UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

TEMPORAL AND SPATIAL CHARACTER OF NEWLY FORMED ICE GOUGES IN EASTERN HARRISON BAY, ALASKA, 1977-1982

BY

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OPEN-FILE REPORT 86-391

Menlo Park, California

1982

ABSTRACT

Each year in the Alaskan Beaufort Sea, shear and compressional forces within the seasonal sea-ice canopy cause the formation of ice keels which may contact the seafloor and become grounded. When a grounded ice keel plows through seafloor sediment it creates a furrow termed an ice gouge. Two tracklines in eastern Harrison Bay, Alaska, were resurveyed with precise navigation techniques each year between 1977 and 1982 using side-scan sonar and a high resolution fathometer in order to determine the yearly rate at which ice gouges are added to the seafloor. The observation and measurement of the number, size and distribution of ice gouges dated as less than one year old indicate that there is significant variability from year to year in the ice gouge process.

The tracklines are divided into 1-km segments, each 250-m wide, in order to tabulate the data. It was found that an average of 8 to 9 new gouges are added to the seafloor each year in each 1-km segment; however, as many as 64 ice gouges can occur in a 1-km segment in any one year. The average depth of the newly formed gouges is calculated as 18-cm. Gouge depth frequency is described as a negative exponential distribution. The area of seafloor disrupted by ice gouging is considerable. Seafloor disruption averages 37-m/km/year with a maximum of 214-m of disruption occurring in a 1-km segment. Average height of the sediment ridges bounding the gouges is 14-cm with a maximum of 90-cm. The largest and deepest gouges generally occur in water depths deeper than 10-m.

Between water depths of 5- to 18-m, the amount of areal disruption caused by new ice gouges increases with increasing water depth when unaffected by seafloor morphology such as shoals. Deep gouges may occur in all water depths if similarly unaffected by seafloor morphology. The area of seafloor disrupted each year by ice gouging ranges between 1 and 6 percent and averages 3.7 percent. The volume of sediment disrupted averages about 6000-m^3/km^2/year. Gouge orientations and terminations indicate that most sediment transport by ice gouging is onshore to alongshore.

INTRODUCTION

Interaction between the dynamic elements of wind, water, ice and seafloor sediment is recorded on the continental shelf of the Alaskan Beaufort Sea (fig. 1) 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 sediment (Barnes et al., 1984). Sea-ice is, therefore, responsible for large volumes of sediment disruption and redistribution across the shelf (Barnes et al., 1984), and 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, 1983).

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 rotating, permanent, polar pack ice and seasonal, stable, shore-fast ice (Hibler et al., 1974; Reimnitz et al., 1978; Stringer, 1978). 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 sediment, ice gouges are formed (fig. 2).

The rate at which ice gouging of the seafloor occurs, 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 to protect 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 small scale sedimentary and biological features (fig. 3), 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, 1984), the creation of ice gouge furrows that act as sediment traps (Reimnitz and Kempema, 1983), and the transport of sediment by bulldozing and resuspension of sediment during gouging (Barnes and Rearic, 1985). Data on yearly ice gouge characteristics are, 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 objective of this study is to extend our understanding of ice gouging in both time and areal distribution and to complement the previous studies of Reimnitz et al. (1977) and Barnes et al. (1978). 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 influence exerted by sea-ice on high-latitude, subglacial seafloor sediment 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, 1977), whereas recent studies have involved attempts to quantify ice gouge characteristics (Toimil, 1978; Wahlgren, 1979; Rearic et al., 1981; Thor and Nelson, 1981; Reimnitz et al., 1982; 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 yearly rate at which ice gouges are created on the inner shelf have been reported (Lewis, 1977; Reimnitz et al., 1977; Barnes et al., 1978; Pilkington and Marcellus, 1981; Weeks et al., 1984; Barnes and Rearic, 1985). Assessing the rate of ice gouge recurrence is difficult. To determine yearly recurrence rates in this study, two tracklines were reoccupied on an yearly basis and the gouges less than one year old were counted and measured. Comparing one year's record with the next year's allows a good approximation to be made of the gouges that were added to the seafloor during the previous year. This technique requires precise navigation and, for optimum survey conditions, open water free of floating ice.

The first attempt to assess ice gouge recurrence rates and their characteristics in the Alaskan Beaufort Sea was by Reimnitz et al. (1977). Preliminary rates were determined for the years 1973-1975. In a later study, estimates for the years 1975-1977 were calculated by Barnes et al. (1978). Ice Gouge recurrence rate estimates from these two studies agreed favorably. The two studies found that approximately 2 percent of the seafloor was gouged yearly in eastern Harrison Bay (fig. 1), with a mean gouge depth of about 20-cm. Although the studies suggested that many gouges shallower than 20-cm existed, the resolution of the survey 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 ice gouge rates.

The extended data base used in this study (5 years for testline 1 and 4 years for testline 2) allows a very accurate estimate to be made of the average yearly rate at which ice gouges are added to the seafloor in eastrern Harrison Bay (fig. 1).

ENVIRONMENTAL SETTING

Harrison Bay is a large shallow embayment of the Alaskan Beaufort Sea coast (fig. 1). The Colville River has created a delta in the southeast portion of the bay and other geomorphic features of Harrison Bay include a barrier island system in the eastern part of the bay and sand and gravel shoals in the eastern and northern parts of the bay (Reimnitz and Maurer, 1978). The northern 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 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 eroded from river banks, mud bars and the thalweg of the river's 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 deposited on the seafloor through holes eroded in the ice or is carried away on the ice during spring break up (Walker, 1974). Thus, sedimentation in this area is highly non-uniform and differs from that of the deltaic environments of temperate climates.

Freezeup 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 currents 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 Bay this ridge zone, termed the stamukhi zone, occurs in water depths between 8- and 12-m (Reimnitz et al., 1978; Stringer, 1978). Farther seaward, in water depths of approximately 20-m, another stamukhi zone occurs which 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 trapped in the seasonal ice canopy during freezeup 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 breakup 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 melting and breakup. Throughout the summer, isolated ice remnants from the previous winter may remain grounded until the next winter freezeup. During the summer, wind creates waves and currents in open water that may rework seafloor sediments (Reimnitz and Maurer, 1979). Shoal crests in particular are reworked yearly (Reimnitz and Kempema, 1984). Summer ice conditions can vary and at times can be severe enough to affect navigation.

The two tracklines surveyed for this study begin offshore of two barrier islands in the southeastern portion of Harrison Bay (fig. 1). The tracklines are hereafter termed testlines, and they have been reoccupied yearly with precise 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 16.5-m when ice conditions have been favorable. The seafloor below testline 1 is relatively smooth, with a gentle slope of approximately 0.05. 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 when conditions were favorable. The seafloor below testline 2 has a slope about the same as that of testline 1, but the seafloor here contains three 2- to 3-m-high shoals, trending east-west, subparallel to the bathymetric contours, in water depths between 8- and 15-m. Ice conditions varied between surveys and, therefore, testline coverage also varied each year.

METHODS

Data Collection

The data analyzed 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 records a map view of the seafloor (Belderson et al., 1972). The slant range (width of the record on either side of the ship's track) was generally 125-m. 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. A count of the number of gouges, and measurements of width and orientation (fig. 4), as well as termination and length were made from the sonographs. It is estimated that the maximum resolution of the sonographs is about 10-cm under ideal conditions.

Bathymetric 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 include water depth, gouge depth, and ridge height (fig. 4).

Navigation along the tracklines was accomplished using a combination of trisponder ranges (acoustic pingers with an accuracy of about ± 5-m) and visual alignment of Oliktok tower and structures found on Thetis and Spy islands. This system, under ideal conditions, will give an accuracy of position to within 5-m. In the worst cases, ice in the path of the boat caused detours in the testline direction and, therefore, caused a loss of coverage along the testlines. Poor weather and sea state, and system failure also degraded record quality in some cases. The overall quality of the survey recordings was excellent.

Navigation along testline 1 was accomplished by maintaining visual alignment between Oliktok tower and a hut (the only structure) on Thetis Island (fig. 1). The distance from Oliktok tower, on which the range trisponder is located, to the begining of the testline is 12557-m. The testline is orientated 305 degrees true from this point. Navigation along testline 2 was acccomplished by maintaing visual alignment between Oliktok tower and a day beacon on Spy Island. The begining of testline 2 lies 7520-m from Oliktok tower and 9670-m from a trisponder located on Thetis Island. The testline then extends due true north from this location. On both testlines, photographs of testline sonographs obtained in previous years were used to verify accuracy of trackline position by comparing observed bottom features with those previously recorded (fig. 5).

Data Analysis

The tracklines were plotted on navigation charts in the field each year. Navigation was initially divided into 1-km segments beginning 1-km from the barrier island coast and continuing in an offshore direction. The time at each 1-km way point was determined, and these points were located on the records by interpolation between time marks on the sonograph and fathogram records. The records were then compared to the preceeding year's recordings in order to determine the number of new gouges added to the seafloor and the means and maxima of their characteristics.

Terminology

A thorough discription 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 sediment of any ice-influenced body of water.

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

5) Number of Incisions - The total number of adjoining furrows created by a multiplet event.

6) 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.

7) 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.

8) 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 percent greater than the gouge width measurement. The width measurements of all multiplets are reported as disruption widths.

9) 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.

10) Gouge Orientation - The orientation of an ice gouge relative to true north. Orientations are reported as a vector between 0 and 180 degrees but do not imply a direction of movement for the ice keel that created the ice gouge.

11) Gouge Termination - The termination of a gouge on the sonograph record. Usually associated with the termination is a moraine of sediment surrounding the final grounding area. The gouge termination is, therefore, 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 the origin and termination of most gouges do not appear on the sonograph records. For the purposes of this study all gouges not having both a visible origin and termination on the sonograph record are considered to be in excess of 250-m long (the width of the sonograph record) for the calculations in which they are used.

RESULTS

The results of this study are based on the observation and measurement of 1292 ice gouges formed between 1977 and 1982. The data used in calculating the following results are available in Barnes and Rearic (1985). For the purposes of this study these gouges will be termed 'new' gouges. This is done in order to distinguish gouges formed after 1977 from gouges formed prior to 1977. The physical measurements of the gouges extracted from the records include gouge depth, width, length, orientation, ridge height, and in the case of gouge multiplets, disruption width, and the number of incisions created by the multiplet event (fig. 4).

Means and Maxima

The average and maximum values calculated for the physical characteristics of the 'new' gouges identified in this study are presented below. The number of new gouges, maximum gouge depths and total disruption widths are summarized for each 1-km segment in Table 1. One of the more important observations noted in this study is the high variability in the number of gouges formed from year to year (Table 1). Both testlines averaged 8 to 9 'new' gouges per 1-km segment per year over the duration of this study. On testline 1, the maximum number of gouges added to the seafloor in a 1-km segment over the course of one year reached as high as 64 while, on testline 2, as many as 44 'new' gouges were added to the seafloor in a 1-km segment. The most highly gouged segments were were generally found in water depths greater than 10-m deep.

Generally, gouges formed in eastern Harrison Bay are shallow, 20-cm deep or less. Deep gouges occur only rarely and, as with the highly gouged areas discussed above, are restricted to deeper water depths of the testlines. Gouge depths range from a minimum of 10-cm (gouges that were observed on the sonographs but not seen on the fathograms) to a maximum of up to 1.4-m.

The formula for calculation of a distribution mean is dependent upon the type of distribution the data assume when plotted (Miller and Kahn, 1962). 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 overall when combiming the data from both testlines. These means are approximately 25 percent shallower than those found in previous studies in this same area (Reimnitz et al., 1977; Barnes et al., 1978). In earlier studies, those gouges less than 20-cm deep were not included in the calculation of mean gouge depth, which may account for the differences noted.

Because gouge depth data from most ice gouge studies assumes an exponential distribution (fig. 6) (Barnes et al., 1984; Lewis, 1977; Weeks et al., 1984; Barnes and Rearic, 1985) the formula that could be used for 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 'new' gouge depth for testline 1, testline 2, and the combined data from both testlines the mean increases to 18-cm for each data set. This value agrees more favorably with the mean 'new' gouge depth of 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 (the sum of all the measured disruption widths) 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 occurring in eastern Harrison Bay. As with the gouge characteristics discussed above, the largest disruptions occurred in water depths greater than 10-m. In 1980 a maximum of 214-m of disruption occurred 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 'new' gouges formed during this study had no measurable 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 very little sediment to be available to form the ridges. Sediment ridges, having vertical relief above the surrounding seafloor, are also most susceptible to erosion by waves, currents and further ice gouging. The shallow water depths of the study area allow the seafloor to be subjected to frequent wave and current reworking and this may also have an effect on the length of time a sediment ridge is in existence. Only 4 ridges of the 384 measured exceeded 50-cm in height. Mean ridge height is 14-cm with a maximum height of 90-cm.

Gouge length is the most difficult measurement to obtain and, therefore, the least amount of data exist on this characteristic. Most 'new' gouges encountered in eastern Harrison Bay both begin and end off the sonographs. When both an origin and termination are encountered on a recording the gouge is generally very shallow, narrow and short. For this reason, the range, mean and maximum of this characteristic have not been calculated.

