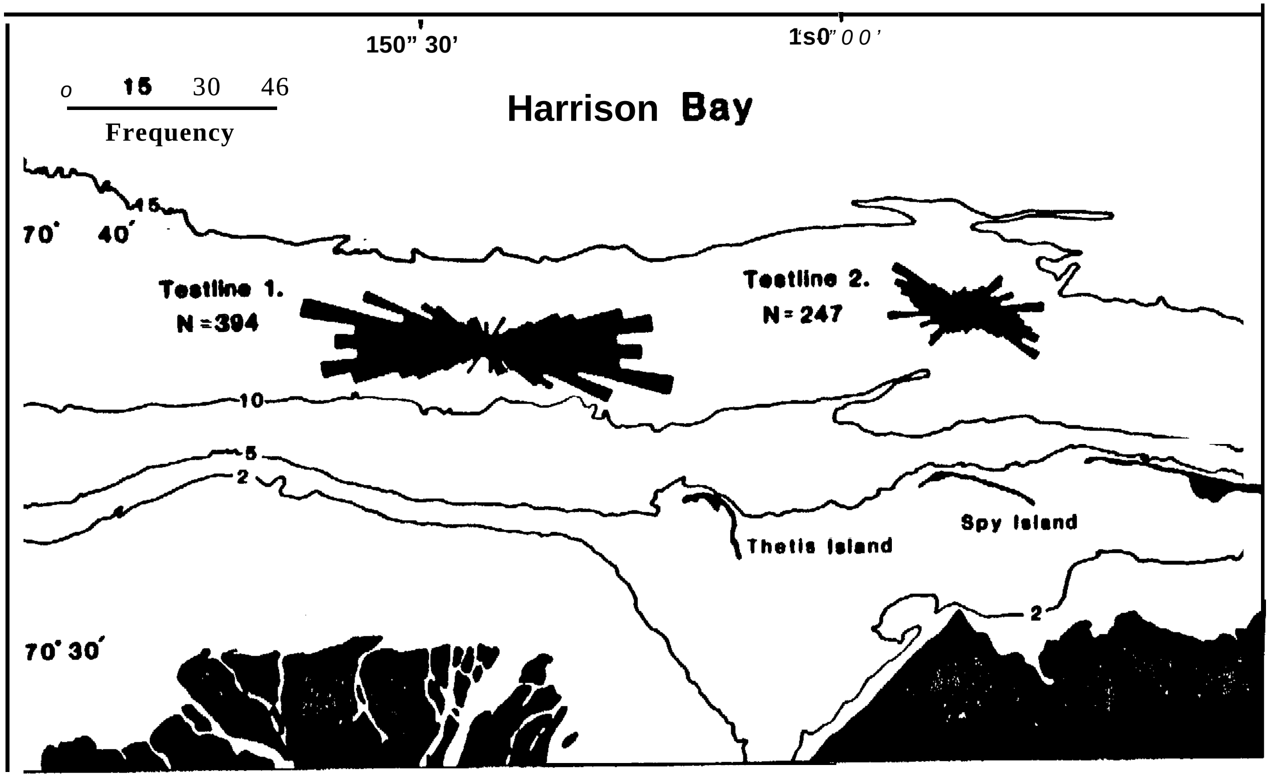


Figure 15. Gouge orientations plotted as rose diagrams for the two testlines. Note that the orientations of testline 1 are subparellel to the bathymetry contours with an approximate east-west orientation. Orientations on testline 2 are more nw-se indicating the possible influence of the shoals on the direction of ice movement.

Gouge terminations for both testlines were plotted as rose diagrams for analysis of direction of ice keel movement during formation of a gouge (Figure 16). Only 0.05% of the 1292 gouges terminated on the monographs. Of the 64 new gouge terminations 34 (53%) terminated in a southeast direction. Westerly movement of the ice keels is also indicated in the rose diagrams by the termination of 15 gouges (23%) in a southwest to west direction. Fifteen new gouges (23%) terminated in either an offshore or northeasterly direction.

Gouge terminations, when compared by year, indicate that ice approaching from the northwest generally creates gouge terminations with onl y one incision (Figure 17). This type of termination dominated the data set for four of the five years of comparisons. In the 1979-80 comparison it was noted that the gouge terminations were mostly multiplet in nature and the ice creating these terminations approached from the northeast.

New Gouge Multiples And New Gouge Events

Multiplet gouging creates a distinguishable gouge pattern formed by several downward projecting keels (Figure 1). Multiplet gouging itself can fall into two categories depending on the number of incisions and their depths. Multiples with only a few incisions and deeper than 0.5 m are considered to have been formed from multiyear ice and are possibly related more to the processes involved in the formation of single gouges. Multiplet gouges having more than 3 to 4 incisions and depths less than 0.5 m are generally considered to be the result of first year pressure ridge gouging (Barnes et al., 1984). As a gouge event, the second type of multiplet is responsible for the widest disruption of the seafloor and greatest number of gouges formed. Table V shows that although only 28% of all gouge events are shallow multiplet events at least 65% of all ice gouge furrows and 67% of the disruption (Table VI.) is accounted for by these events.

DISCUSSION

The data in this study are are the result of the measurement of horizontal and vertical sediment transport caused by the passing of a grounded ice keel through the bottom sediments. Determining the volume and direction of transport will help resolve the role of ice gouging in sediment transport on the Beaufort Sea shelf during winter. Hydraulic influence on the environment is minimal during the 9 months of winter ice cover and sub-ice ocean currents play only a minor roll, if any, in winter sediment transport (Barnes, 1981; Matthews, 1981; Barnes and Reimnitz, 1982).

The results of this study need to be placed in perspective with previous studies of the same area (Reimnitz et al., 1977; Barnes et al., 1978; and Table VII). The differences noted in the gouge character values and in particular the higher rates of reworking are considered to be the effects of better record quality in recent years, allowing a more acurate count of the small gouges. Reimnitz et al. (1977) noted that only disruptions from gouges 20 cm deep or greater were used in estimating their rates of reworking by ice. Barnes et al. (1978) observed in their study an increase in record quality over previous study records. A further increase in record quality is noted in the present study and ice gouges less than 20 cm were routinely observed.

Frequency Distributions

The frequency distribution of ice gouge depths, widths and ridge heights is a negative exponential and similar to that found in previous studies (Barnes et al., 1984; Barnes and Rearic, in press; Weeks et al., 1984). There are many more small gouge depths, gouge widths and ridge

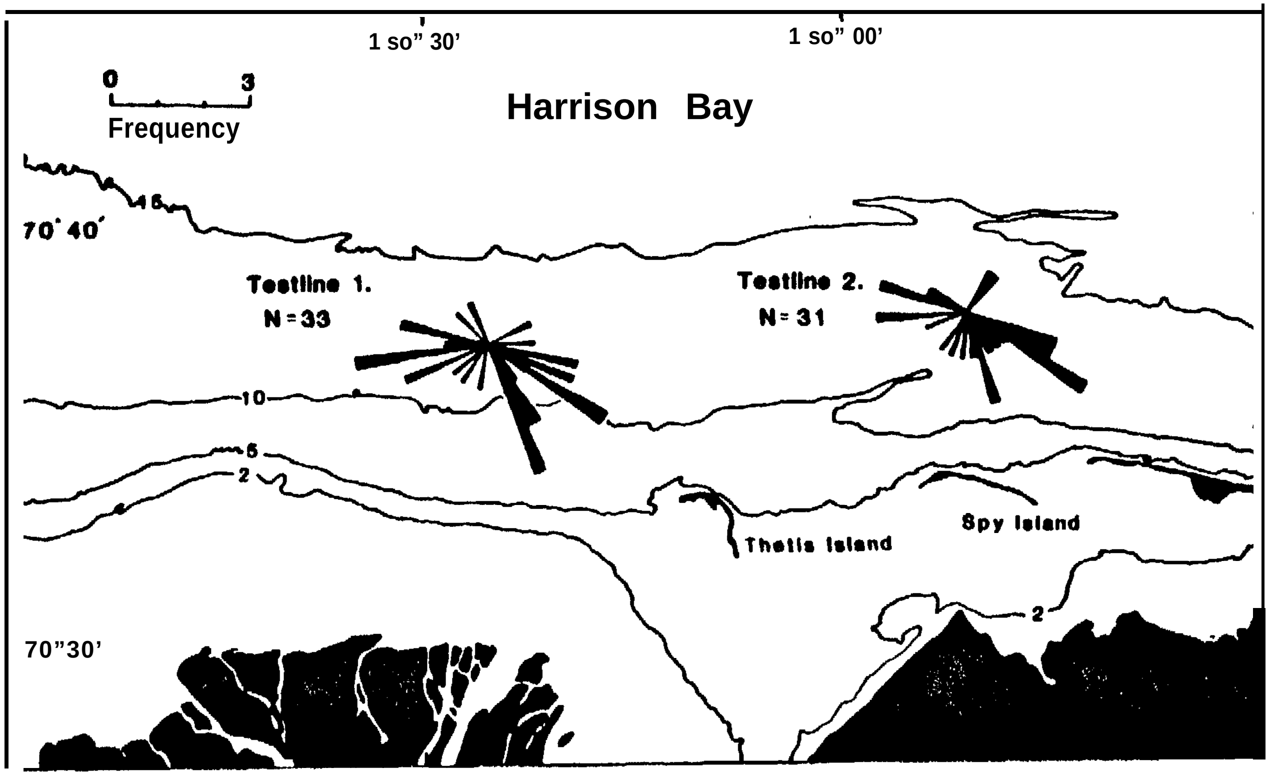
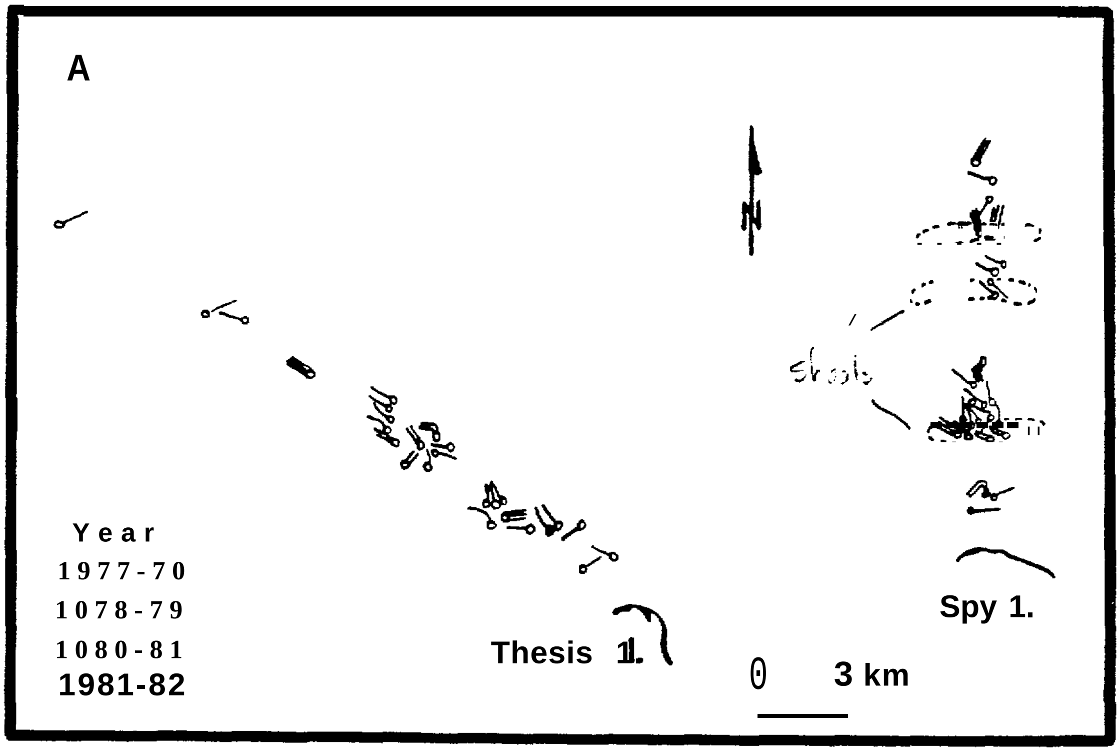