Yearly Variations in 'New' Gouge Characteristics

Although ice gouge occurrence is ubiquitous in the study area, both consistency and variation are noted between years and areas. Gouge frequency curves of testline 2 data exhibit a yearly consistency in the peaks of frequency which correlate with the areas and water depths of the shoals (fig. 7). Seaward of the outermost shoal, 'new' gouge frequencies increase abruptly with increasing water depth. Conversely, on testline 1, 'new' gouge frequeny curves do not exhibit a 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 14-m 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., 1984) and, therefore, the disruption width curves (fig. 8) of both testlines reflect the same peaks as their respective frequency curves (fig. 7). Disruption width curves of testline 1 show that disruptions in excess of 100-m/km/year occur in water depths shallower than 10-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 13-m. Relatively large disruptions can occur between the shoals, as happened between 1977 and 1978 surveys (fig. 8).

The maximum depth of 'new' gouges was determined for each 1-km segment. On testline 1, maximum depths increase with increasing water depth and show an abrupt increase at a water depth of 10-m (fig. 9). On testline 2, the yearly consistency of the frequency curve peaks and the disruption width curve peaks is again noted in the curves of maximum gouge depth. However, although there are peaks inshore of the most seaward shoal of testline 2, these peaks are of low value (20-cm or less) and the deepest gouges (>50-m) occur offshore of the most seaward shoal in 15-m or more of water.

Maximum gouge depth and mean gouge depth in 1-m water depth intervals, averaged over the 5 years and 4 years of data from testlines 1 and 2 respectively, demonstrate the effects of the shoals of testline 2 in controlling the depth of gouging (figs. 10 and 11). 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 occur in water depths as shallow as 8-m and gouge depth means steadily increase with increasing water depth. On testline 2, inshore of 15-m water depth, the deepest gouges were consistently 20-cm or less and the mean gouge depth was about 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 (fig. 12) approximate a negative exponential distribution when plotted on a semilog graph (Benjamin and Cornell, 1970; Miller and Freund, 1977; Weeks et al., 1984). There are many more small gouges than there are large ones. In studies by Barnes et al. (1984), Barnes and Rearic (1985), and Weeks et al. (1984) the gouge depth distributions of the 'total' gouge population and the 'new' gouge population were also found to be negative exponentials (fig. 6), 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 (1977) and Wahlgren (1979). 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 maximum end of the distributions.

The semilog plots of disruption width frequency vs. water depth and ridge height frequency vs. water depth (fig. 12) are similar in shape to the gouge depth frequency plot and suggest a negative exponential might also best describe the distribution of these data. Again, as with the gouge depths, the widest gouges and the highest ridges do not fit the distribution. It should be noted that this problem may be due to the short time and small area 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 12 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 discernible 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

The area of the seafloor that is disrupted 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 (Table 1) and determining what percentage of the total trackline length was gouged.

The amount of area on the seafloor disturbed each year was variable and ranged from a maximum of 6.1 percent to a minimum of 1.3 percent. The mean percent of seafloor disruption over the study period was 3.7 percent (Table 2 and fig. 13). Mean disruption was similar on both testlines when averaged over the length of the study, even though the bottom morphologies are different. Data from Barnes et al. (1978) are included in the plot of Figure 13 as a reference for values calculated from earlier work, although it does not distinguish between disruption widths of multiplets and single gouges. The new mean values that are calculated for seafloor disruption (4.0% and 3.4%) are about double the 2 percent value found in previous studies. Although seafloor disruption percentages exhibit a wide range of values, the amount of disruption occurring most often (in 56% of the surveys) is in the 2 to 3 percent range (Table 2).

Minimum Volume of Sediment Disrupted

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 gouge width measurements. A minimum value for the average volume of sediment disrupted annually (V) was calculated as follows. The mean annual gouge depth (X) and mean annual disruption width (Y) were calculated for 1-m water depth intervals (Table 3). The measured length of a gouge was used wherever possible to calculate mean length (Z). The remaining gouges from the sonograph records (about 95% of the 'new' gouges) were assigned a length of >250-m because they do not cross the record at an angle normal to the testline orientation and, therefore, these gouges are in fact slightly longer than 250-m. For this reason these values represent a minimum length. The mean values (X,Y,Z) for each 1-m water depth interval were multiplied together ($V = X \times Y \times Z$) 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 offshore profile of testline 1 (fig. 14), the volume of sediment disrupted increases as water depths increase from about 7-m water depth to the end of the testline. In the 0.25 km wide corridor, approximately 2000 m^3 of sediment are disrupted annually in 10-m of water and 7000 m^3 of sediment are disrupted in 15-m of water. The 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-m^3 of disruption per year over the disruption volume of the preceeding depth interval. If this correspondence holds true, at least to the inner edge of the stamukhi zone, we could expect about 12000-m^3 of disturbed sediment per year in 20-m water depths. Stamukhi zone values will undoubtedly be greater due to greatly increased intensity in ice gouge processes in this zone (Reimnitz and Barnes, 1974; Barnes and Reimnitz, 1974; Barnes et al., 1984; Barnes and Rearic, 1985). On testline 1, in water depths of between 7- and 15-m (a trackline length of about 17-km) a total of about 25000-m^3 of sediment will be disrupted yearly. The area of the corridor in which this occurs is approximately 4.25-km^2. This gives an average sediment disruption volume on testline 1 of 5800-m^3/km^2/per year .

The shoal-dominated profile of testline 2, inshore of 15-m water depth, is disrupted annually on the shoal crests and on their seaward slopes at a rate of about 2000-m^3/year, while in the lee of the shoals, volumes on the order of 200- to 300-m^3 of sediment are disturbed yearly. Seaward of the shoals, in water greater than 15-m, the disruption volume increases abruptly with increasing water depth and begins to aproximate the slope of the testline 1 graph. In water depths of between 7- and 15-m (a trackline length of about-10 km) about 7500-m^3 of sediment will be disrupted yearly. The area of the corridor in which this occurs is approximately 2.5-km^2. This gives a disruption volume value of 3000-m^3/km^2/year. Of this volume, 75 percent occurs in the vacinity of the shoals. An additional 7500-m^3 of sediment is disrupted between water depths of 15-m and 18-m (a corridor length of about 5-km). This gives an additional disruption volume value of 6000-m^3/km^2/year seaward of the shoals.

On testline 2, in water depths of 17-m, 5000-m^3/year of bottom sediment can be disrupted annually, while on testline 1 this volume can be disrupted in water depths as shallow as 13-m.

Mean annual sediment disruption can also be calculated using an average seafloor disruption value of 3.7% and an average gouge depth of 18-cm, both of which were calculated in previous sections. From the above values it found that 37000-m^2/km^2 are disrupted yearly. Multipling this value by the average gouge depth we find that the average amount of sediment disturbed is about 6700-m^3/km^2/year.

New Gouge/Old Gouge Ratios

The number of 'new' gouges in relation to the 'total' gouge population at the time of survey can be an important tool in determining relative rates of sediment reworking by determining the length of time an ice gouge remains in existence on the seafloor. If we compare two areas having equal yearly disruption rates from gouging, and we then determine that the 'new' gouge to 'total' gouge ratio is higher at one site than at the other, it could imply that reworking of the seafloor occurs at a higher rate at a particular site.

All of the gouges observed on the sonographs were counted and the percent of new gouges of this total was calculated (Table 4). Because of differences in record quality in different years the number of new gouges when added to the previous years total does not equal the current year's total. This also may occur because some gouges from the previous year have been reworked by ocean currents and waves until completely infilled with sediment. 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 range from 8.6 percent to 21.1 percent of the observed on testline 1, 14.8 percent are 'new'. On testline 2, 49.1 percent to 76.6 percent of the 'total' gouge population are 'new' gouges. Of the 188 'total' gouges observed on testline 2, 59.6 percent are 'new'. Apparently, infilling of the gouges on testline 2 is occurring at a greater rate than that of testline 1 since the average yearly recurrence rate of 'new' gouges on testline 2 (3.4%) is not as great as that of testline 1 (3.9%) while the ratio of 'new' gouges to the 'total' gouge population is much higher than that of testline 1.

New Gouge Orientations and Terminations

The orientation of an ice gouge records a track along which ice motion occurred. After delineating the track, the probable direction of ice movement can be determined. Estimates can then be made as to which areas of the shelf may be more susceptible to ice gouging and which areas, such as the lee of shoals, may be protected from gouging.

Orientations were taken on all 'new' gouges and plotted as circular histograms (fig. 15). The orientation of the ice gouges relative to the ship's track was measured after which their orientation relative to true north was calculated by correcting for the ship's course. Gouge multiplet orientations were counted as only one occurrence 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 subparallel to the bathymetic contours. Previous studies from other areas of the Beaufort Sea shelf have documented that ice gouge orientations tend to parrellel bathymetic contours when unaffected by seafloor morphology or other factors influencing sea-ice movement (Barnes et al., 1984). Gouge orientations on testline 2 are generally northwest-southeast and more variable than those of testline 1. This is possibly due to the influence of the shoals interfering with the normal direction of flow of the sea-ice.

Gouge orientations can show that ice motion occurred along a particular track but can not delineate the actual direction of motion. However, gouge terminations can indicate the direction of ice keel motion during its disruption of the seafloor.

Gouge terminations for both testlines are plotted as circular histograms in Figure 16 for analysis of the direction of ice keel movement during gouging. Only 5 percent of the 1292 'new' gouges in this study contained terminations which were recorded on the sonographs. Of the 64 'new' gouge terminations 34 (53%) terminated in a southeast direction. Westerly movement of the ice keels is also indicated 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 north through northwest generally creates single gouges although some of these gouges do occur as multiplets, particularly on the shoals of testline 2 (fig. 17). The single gouge termination dominates the data set for four of the five years of comparisons. In the 1979-80 comparison it can be seen that the 'new' gouge terminations are mostly multiplet in nature and the ice creating these terminations approached from the east.

New Gouge Multiplets And New Gouge Events

Multiplet gouging creates a distinguishable gouge pattern formed by several downward projecting keels (fig. 2). Multiplet gouging itself can fall into two catagories depending on the number of incisions and their depths. Multiplets with only a few incisions and deeper than 50-cm may have been formed by multiyear-ice in which the sea-ice has undergone years of thawing and refreezing, strengthening the ice keels in much the same way as has been suggested for the processes involved in the formation of sea-ice related to the formation of single gouges. Multiplets having many incisions and depths shallower than 50-cm (fig. 2) 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 5 shows that, although only 28 percent of all gouge events are shallow multiplet events, at least 65 percent of all ice gouge furrows are accounted for by these events as well as 67 percent of the associated disruption (Table 6).

DISCUSSION

The differences between the values calculated from previous studies (Reimnitz et al., 1977; Barnes et al., 1978) and the values calculated from this study for average gouge characteristics and, in particular, ice gouge recurrence rates 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 by them in estimating yearly rates of reworking by sea-ice at 2 percent. Barnes et al. (1978) observed an increase in record quality over previous study records, although their data also indicated a yearly ice gouge recurrence rate of 2 percent. A further increase in record quality is noted in the present study, and ice gouges less than 20-cm were routinely observed. A comparison of data from the 3 studies is shown in Table 7.

Frequency Distributions

The frequency curves for ice gouge depths, widths and ridge heights are negative exponentials and similar to those found in previous studies (Barnes et al., 1984; Weeks et al., 1984; Barnes and Rearic, 1985). There are many more low values found for gouge depth, gouge width and ridge height than high values (fig. 12).

The negative exponential distribution, however, fails to fit the extremely 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. Infilling of ice gouges from storm waves was observed in the fall of 1977 by Barnes and Reimnitz (1979). They found that many gouges on the inner shelf were completely filled during just one storm event. These events may occur at short enough time intervals that the unusually deep and/or wide gouge may survive while most of the shallow/narrow gouges are obliterated before a truly representative distribution can accumulate on the seafloor. Another possible explanation may be that there are two distributions contained in the data. First-year ice (pressure-ridges) may account for numerous shallow gouges (Barnes et al., 1984). The deepest features may be created by older, more consolidated ice keels and, therefore, fail to fit the same distribution.

Gouge depths vary across the shelf (fig. 9). 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 (fig. 9). In other words, inshore there are many shallow gouges and a few large gouges and offshore there are many relatively large gouges and fewer small gouges.

The sea-ice environment of the offshore (>20-m water depth) differs from that of the inner shelf. Inshore, ice keels reaching the seafloor are smaller and will leave shallow, narrow gouges in their wake whereas offshore, in the stamuki zone, many large, competent ice keels are available for gouging. In the offshore areas, one deep, wide gouge can obilterate many smaller gouges during one gouge event, leaving a trough that is too deep for many of the shallower keels to reach. This reduces slightly the area of seafloor available for creation of 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 in water depths of between 5- and 16-m. At this rate, the seafloor could be reworked to a depth of 1-m in about 800 years.

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 7 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 greater 1-m deep were found in 156-km of trackline, an average of one every 78-km. Combining the data from both studies it is estimated that, in eastern Harrison Bay and in water less than 18-m deep, for every 77-km of linear survey distance over the seafloor one gouge greater than 1-m deep will be found that is less than one year old.

Figures 9 and 10 show 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 when free from the effects of seafloor morphology such as shoals. Data from other recent ice gouge studies (Barnes et al., 1978; Rearic et al., 1981) as well as the data from this study (Table 1) suggest that there may be a maximum gouge depth that can occur in any given water depth (Table 8). These data show that in any given water depth the maximum gouge depth will be approximately 10 percent (± 2%) of the water depth, 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 to 3 percent 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 percent of the seafloor is reworked yearly by sea-ice (Barnes et al., 1978). This is probably the low end of the yearly reworking rates. Rates as great as 6.1 percent per year were noted during the current study and rates greater than 5 percent were calculated for 3 of the 9 yearly data sets, although many values are in the 2 to 3 percent range and agree favorably with the earlier studies. The approximate doubling in mean rate of seafloor disruption from the 2 percent of earlier studies to 3.7 percent in the present study also points out the year to year variability in the ice gouge process as well as equipment resolution differences.