Figure 16. Gouge terminations plotted as rose diagrams for the two testlines. Note the similarity between the two testlines with the dominant trends either onshore in a southeasterly direction or along shore in a westerly direction, Although gouging is believed to be an upslope process some gouges are seen to move in an offshore direction. See text for possible explanations.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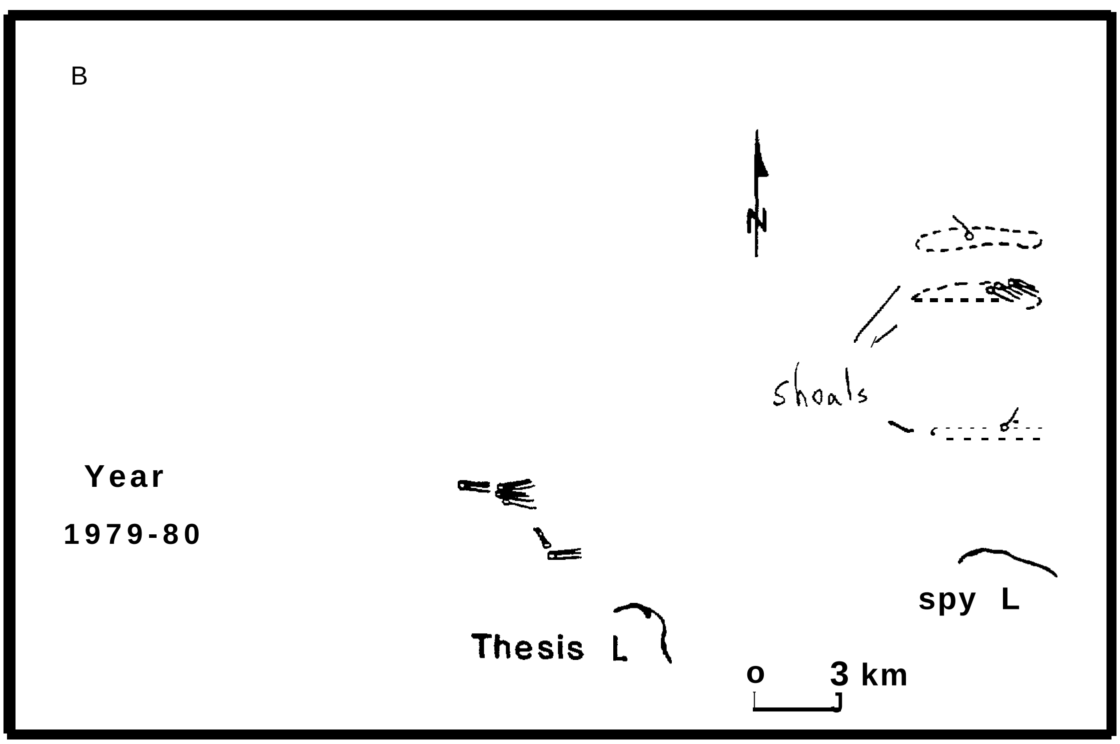
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Testline	Year	Single Gouge Events	Multiplet Gouge Events	Percent Multiplet Events	Number of Gouges From Single Events	Number of Gouges From Mult. Events	Percent of Gouges From Mult. Events
1.	1978	24	25	51	24	103	81
2.	1978	61	24	28	61	109	64
1.	1979	59	18	23	59	92	61
2.	1979	24	12	33	24	89	79
1.	1980	34	38	53	34	243	88
2.	1980	22	5	19	22	24	52
1.	1981	93	35	27	93	114	55
2*	1981	87	12	12	87	31	26
1.	1982	56	13	19	56	35	38
				TOTALS			
1.	all.	266	129	33	266	587	69
2*	all	194	53	21	194	253	57
130th	all	460	182	28	460	840	65

calculations are based on 1292 new gouges from 642 new gouge events.

Table V. Testline comparisons between multiplet and single gouge events and the number of new gouges accounted for by the events.

TOTAL DISRUPTION WIDTH (m)

	TESTLINE 1.		TESTLINE 2.	
YEAR	Multiplet	Single	Multiplet	Single
1978	512	97	602	221
1979	383	180	292	66
1980	1004	160	100	70
1981	567	408	201	339
1982	146	202		
Mean	522	209	299	174
Percent Of Total	71	29	63	37

Table VI. Comparison of the amount of seafloor disruption accounted for by multiplet and single gouges.

	survey line length (km) TL1	TL2	number of new gouges TL1	TL2	maximum gouge depth (cm) TL1	TL2	mean gouge depth (cm) TL1	TL2	total gouge width (m) TL1	TL2	percent of seafloor disturbed TL1	TL2
Reimnitz et al (1977)												
1973 -197s	16	--	11	--	75	--	*37	--	263	---	1.9	---
Barnes et al (1977)												
1975-1976	16	16	39	41	120	80	31	21	161	268	1.2	1.9
1976-1977	26	18	63	42	60	40	19	12	271	169	1.9	1.1
Rearic (this study)												
1977-1978	25	15	127	170	50	70	17	14	609	826	2.4	5.5
1978-1979	23	13	142	113	40	20	11	11	563	350	2.7	2.8
1979-1980	21	13	270	46	40	30	15	11	1164	171	6./$/1.3	
1980-1981	18	14	207	118	70	140	18	16	975	540	6.1	3.9
1981-1982	14	--	91	--	100	--	17	--	348	---	2.5	---

* - Note: This value comes from the raw data. Gouges less than 20cm deep on the 1973 record were unresolvable while on the 1975 record they were easily resolved. Reimnitz et al. (1977) did not use gouges less than 20cm deep in their calculations but estimated that if the smaller gouges were included in the calculations the mean gouge depth would be in the 20cm range.

Table VII. Gouge characteristic comparisons between three studies of the same area in eastern Harrison Bay.

heights than large ones (Figure 11).

The negative exponential distribution, however, fails to fit the extreme high values in this study and in all previous studies. The very largest values (gouges >80 cm deep and >75 m wide and ridges >50 cm high in the present study) do not fit this distribution. In most calculations there are more large gouges on the seafloor than the distribution would account for. Weeks et al. **(1984)** ascribed this lack of fit to the short time span of ice gouge record that is represented on the seafloor. Milling of gouges from storms such as occured in the fall of 1977 (Barnes and Reimnitz, 1979) may occur at short enough time intervals that the occasional deep and/or wide gouge may survive while most of the shallower/narrower gouges are obliterated before a true representative distribution can accumulate on the seafloor. Another possible explanation may be that there are two distributions contained in the data. Firat year ice (pressure ridges) may account for numerous shallow gouges while the deepest features are created by older, more consolidated ice keels and, therefore, fail to fit the same distribution.

Gouge depth distributions vary across the shelf (Figure **12). In** deeper water (the stamukhi zone) there are fewer shallow gouges (Rearic et al., **1981)** while in the shallow waters (<20 m) of the present study very few deep gouges were found (Figure 11). In other words, there may be an inshore distribution containing many shallow gouges and a few large gouges and an offshore distribution containing many relatively large gouges and fewer small gouges.

The sea ice environment differs between the offshore and inner shelf. Inshore, ice keels reaching the seafloor are smaller and will leave shallow, narrow gouges in their wake while offshore, in the stamuki zone, many large, competent ice keels are available for gouging. In the offshore areas one deep, wide gouge can oblterate many smaller gouges during one gouge event leaving a trough that is to deep for many of the shallower keels to reach. This effectively limits the area of seafloor available for creation small gouges.