Barnes et al. (1978) developed a formula to determine the fraction of seafloor disrupted over time. 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 discription 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 since initiation of new gouging

k = Fraction of the seafloor impacted in 1 year

Using the data from the current study, the proportional curve indicates that less time is required to completely gouge the seafloor than was previously thought (fig. 18). 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 (fig. 18). 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 occur in all water depths along both testline, the shoals on testline 2 exhibit some control over the gouge process (fig.. 7, 8, and 9). 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 most seaward shoal, the peaks in the data curves do not reflect high volumes of sediment disruption (fig. 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 most seaward shoal on testline 2 is 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, is subjected not only to high a frequency of gouging (50+ gouges/km) but also to deep gouging (>50 cm) of the sediments. As the water depth increases on the inner shelf, so do the values for 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 parallels bathymetric contours (Barnes et al., 1984; Barnes and Rearic, 1985). 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 from gouge terminations were in the southeast (53%) or southwest (23%) quadrants with only 23 percent 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 and northeast quadrants (fig. 17). Ice keels contacting the bottom evidently bulldoze sediment in an alongshore direction with only a minor amount of sediment moved offshore during gouging.

Because most gouging takes place in a horizontal or upslope direction, 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, sea-ice motion, or a combination of these forces (fig. 17). However, not all of the seaward-terminating gouges are associated with the shoals. Another possible answer may be that the encompassing ice-pack has driven an ice floe into water that is too 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.

Because most ice gouging takes place under the seasonal ice-pack in the winter when ocean currents are small (Barnes, 1981; Matthews, 1981; Barnes and Reimnitz, 1982), sediment transport by ice gouging plays a signifcant role in winter (Harper and Penland, 1982). Barnes (1982), in a study of an ice-pushed, coastal boulder ridge in Camden Bay, about 200-km east of Harrison 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 (figs. 16 and 17) is more southeasterly through southwesterly than northerly. Because sea-ice is driven by ocean currents and winds, which generally move in a westerly direction, sediment that is resuspended during ice gouging will also be driven along the coast or onshore (Barnes and Reimnitz, 1982).

The distance that sediment is transported by ice gouging is difficult to assess. To date no data exist 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 sediment during gouging may allow existing currents to transport the sediment greater distances than the actual bulldozing of sediment does. The most significant 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, 1983).

Hydraulic Reworking

The sand and gravel shoals of testline 2 are less cohesive than the sediment of testline 1, and the gouges generally are shallower for equivalent water depths (figs. 9 and 10). These conditions are conducive to high infilling 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 gouges on testline 1 are 'new' gouges. These figures suggest that testline 2 has a higher rate of hydraulic reworking, which causes ice gouges to be infilled and obliterated (Table 4). Hydraulic forces are focused on the shoal crests (areas where most of the gouging on testline 2 takes place) and gouges fill at a rate that is greater than that of the gentler slope of testline 1. On testline 1, hydraulic energy is lower per unit area and the energy is dissipated over an area of more cohesive shelf sediment, 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.

Gouge Morphology, '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 that the many ice blocks forming the ice ridges, when forced to the seafloor, conform to the bottom topography before consolidation of the keel and gouging occur. The gouges created by this type of ice keel are typically the widest disruptions occurring on the seafloor, but they also are the shallowest gouges. The deepest gouges are created by sea-ice with generally only one or two keels , often of unequal depth, contacting the seafloor (Barnes et al., 1984). These keels 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 5 and 6 show that 65% of the new gouges and 67% of the seafloor disruption occurring in eastern Harrison Bay are 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 and 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 and the remaining 30% of seafloor disruption was from individual gouges.

There appear to be two ice gouge populations, each having distinctive morphologies and creating gouges with different depth and width characteristics. One population is caused by many-keeled ice. These wide and shallow multiplet gouges result in large horizontal, shallow disruptions of the seafloor. Another population is caused by ice ridges with few keels or only one keel and these gouges are relatively narrow and may be shallow or deep, although the deepest gouges are associated with this type. The deepest gouges from this study are of the single keeled type.

On testline 1, in 1978 and 1980, multiplets accounted for over 50% of all gouge events and an average of about 85% of the seafloor disruption (Tables 5 and 6). In contrast, in 1981 on testlines 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. 1981 and 1982 were the years in which the deepest gouges (>1-m) were formed, and again, this suggests that two types of ice gouging are occurring on the shelf today.

In 1981 there was very little multi-year ice on the shelf at freeze-up. This also was a year in which there was the least amount of disruption on the shelf and also one in which one of the deepest new gouges was formed. This suggests that when there is no multi-year ice on the shelf at freezeup, a solid ice canopy can form with very little ridging occurring 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 freezeup. 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. Conversely, when there is a significant amount of multi-year ice grounded on the inner shelf at freezeup there will be less chance of creating a very deep gouge. This occurs because the grounded multi-year 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 multi-year ice. The ice ridges thus formed are young and relatively unconsolidated and will create wide, shallow disruptions.

CONCLUSIONS

Observations and measurements made on recently formed ice gouges in eastern Harrison Bay, Alaska indicate significant variability in ice gouging from year to year based on their number, size, and distribution. The additional following conclusions can be drawn from the results of this study:

1) Gouge production rates are higher than previously reported. The average rate of seafloor area disrupted is 3.7 percent per year, and this suggests that approximately 50 percent of the seafloor is reworked to a depth of 18-cm in 20 years and 98 percent of the seafloor is reworked to the same depth in 100 years.

2) 'New' ice gouge characteristic frequencies exhibit a negative exponential distribution similar to that determined for the 'total' ice gouge population on the Alaskan Beaufort Sea shelf (Weeks et al., 1984). The slope of the distribution curves differs from area to area and is an indication that ice gouge populations differ in their characteristic measurements and are dependent on the area of the shelf surveyed.

3) In the 250-m wide corridors of the study area, in water depths of 5- to 16-m, gouges greater than 1-m deep occur every 6 years and account for 0.1 to 0.2 percent of all gouges in this area. In water depths greater than 10-m, the seafloor can be completely disrupted to a depth of 1-m in about 800 years. On the average, every 77-km of linear survey coverage of the seafloor, one 'new' gouge greater than 1-m deep will be encounted.

4) In areas unaffected by the influence of shoals, the maximum depth of gouging will be approximately 10 percent (± 2%) of the water depth 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. Shoals may deflect the direction of sea-ice movement, while, at the same, sustaining a high rate of gouging on their crests and seaward flanks and protecting the shoal lee from gouging.

6) The dominance of southwesterly through southeasterly ice gouge terminations suggests that most sediment transport by ice gouging is alongshore to onshore. This corresponds to the dominant wind and current patterns for the Beaufort Sea.

7) On testline 1, between 7- and 15-m water depth, sediment disruption occurs at a rate of 5800-m^3/km^2/year. In water depths greater than 10-m, cumulative disruption volume increases at a rate of about 1000-m^3 per 1-m of increased water depth. On testline 2, between 7- and 15-m water depth, sediment disruption occurs at a rate of 3000-m^3/km^2/year. Seventy-five percent of the disruption occurs on the crests and seaward slopes of the shoals. Offshore of the most seaward shoal, to water depths of about 20-m, sediment disruption occurs at a rate of 6000-m^3/km^2/year. The average rate of sediment disruption for eastern Harriso Bay is 6700-m^3/km^2/year when calculated using the mean yearly disruption rate (3.7%) and the mean gouge depth (18-cm) determined from this study.

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, and high rates of gouge obliteration on these shoals suggest that 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 area impacted by ice. The most common and often the deepest gouge events are single gouges and multiplets with few incisions, and these account for the greatest vertical displacement of seafloor sediment.

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Figure Captions

Figure 1. 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.

Figure 2. 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 took place in a southeasterly, onshore direction.

Figure 3. Sonograph record of an ice gouge produced in a ripple field. Note the destruction of the bedforms. The gouge is about 5m wide and 20cm deep.

Figure 4. Sketch illustrating the terms used to describe the characteristics of an ice gouge and gouge multiplet

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

Figure 6. Gouge depth frequency distributions from the studies of A) Weeks et al. (1984), B) Barnes et al. (1984), and Barnes and Rearic (1985). Note that in all these studies, as with the present one, a negative exponential distribution is indicated.

Figure 7. Yearly gouge frequency along both testlines. Note the correspondence of the major peaks of the testline 2 graphs to the shoal locations on the depth profile.

Figure 8. Total yearly disruption width in each 1 km segment along both testlines. Note the similarity of these graphs to those of gouge frequency.

Figure 9. Deepest gouge in each 1 km segment each year. Note that there is no similarity to the graphs of gouge frequency and disruption width.

Figure 10. Deepest gouge found in each 1-m water depth interval over the entire course of the study.

Figure 11. Mean gouge depth in each 1-m water depth interval averaged over the entire course of the study.

Figure 12. Frequency distributions plotted on semilog coordinates for three gouge characteristics measured in this study; A) gouge depth, B) disruption width, and C) ridge height.

Figure 13. 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.

Figure 14. Average minimum volume of sediment disturbed on the 250-m testline corridors in 1-m water depth intervals. The influence of the shoals is again noted in that values inshore of 15-m water depth are relatively low on testline 2. Testline 1 demonstrates a consistent increase in disruption volume between 7- and 14-m water depth of about 1000-m^3 per 1-m of water depth increase.

Figure 15. Gouge orientations plotted as circular histograms for the two testlines. Note that the orientations of testline 1 are subparrellel to the bathymetric contours with an approximate east-west orientation. Orientations on testline 2 are more northwest-southeast.

Figure 16. Gouge terminations plotted as circular histograms 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.

Figure 17. Ice gouge terminations plotted by year. Termination is indicated by a circle at the end of a line depicting direction of movement.

Figure 18. Plot of the percent of seafloor gouged vs. time (Barnes et al., 1978). The plot is from a model considering yearly replow of previously gouged areas as well as non-gouged areas. Dashed line is calculated from the data of Barnes and others (1978) and the solid line is calculated from the data of this study.

Table Captions

Table 1. Tabulated data for testlines 1 and 2 from Barnes and Rearic (1985) showing gouge characteristics and distribution. Dashes indicate that no data are available.

Table 2. Annual variations in areal percentage of seafloor disruption for eastern Harrison Bay.

Table 3. Volume of disrupted sediment in 1 m water depth intervals averaged over the course of this study.

Table 4. Percent new gouges of the total gouge record observed on the seafloor in eastern Harrison Bay.

Table 5. Testline comparisons between multiplet and single gouge events and the number of new gouges accounted for by the events.

Table 6. Comparison of the amount of seafloor disruption accounted for by multiplet and single gouges.

Table 7. Gouge characteristic comparisons between three studies of testlines 1 and 2 in eastern Harrison Bay.

Table 8. The deepest gouges and the water depths in which they were found. Data are from two studies from eastern Harrison Bay and one study on the Alaskan Beaufort Sea shelf.