Maximum Depth of Gouging

The return interval for deeper gouges (> 1 m) can be calculated. Barnes et al. (1978) in a 3 year study of new gouges formed in the same area between 1975 and 1977 noted only one new gouge on testline 1 in 1976 that was >1 m deep; none were noted on testline 2 during this period. In the present study one gouge deeper than 1 m was found on each testline. By combining these data a return interval of about 6 years is calculated for gouges greater than 1 m deep. At this rate, in water depths of between 10 and 16 m, the seafloor could be reworked to a depth of 1 m in about 800 years. In 20 years of surveying this environment only 6-8 new gouges >1 m deep will occur. When this number is compared to the more than 5000 new gouges that would be formed over the 20 year period only 0.1- 0.2% of the new gouges would be >1 m deep.

The return interval can also be calculated as kilometers of trackline covered before a gouge less than one year old and greater than **1** m deep is encountered. Data from Table VII indicates that Barnes et al. (1978) found 1 new gouge greater than 1 m deep in 76 km of trackline coverage. In this study 2 new gouges >1 m deep were found in 156 km of trackline, an average of one every 78 km. Combining the data from both studies we can estimate that in eastern Harrison Bay and in water less than 18 m deep, for every 77 line kilometers of seafloor one gouge greater than 1 m deep will be plowed each year.

Figures 8 and 9 describe the distribution of maximum gouge depths with respect to water depth. Both figures suggest a general increase in maximum gouge depths with an increase in water depth. This seems reasonable when we consider that there are larger ice keels available in deeper water to produce the deeper gouges. A survey of data from other recent ice gouge studies (Barnes et al., 1978; Rearic et al., 1981) as well as the data from this study (Table I) suggests that there may be a maximum depth to which gouging can occur at any given water depth (Table VIII).

gouge depth (m)	water depth (m)	percent of-water depth (%)	
0.7	8.7	8.0	Present Study
1.0	12.3	8.1	" "
1.4	15.8	8.9	" "
1.2	13.2	9.1	Barnes et al (1978)
1.8	19.0	9.5	" "
3.8	37.5	10.1	Rearic et al (1981)
4.0	36.2	11.0	" "
4.0	31.4	12.7	" "
	Mean = 9.7%		

Table VIII. The deepest gouges and the water depths they were found in from 3 studies in eastern Harrison Bay and on the Beaufort Sea shelf. Alaska.

These data show that in any given water depth the maximum gouge depth will be approximately 10% of the water depth (±2%) at least to water depths of about 40 m. However, in areas sheltered by shoals this value will be in the range of only 2-3% of the water depth. This occurs because the larger ice keels capable of deeper gouging are intercepted by the shoals before they can ground on the shelf inshore of the shoals.

Seafloor Disruption

Previous studies have shown that approximately 2% of the seafloor is reworked yearly by sea-ice (Barnes et al., 1978). This is probably the low end of the yearly reworking rates (Figure 17). Rates as great as 6.1% per year were noted during the current study and rates >5% were calculated for 3 of the 9 yearly data sets, although many values are in the 2-3% range and agree favorably with the earlier studies (Figure 17). The approximate doubling in mean rate of seafloor disruption from the 2% of earlier studies to 3.7% in the present study also points out the year to year variability in the ice gouge process.

Barnes et al. **(1978)** developed a formula to determine the fraction of seafloor disrupted over time (Figure **18).** The formula incorporates the concept of proportional replow of previously gouged areas of the seafloor. This assumes that each year new gouges are proportionally divided between ungouged and previously gouged areas. A description of the method for calculating this curve can be found in Barnes et al. **(1978).** The formula is as follows

$$G_T = 1 - (1-k)^T$$

where:

G_T = Fraction *of the seafloor impacted after T years*

T = Time in years from an arbitrary TO initiation of *new* gouging

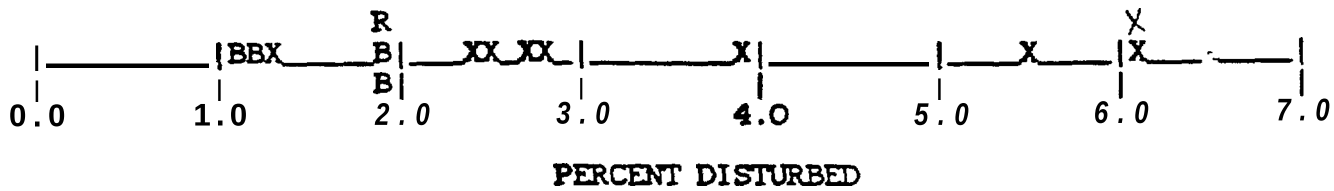
k = Fraction of the seafloor impacted in 1 year

Using the data from the current study the proportional curve indicates less time is required to gouge the seafloor. From the study of Barnes et al. (1978) the amount of seafloor disturbed in eastern Harrison Bay after 10, 20, 50, and 100 years is 13, 25, 52, and 77 percent. Almost doubling the disruption rate from 2.0 to 3.7 percent increases the amount of seafloor impacted for these same time periods to 32, 52, 84, and 98 percent (Figure 18). The change is considerable as for example the time needed to rework 50% of the seafloor drops from 50 years to only 20 years. Essentially the entire seafloor (98%) is reworked every 100 years to an average depth of 18 cm with most areas reworked many times during this period.