Figure 1

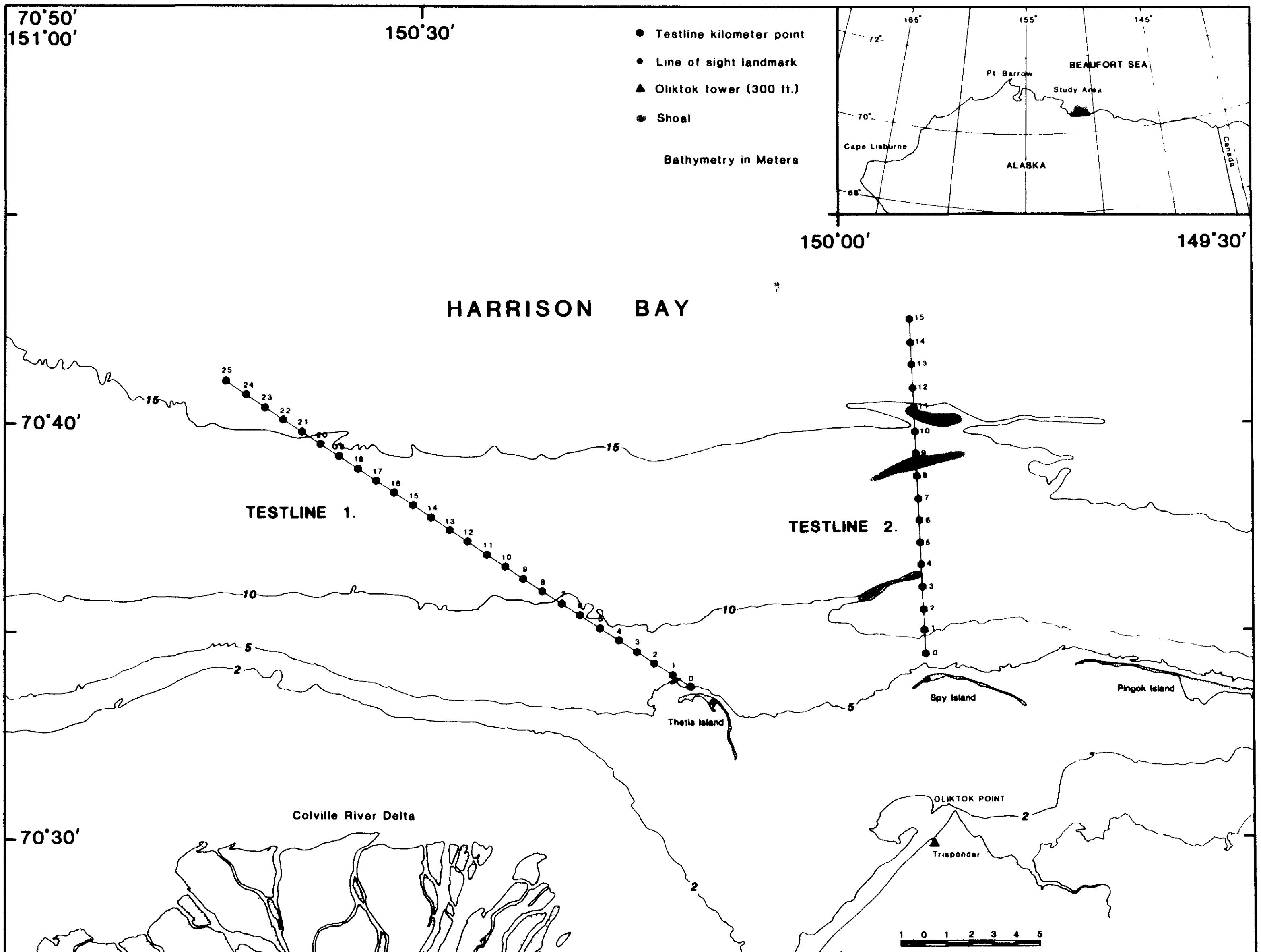

70°50′
151°00′
150°30′
150°00′
149°30′
70°40′
70°30′
Testline kilometer point
Line of sight landmark
Oliktok tower (300 ft.)
Shoal
Bathymetry in Meters
BEAUFORT SEA
Pt Barrow
Study Area
Cape Lisburne
ALASKA
Canada
HARRISON BAY
TESTLINE 1.
TESTLINE 2.
Thetis Island
Spy Island
Pingok Island
OLIKTOK POINT
Trisponder
Colville River Delta
Kilometers
Mercator Projection

Figure 2

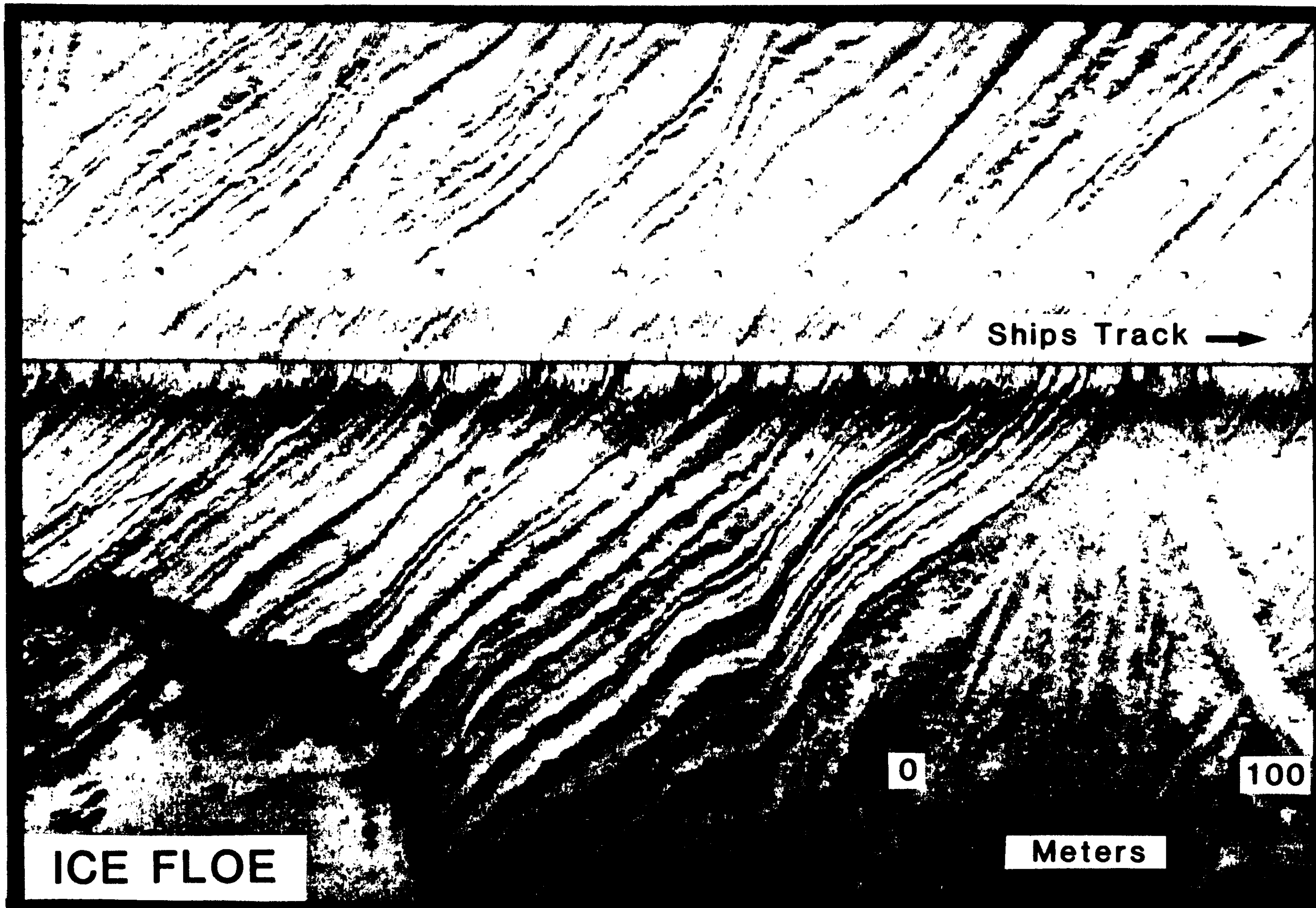
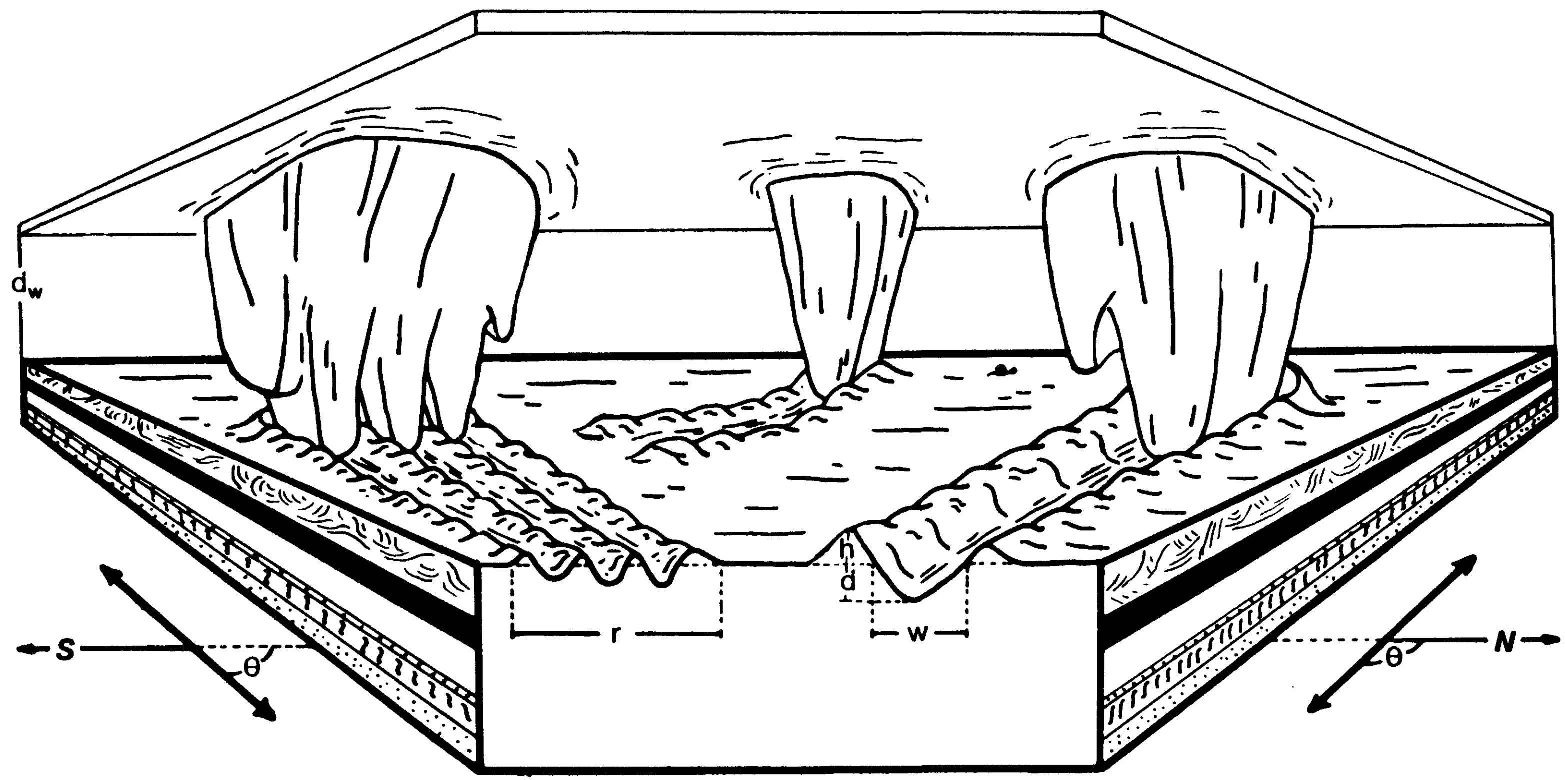