Effects Of Seafloor Morphology On Ice Gouging

Although ice gouges may occur anywhere along either testline, the shoals exhibit some control of gouging on testline 2 (Figures 6, 7, and 8). The peaks in the graphs of the gouge data for testline 2 are a result of the high impact rate on shoal crests due to positive relief of the shoals. Inshore of the seaward most shoal the peaks in the data curves do not reflect high volumes of

X - Current Study B - Barnes et al. (1978) R - Reimnitz et al. (1977)



Mean of all studies = 3.2% (seafloor disruption per year)

Figure 17. Plot of the disruption percentages from the present study and that of Barnes et al. (1978) and Reimnitz et al. (1977).

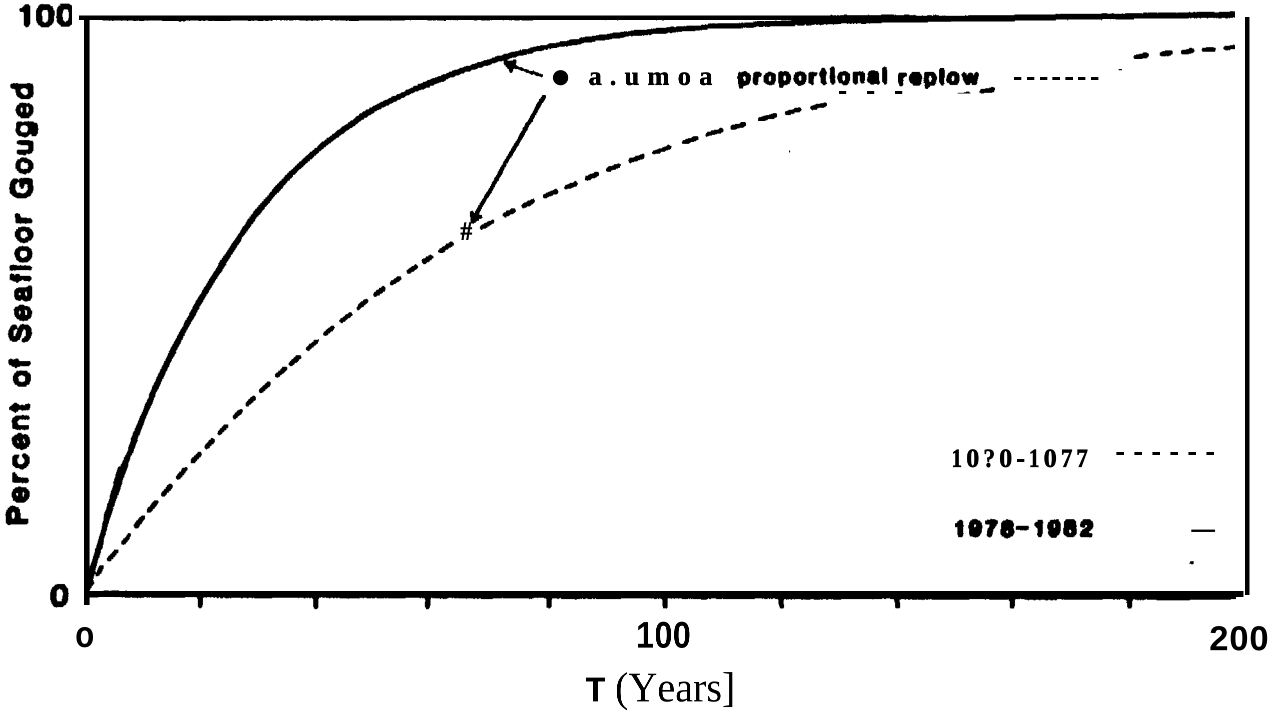


Figure 18. Plot of the percent of seafloor gouged over time from Barnes et al. (1978). The **plot is** from **a model considering yearly replow of previously** gouged **areas as** well **as** non-gouged areas. **The increased percentage of gouging with time determined from this study indicate that the entire seafloor (98%) could be reworked in about 100** *years* **while in** 50 yeara there **is still considerable gouging of the bottom (about 85%). Figures from the** curve of Barnes et **al.** (1978) indicate values on the order of 80% **and 55% for these same time spans.**

sediment disruption (Figure 14) because the deepest gouges occur offshore and these gouges apparently have the greatest affect on the volume of sediment disrupted on testline 2. The mean gouge lengths and widths remain fairly constant throughout the water depth intervals. The shelf inshore of the seaward most shoal on testline 2 can be subjected to a high frequency of gouging but is apparently protected from ice capable of deep gouging.

The inner shelf (water depth <15 m) of testline 1, not having the protection of the shoals, can be subjected not only to high frequency gouging (50+ gouges/km) but also to deep gouging (>.5 m) of the sediments. As the water depth increases on the inner shelf so do the values for all the volume parameters (mean gouge length, width, and depth) leading to higher disruption volumes for equivalent water depths when comparing testline 1 to testline 2.

Orientations, Terminations, And Sediment Transport

On a smoothly sloping bottom the movement of ice keels parellels the coast and bathymetric contours (Barnes et al., 1984; Barnes and Rearic, in press). In the present study, the gouges occur on a gently sloping seafloor and are essentially east-west, paralleling the bathymetric contours, although the shoals of testline 2 affect the movement of sea-ice in their vacinity (Barnes et al., 1978; Reimnitz and Maurer, 1978). Barnes et al. (1978) observed that gouge trends on testline 2 were northwest-southeast on the outer parts of the testline and northeast-southwest on the inner part. In the present study it was found that about 76% of the gouge directions measured (gouge terminations) were in the southeast (53%) or southwest (23%) quadrants with only 23% divided between the two northern quadrants. Using these figures as a base for estimating sea-ice movement in the nearshore environment, most sea-ice would seem to be approaching the coast from the northwest through northeast quadrants (Figure **17).** Ice keels contacting the bottom should bulldoze sediment in an onshore to alongshore direction with only a minor amount of sediment moved offshore during gouging.

Because most gouging is believed to take place in an upslope direction (Barnes et al., 1984) it is difficult to determine the causes for the termination of gouges in an offshore direction. Some of these gouges are associated with the shoals of testline 2 and have terminated on the inshore side of the shoals possibly as the ice was driven offshore by winds, currents, ice pack motion, or a combination of these forces (Figure 17). However, not all of the seaward terminating gouges can be explained by the shoals. Another possible answer may be that the encompassing ice pack has driven a ice bound floe into water that is to shallow to float the floe and as it moves back offshore by a change in ice motion the floe continues to settle into the bottom sediments until release from ice pack pressure causes further movement to cease.

Since most ice gouging takes place in the winter under the seasonal ice-pack when ocean currents are small (Barnes, 1981; Matthews, 1981; Barnes and Reimnitz, 1982) sediment transport by ice gouging plays a significant roll in winter (Harper and Penland, 1982). Barnes (1982), in a study of an ice pushed coastal boulder ridge in Camden Bay, suggested that sand, gravel and boulders were moved onshore by direct contact with the sea-ice. The direction of sediment transport suggested by gouge terminations in the present study (Figures **16** and **17)** is essentially southeasterly through southwesterly. Because sea-ice is driven by ocean currents and winds, sediment that is resuspended during ice gouging will also be driven along the coast or onshore (Barnes and Reimnitz, 1982).

The distance of transport by ice gouging is difficult to assess. To date no data exists on the actual distance covered by sediment grains during gouging although it seems reasonable to assume that the distances are small. The suspending of fine grained sediments during gouging may allow any existing currents to transport the sediments greater distances. The most significant sediment sinks for this sediment (transported either by actual ice shove or from resuspension by currents) may be the adjacent gouges themselves as well as other seafloor depressions such as strudel scours

(Reimnitz and Kempema, 1982),

Hydraulic Reworking

The sand and gravel shoals of testline 2 are less cohesive than the sediments of testline 1 and the gouges are generally shallower for equivalent water depths (Figures 9 and 10). These conditions are conclusive to high in filling rates. In the present study an average of about 60% of all observed gouges on testline 2 are new gouges while an average of about only 15% of the observed gouges on testline 1 are new gouges. These figures suggest that testline 2 has higher rate of hydraulic reworking which infills and obliterates ice gouges (Table V). Hydraulic forces are focused on the shoal crests (areas where most of the gouging on testline 2 takes place) and gouges infill at a greater rate than that of the gentler slope of testline 1. On testline 1, hydraulic energy is lower per unit area and the energy is disapated over a area of more cohesive shelf sediments allowing gouges to withstand reworking for a longer period of time although occasional large storms may cause unusually high rates of infilling (Barnes and Reimnitz, 1979). Ice gouges are preserved for a longer period of time on testline 1 than on testline 2 and the seafloor of testline 1, therefore, records a longer time span of ice gouging.

Multiplet Gouges - Old Ice and New Ice

Barnes et al. (1984) theorized from their data that wide, shallow multiplet gouges were created by newly formed ice ridges and the many ice blocks forming the ice ridges conform at equivalent depths to the bottom topography before consolidation and gouging occur. These gouges are usually responsible for the widest disruptions of the seafloor by a gouge event but they are also the shallowest gouge events. The deepest gouges are created by ice ridges with generally only one or two keels often of unequal depth (Barnes et al., 1984) that have undergone more than one years incorporation into the winter ice canopy, resulting in a welding of the ice blocks together, which creates coherent ice keels with sufficient strength to cause deep ice gouges.

Tables V and VI of the present study show that 65% of the new gouges and 67% of the seafloor disruption occuring in eastern Harrison Bay is caused by multiplet gouging. These multiplets are of both the shallow many keeled type and also the deeper fewer keeled type. Multiplet gouges make up only 28% of the gouge events while the remaining 72% are single gouge events. Reimnitz et al. (1977) noted in their studies of testline 1 that 70% of the disruption between 1973 and 1975 was from 3 multiplet gouges while the remaining 30% of seafloor disruption was from individual gouges.