Figure 3

Figure 4



d – Gouge Depth

w – Gouge Width

h – Ridge Height

r – Disruption Width

θ – Gouge Orientation

d_w – Water Depth

Figure 5

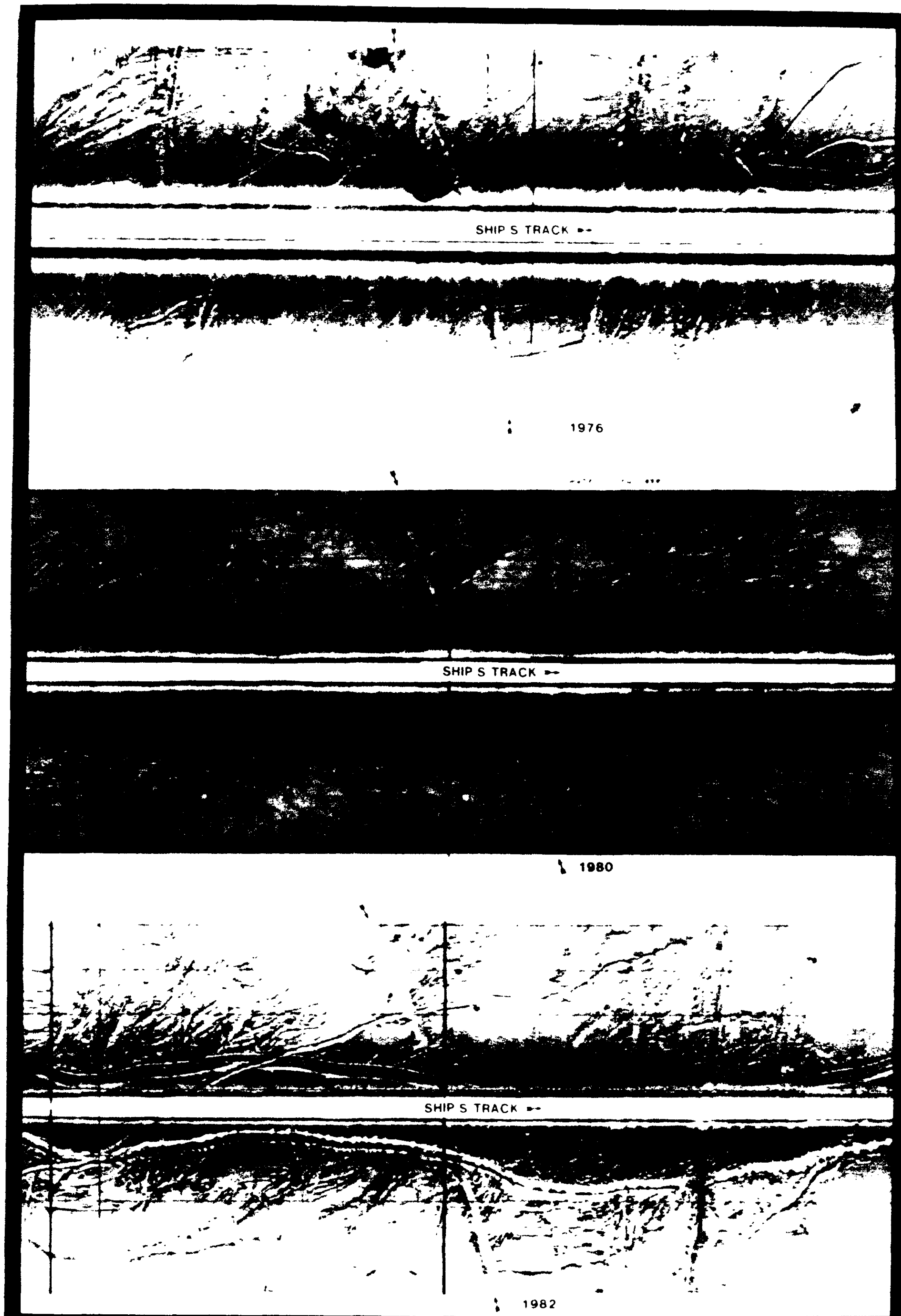


Figure 6

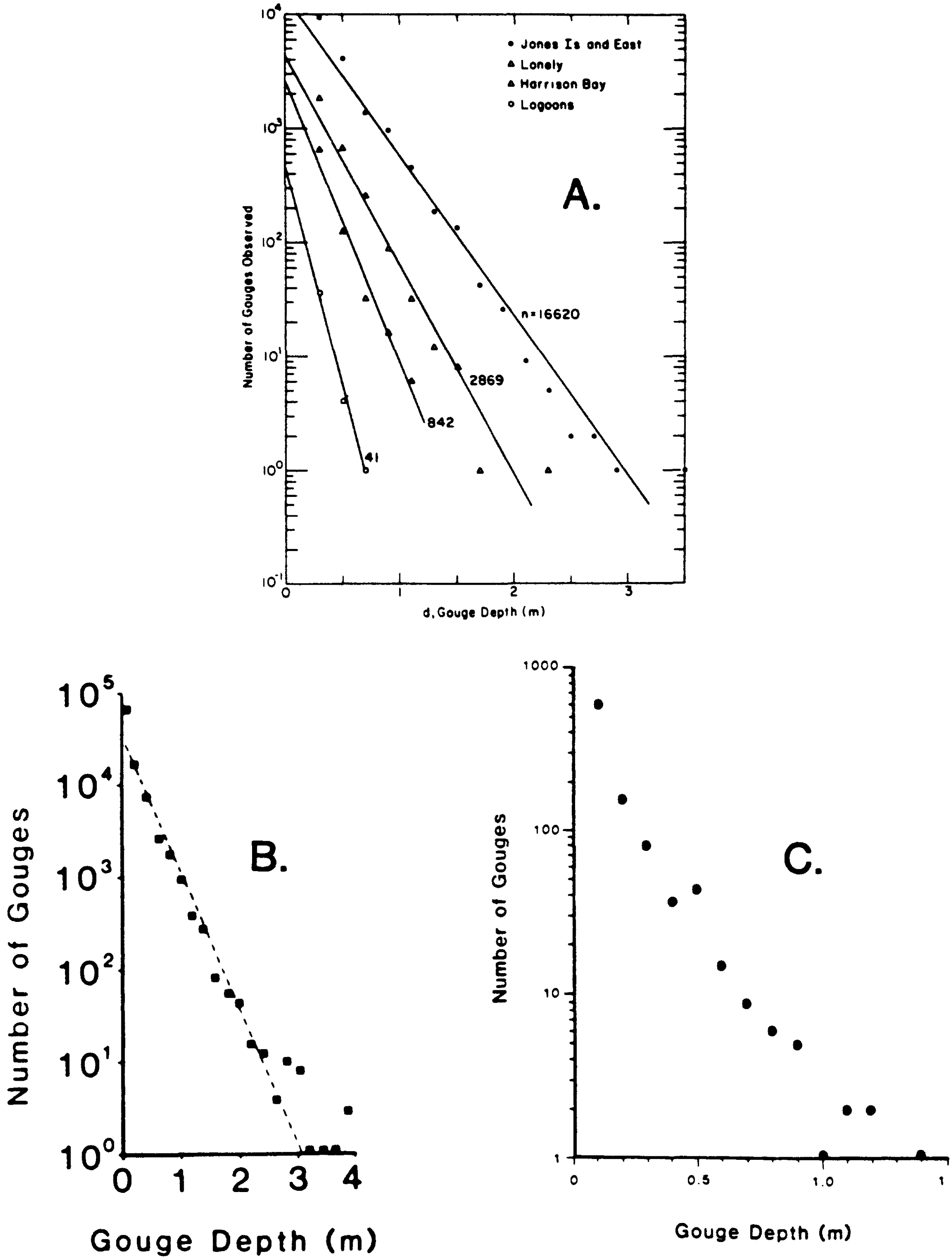
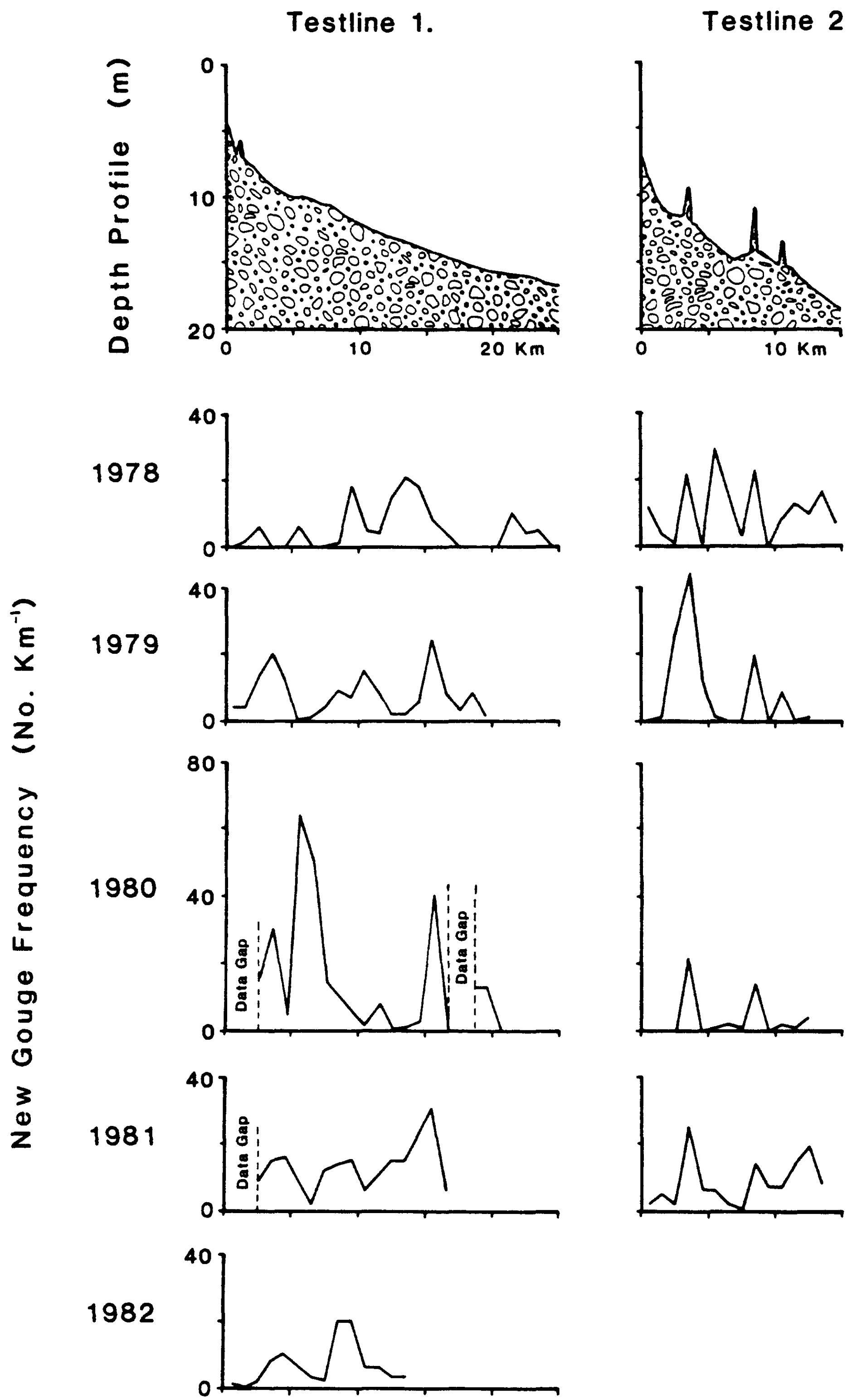

Jones Is and East
Lonely
Harrison Bay
Lagoons
A.
n=16620
2869
842
41
Number of Gouges Observed
d, Gouge Depth (m)
B.
Number of Gouges
Gouge Depth (m)
C.
Number of Gouges
Gouge Depth (m)

Figure 7



Testline 1.
Testline 2.
Depth Profile (m)
0
10
20
0
10
20 Km
10 Km
New Gouge Frequency (No. Km^{-1})
1978
1979
1980
1981
1982
40
80
Data Gap

Figure 8

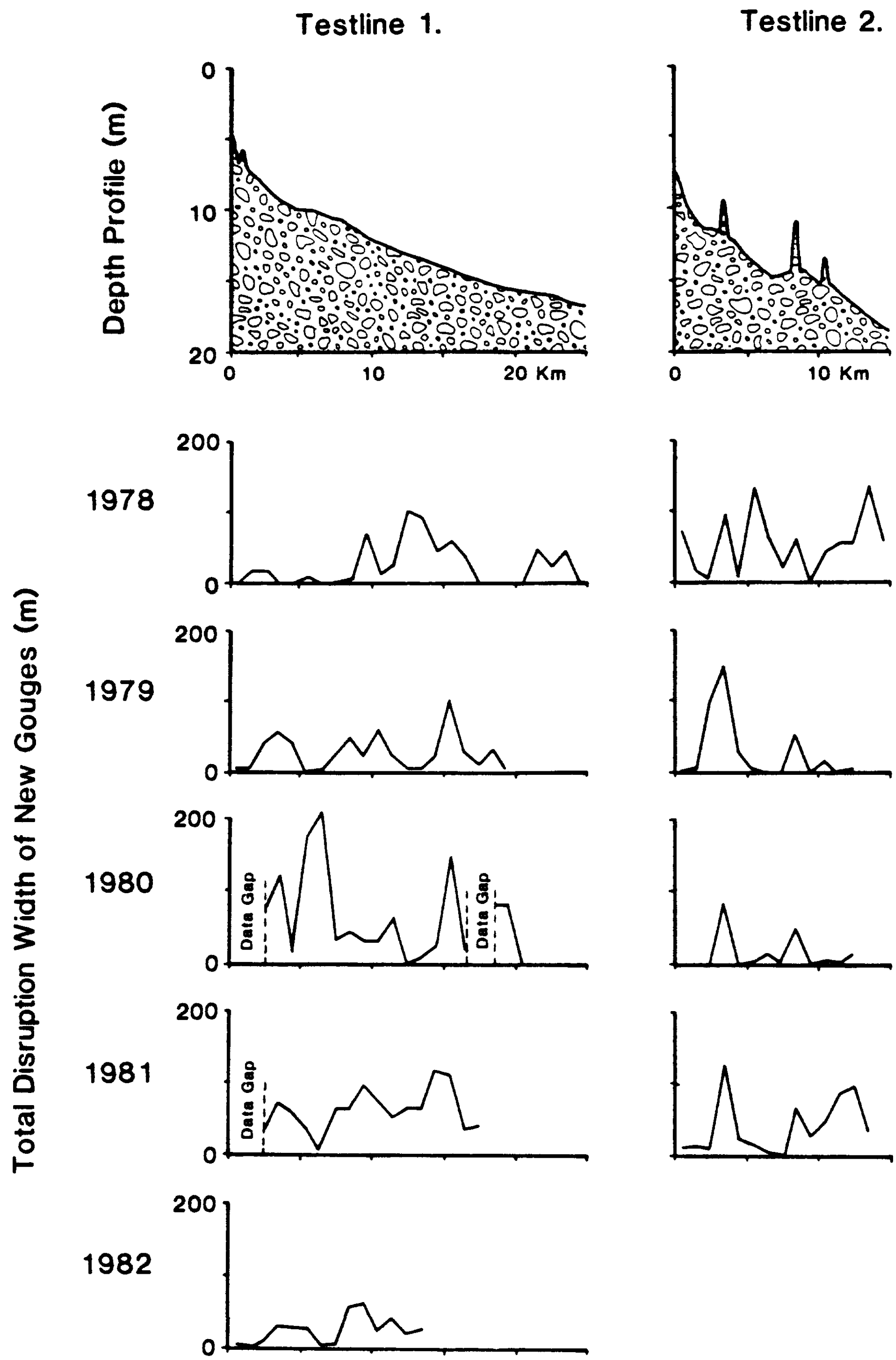

Testline 1.
Testline 2.
Depth Profile (m)
0
10
20
0
10
20 Km
0
10 Km
Total Disruption Width of New Gouges (m)
1978
1979
1980
1981
1982
200
0
Data Gap

Figure 9

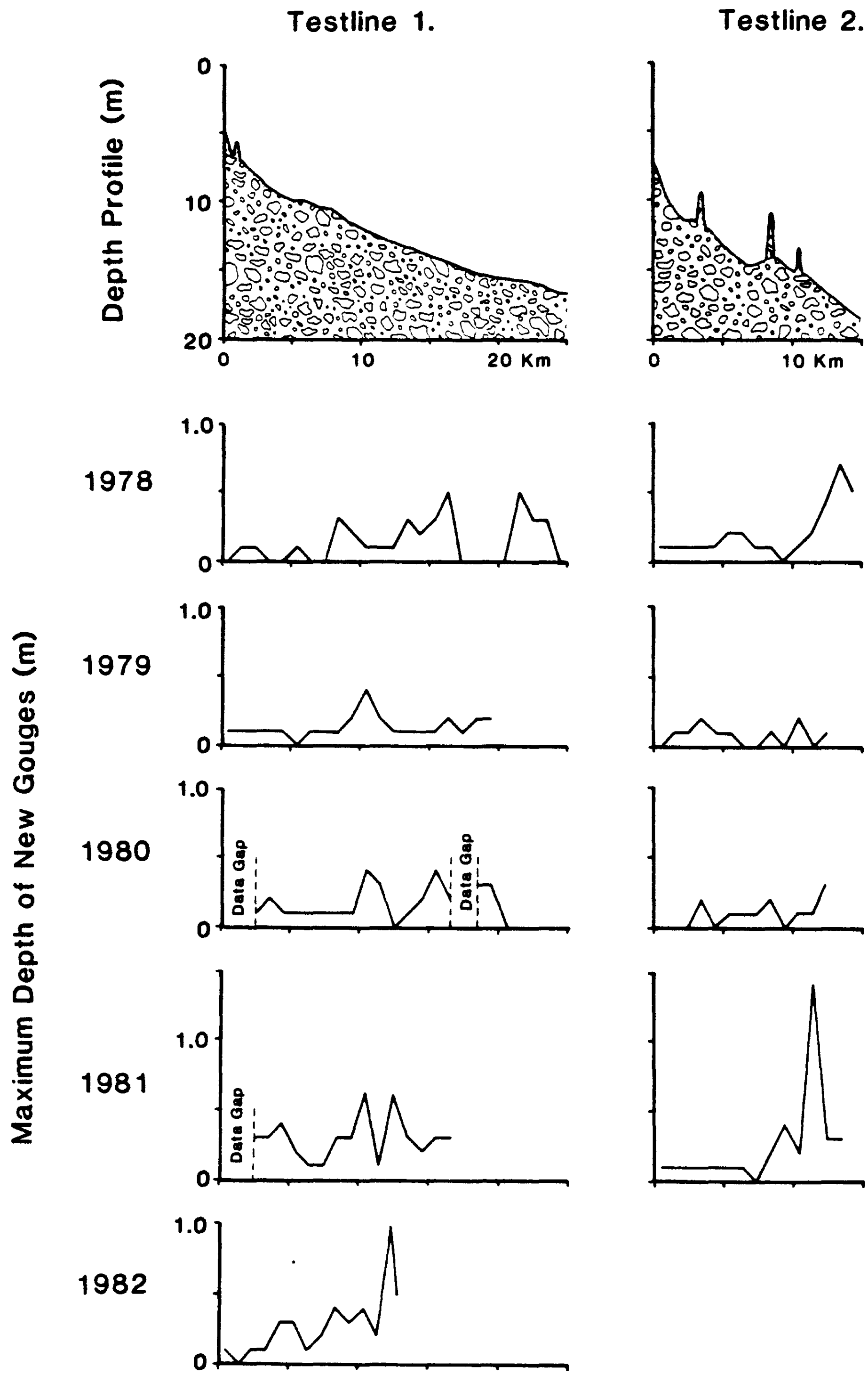
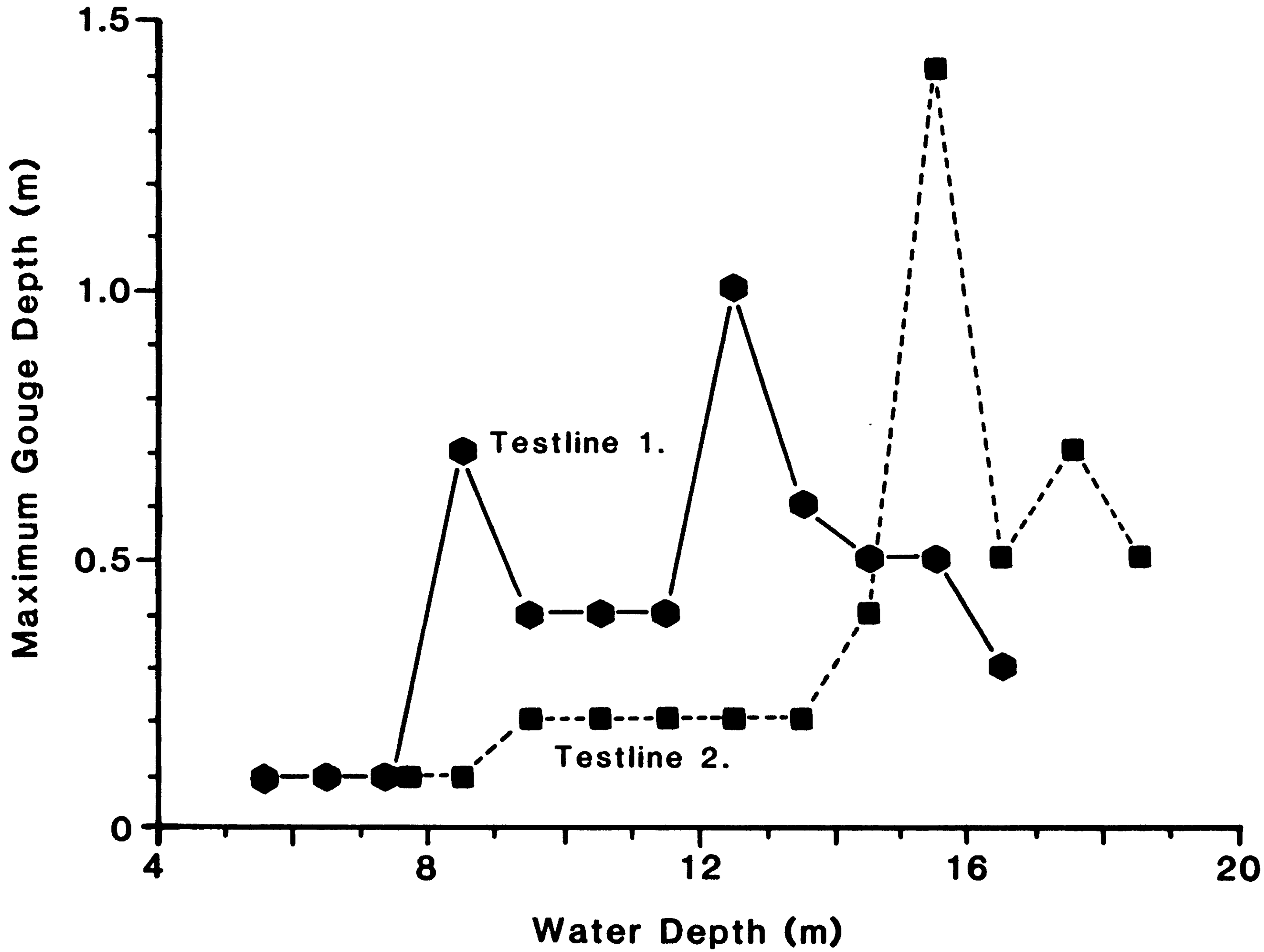

Testline 1.
Testline 2.
Depth Profile (m)
0
10
20
0
10
20 Km
0
10 Km
Maximum Depth of New Gouges (m)
1978
1979
1980
1981
1982
1.0
0
Data Gap

Figure 10



1.5
1.0
0.5
0
4
8
12
16
20
Maximum Gouge Depth (m)
Water Depth (m)
Testline 1.
Testline 2.

Figure 11

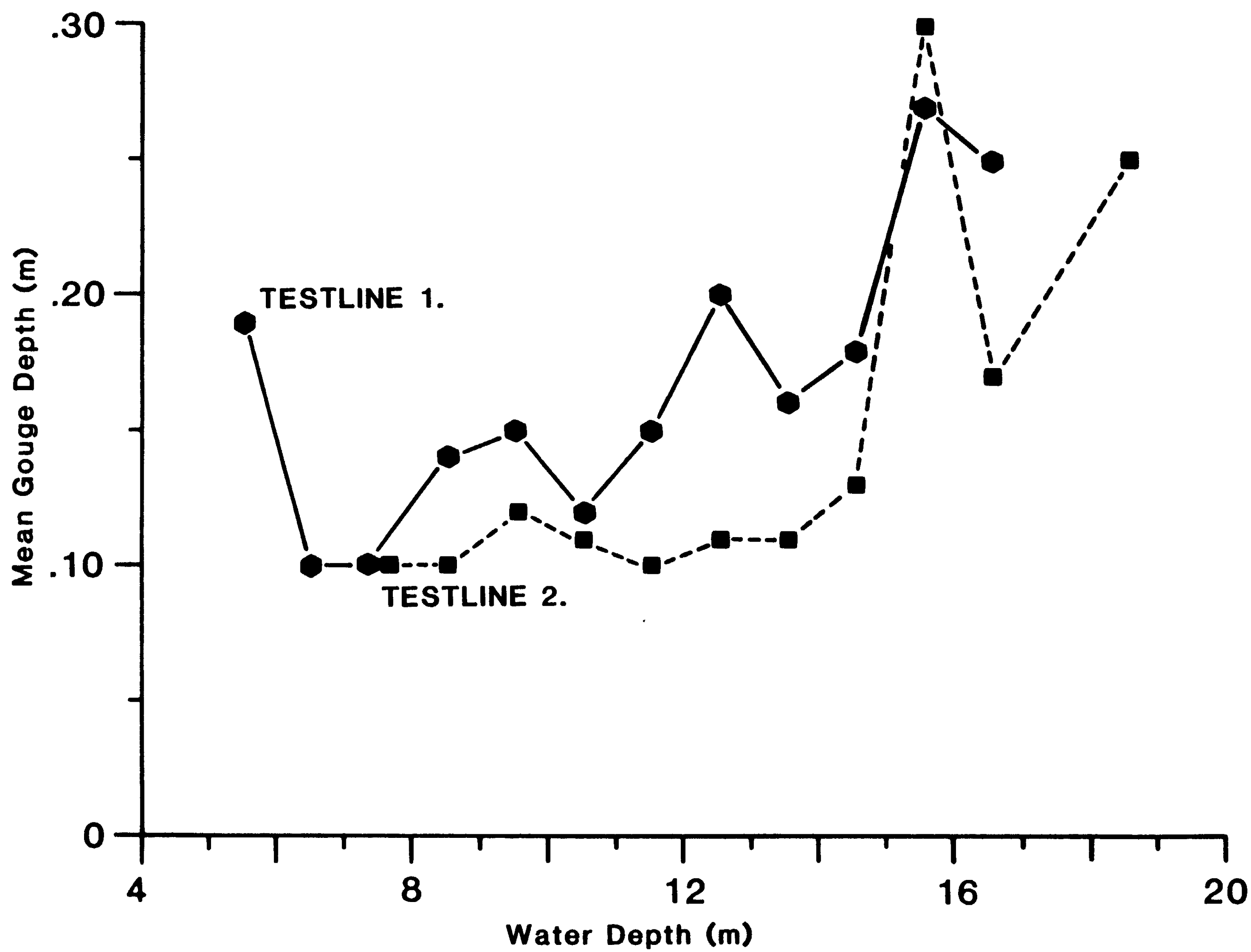
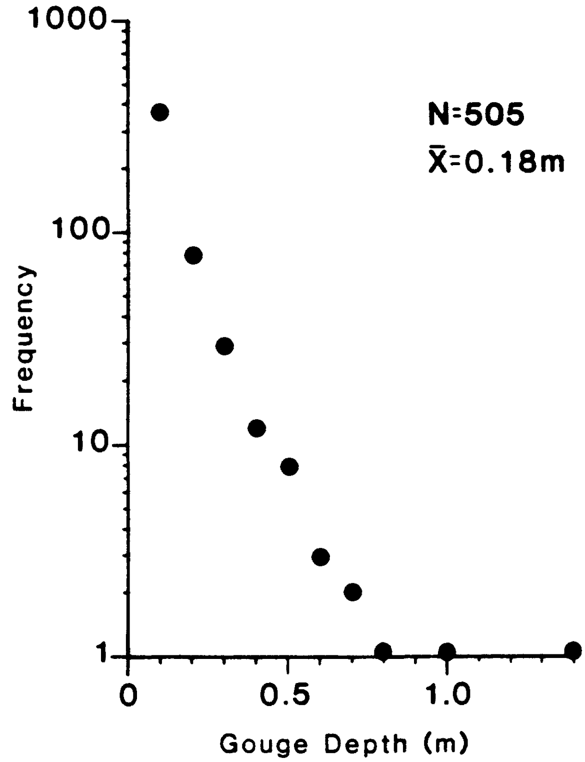
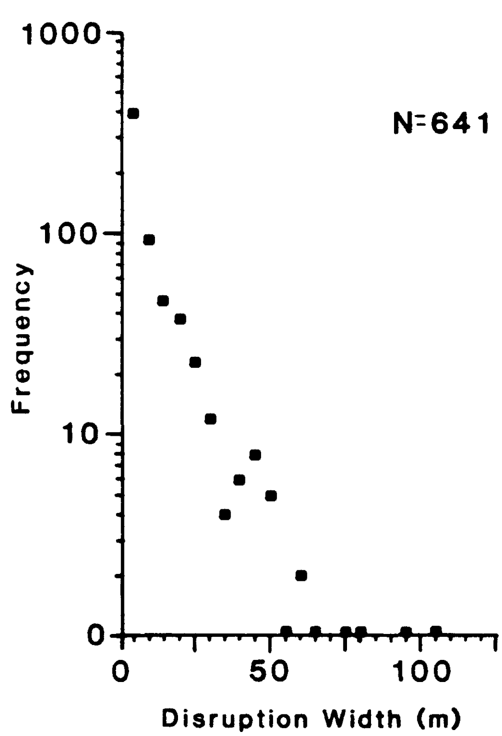