Given the above, we postulate two ice gouge populations which have distinctive characteristics and create gouges with different depth and width characteristics. The first population is caused by many keeled ice. These wide and shallow multiplet gouges result in large horizontal disruptions of the seafloor. The second population is caused by ice ridges with few or only one keel and results in gouges which are relatively narrow and may be shallow or deep although the deepest gouges are associated with this type.

On testline 1, in 1978 and 1980, multiples accounted for over 50% of all gouge events and an average of about 85% of the seafloor disruption (Tables V and VI). In contrast, in 1981 on testline 1 and 2 and in 1982 on testline 1 multiplet gouges accounted for only about 10 to 30% of the gouge events and 40% of the seafloor disruption in each area. It is interesting to note that 1981 and 1982 were the years in which the deepest gouges (>1 m) were formed and again suggests that two types of ice gouging are occuring on the shelf today.

In 1981 there was very little multi-year ice on the shelf at freeze-up (Kovacs, 19_). This is also a year in which we find the least amount of disruption on the shelf floor and also one in which we find one of the deepest new gouges. It may be that in the years in which there are significant amounts of multiyear ice grounded on the inner shelf at freeze-up will be years in which there will be less chance of a very deep gouge. This occurs because the grounded multiyear floes act as a barrier to the onshore and alongshore movement of the newly formed winter ice canopy causing sea-ice to pile up behind the barrier of grounded multiyear ice. The ice ridges thus formed are young and relatively unconsolidated and will be responsible for the wide, shallow disruptions that will occur over the winter. Conversely, when there is no multi- year ice on the shelf at freeze-up a solid ice canopy can form with very little ridging occuring on the inner shelf. The multi-year ice that becomes incorporated into the ice canopy will do so in the deeper waters of Harrison Bay and will not be grounded at freeze-up. As the winter progresses, however, the sea-ice containing the older, consolidated keels can move onshore causing the older ice to ground with the results being deeper, narrower single and multiplet gouge events.

CONCLUSIONS

Observations and measurements made on recently formed ice gouges in eastern Harrison Bay, Alaska combined with those of previous studies (Reimnitz et al., 1977; Barnes et al., 1978) indicate significant variability from year to year in ice gouge processes based on their number, size, and distribution. The additional following conclusions can be drawn from the results of this stud y:

1) Gouge recurrence rates are higher than previously reported when the smallest gouges (<20 cm deep) are included in the calculations. The average rate of of seafloor disruption of 3.7% per year from the present study means that approximately 50% of the seafloor can be reworked in 20 years when using the proportional replow model of Barnes et al. (1978). A rate of 3% is suggested when the earlier work of Reimnitz et al. (1977) and Barnes et al. (1978) are included in the calculation of the average disruption rate.

2) Frequencies of new ice gouge characteristics have negative exponential distributions similar to that determined for the total ice gouge population on the shelf (Weeks et al., 1984). The slope of the distribution curves varies from area to area and is an indication of the intensity of ice gouging and the major distinction between the ice gouge populations discussed here.

3) In the study area, in water depths of 5-16 m, gouges >1 m deep occur every 6+ years and account for 0.1-0.2% of all gouges in this area. In water depths >10 m the seafloor can be completely disrupted to a depth of 1 m in approximately 800 years. One **gouge >1 m** deep and plowed this year will be crossed for every 77km of trackline coverage of the seafloor.

4) In areas unaffected by the influence of shoals the maximum depth of gouging can be approximately 10% of the water depth (+- 2%) at least to water depths of about 40 m.

5) Seafloor morphology affects the areal distribution and size of ice gouges and the direction of gouging.

6) Most sediment transport by ice gouging is onshore to alongshore which is suggested from the southwesterly through southeasterly ice gouge terminations.

7) On testline 1, in a corridor about 17 km long and 250 m wide, between 7 and 15 m water depth, at least 5800 cubic meters of sediment per square kilometers disrupted

yearly. In water depths >10 m cumulative disruption volume increases about 1000 cubic meters per 1 m of increased water depth. On testline 2, in a corridor about 10 km long and 250 m wide, between 7 and 15 m water depth, at least 3000 cubic meters of sediment per square kilometer is disrupted, however, 75% of the disruptions occurs on the crests and seaward slope of the shoals of this testline so that the amount of sediment disrupted is more likely to be concentrated in these areas. Offshore of the most seaward shoal about 6000 cubic meters of sediment per square kilometer is disrupted.

8) Ice gouges on testline 2 are hydraulically reworked" and infilled at a faster rate than those on testline 1. The shoals of testline 2 contain most of the gouges that are formed each year. High rates of gouge obliteration on these shoals suggest the shoals are a focal point for the energy expended by waves and currents on the ocean floor during summer.

9) Although multiplet events occur less frequently than single gouge events they account for most of the seafloor axea impacted by ice. The most frequent and often the deepest gouge events are single gouges and multiples with few incisions and these account for the greatest vertical displacement of seafloor sediments.

The conclusions reached in this study derive from one area of the Beaufort Sea shelf. However, we believe the processes operating in other areas are the same, although the number, size, frequency, and distribution of new ice gouges will differ. These conclusions form a basis upon which ice gouge processes in areas of similar water depth and seafloor morphology may be estimated.