.30
.20
.10
0
Mean Gouge Depth (m)
TESTLINE 1.
TESTLINE 2.
4
8
12
16
20
Water Depth (m)

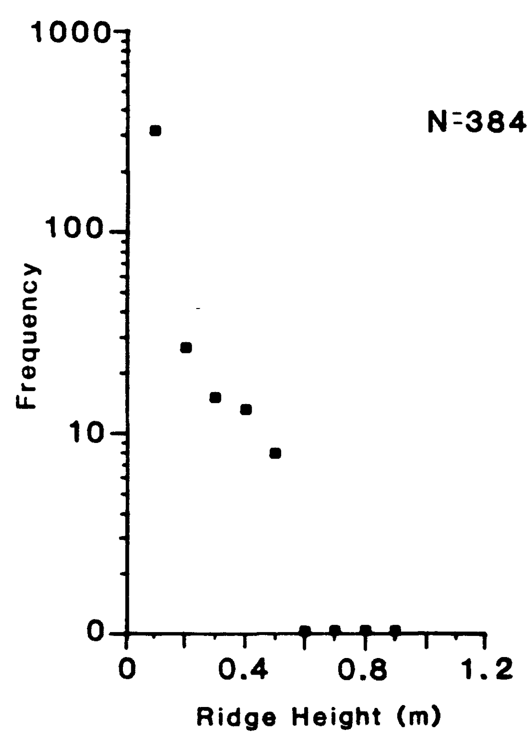
Figure 12



1000
100
10
1
Frequency
N=505
X̄=0.18m
0
0.5
1.0
Gouge Depth (m)



1000
100
10
0
Frequency
N=641
0
50
100
Disruption Width (m)



1000
100
10
0
Frequency
N=384
0
0.4
0.8
1.2
Ridge Height (m)

Figure 13

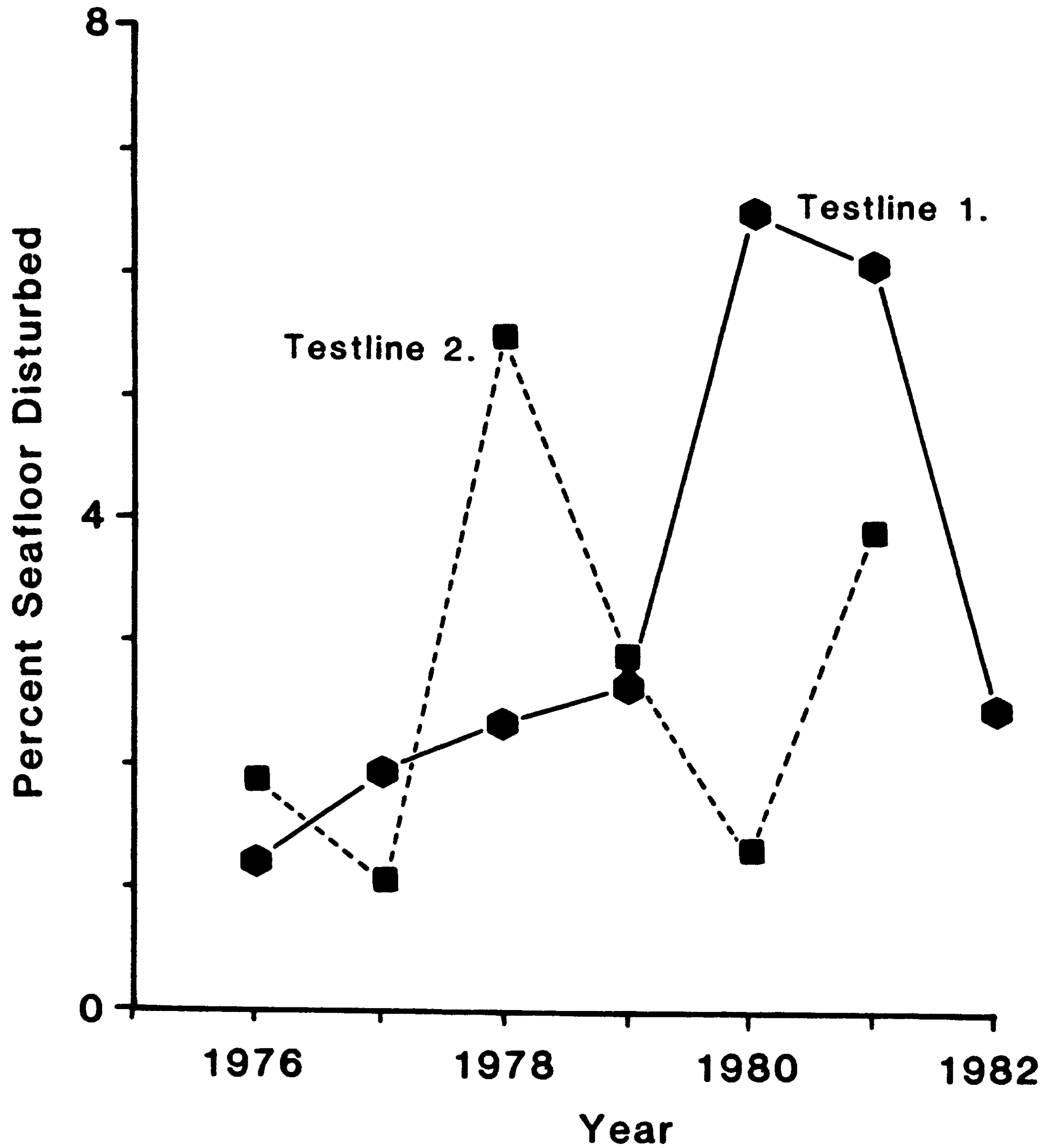

8
4
0
Percent Seafloor Disturbed
Testline 1.
Testline 2.
1976
1978
1980
1982
Year

Figure 14

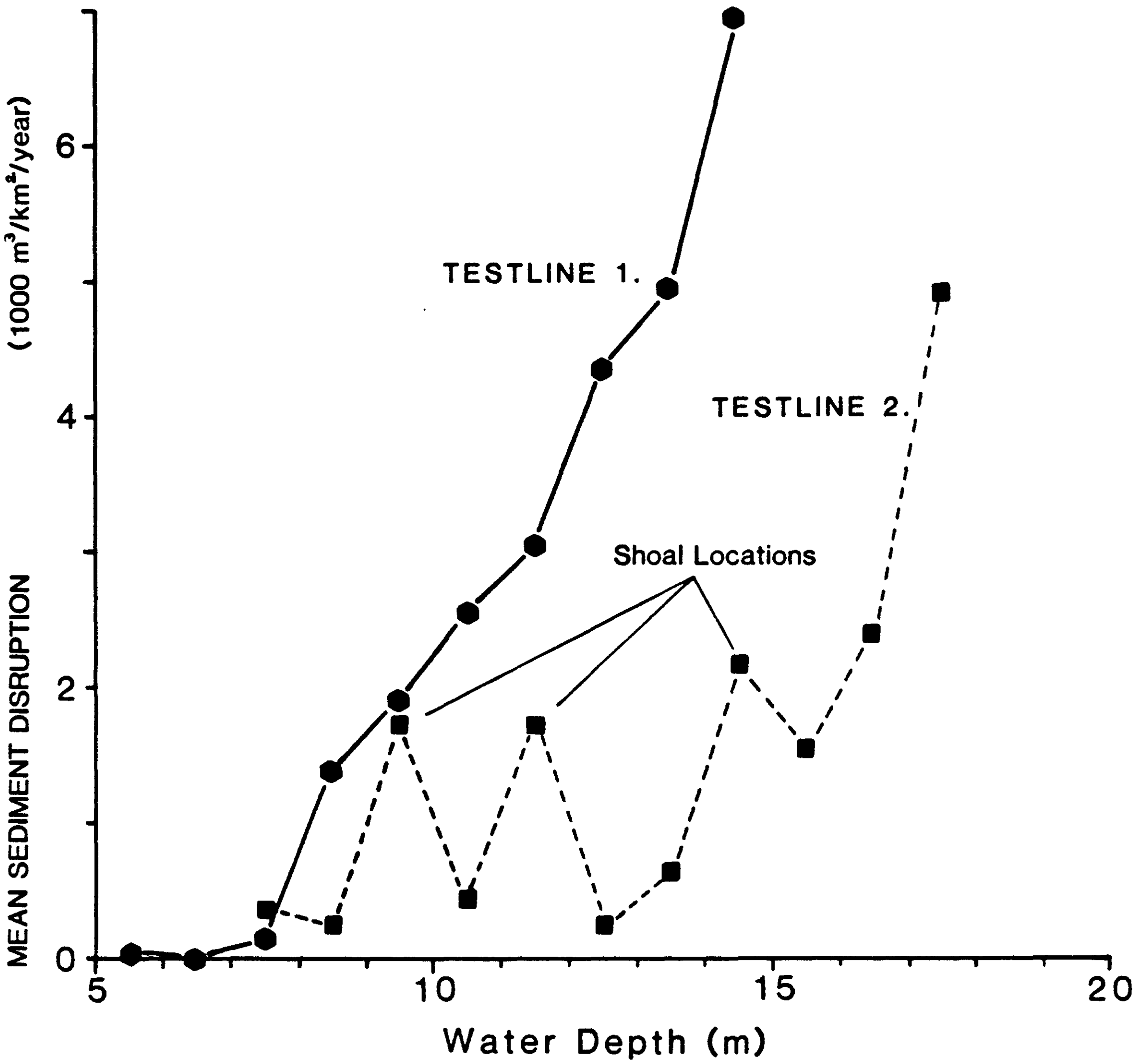

MEAN SEDIMENT DISRUPTION
(1000 m³/km²/year)
TESTLINE 1.
TESTLINE 2.
Shoal Locations
0
2
4
6
5
10
15
20
Water Depth (m)

Figure 15

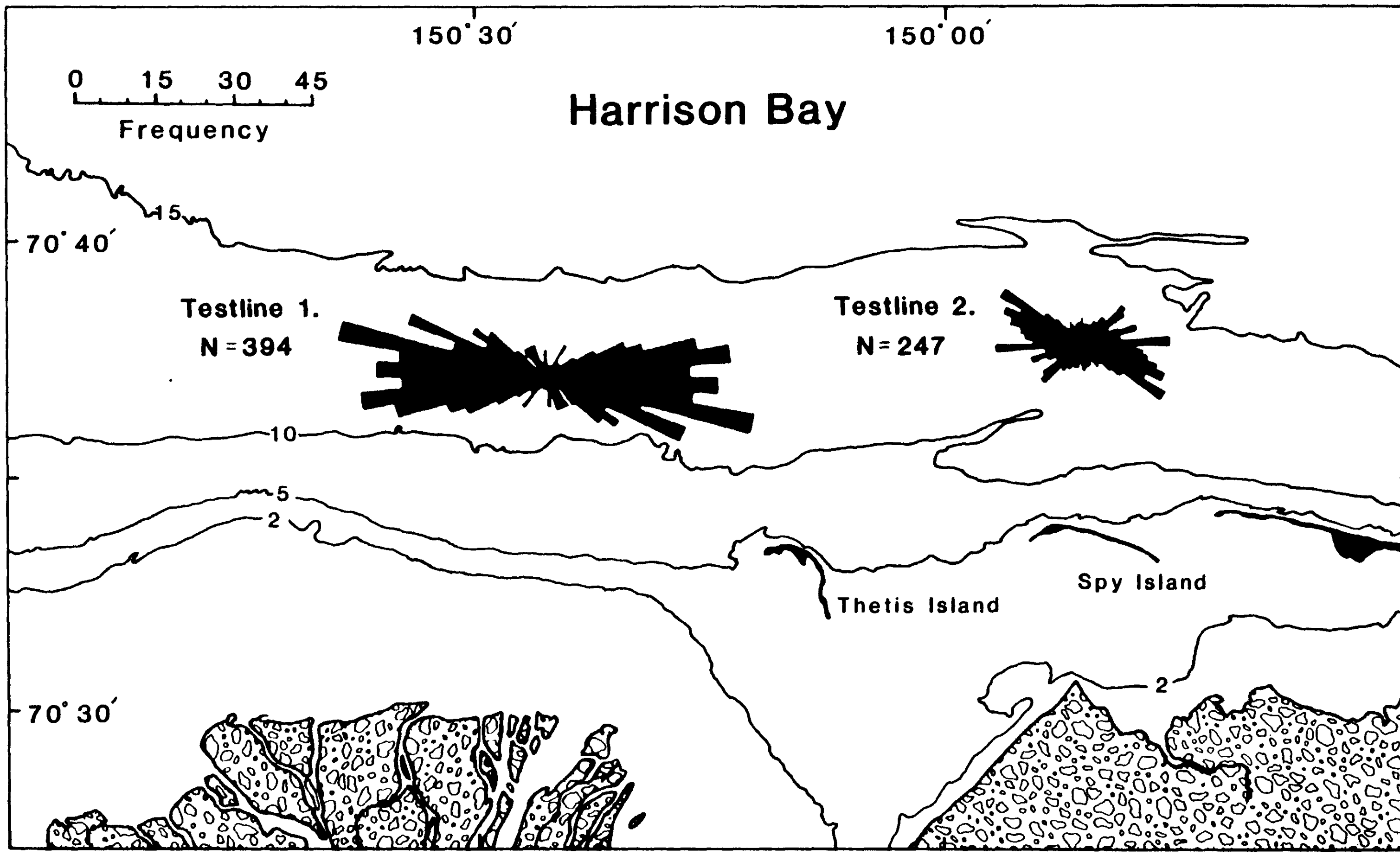

150° 30′
150° 00′
0 15 30 45
Frequency
Harrison Bay
15
70° 40′
Testline 1.
N = 394
Testline 2.
N = 247
10
5
2
Thetis Island
Spy Island
2
70° 30′

Figure 16

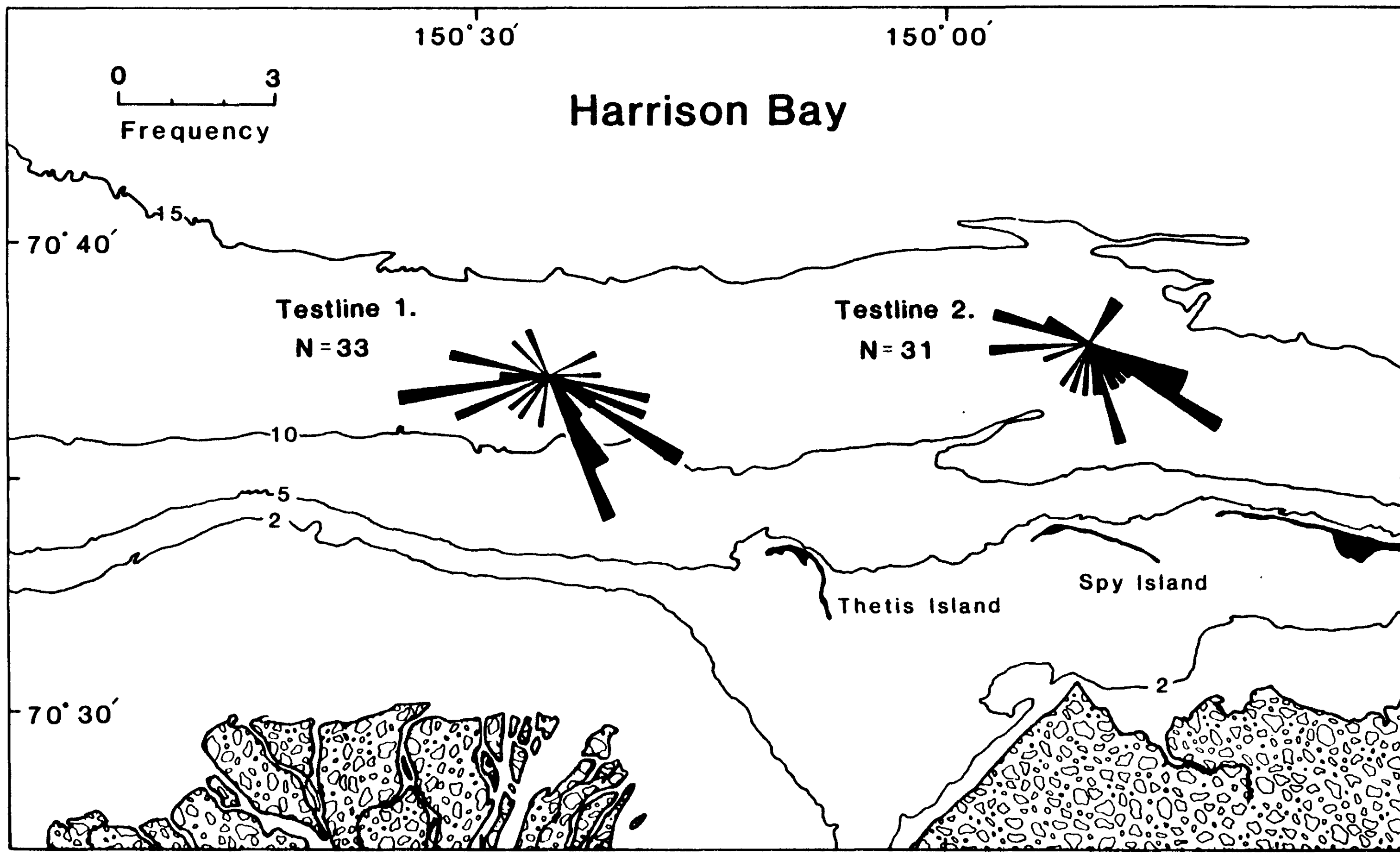
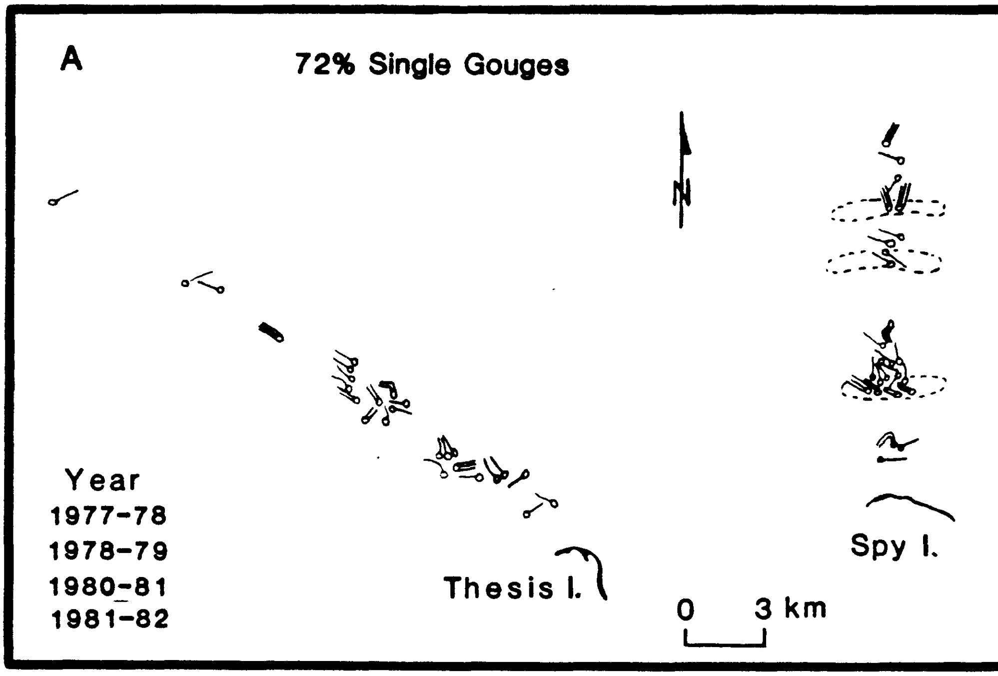

150°30′
150°00′
0
3
Frequency
Harrison Bay
15
70°40′
Testline 1.
N=33
Testline 2.
N=31
10
5
2
Thetis Island
Spy Island
2
70°30′

Figure 17


A
72% Single Gouges
N
Year
1977-78
1978-79
1980-81
1981-82
Thesis I.
Spy I.
0
3 km

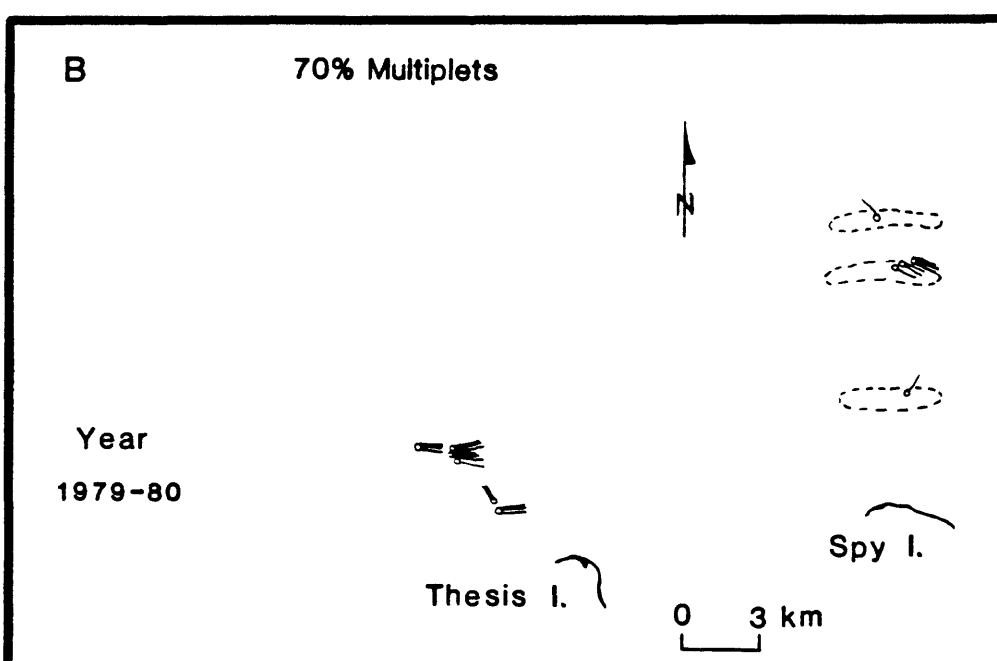
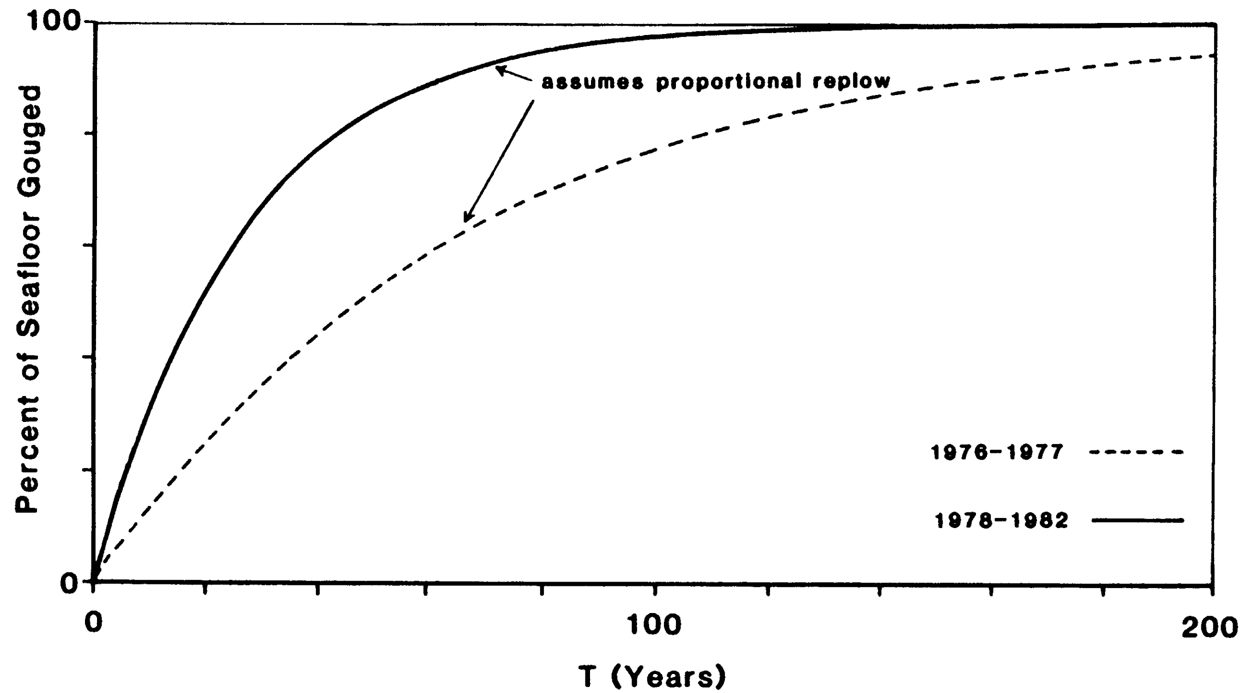

B
70% Multiplets
N
Year
1979-80
Thesis I.
Spy I.
0
3 km

Figure 18



100
0
Percent of Seafloor Gouged
0
100
200
T (Years)
assumes proportional replow
1976-1977
1978-1982

Table 1

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	4	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	4	64	51	14	10	5	2	8	0	1	3	40	4	-	13	13	0						278
1980-1981	-	-	9	15	16	9	2	12	14	15	6	11	15	15	22	30	7	9									207
1981-1982	1	0	2	8	10	7	3	[illegible]	20	20	6	6	3	2													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	.2	.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	.3	.1	.2	.4	.3	.4	.2	1.0	.5													1.0
Total Disruption Width (m)																											**Total**
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
1978-1979	8	8	42	59	45	0	3	25	50	24	60	25	6	5	23	101	30	12	33	4	-	-	0				563
1979-1980	-	-	71	123	14	174	214	31	43	33	31	62	0	10	27	146	21	0	82	82	0						1164
1980-1981	-	-	30	70	58	36	8	64	62	96	71	51	74	62	105	113	35	40									975
1981-1982	1	0	10	31	31	29	4	5	58	62	25	42	22	28													348

Total No. of New Gouges: 845 **Deepest New Gouge:** 1.0m **Total Disruption Width:** 3659m

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	12.2	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	14	7	7	14	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**
1977-1978	72	19	3	97	9	134	65	20	50	0	44	58	56	139	60												826
1978-1979	0	4	97	149	30	3	0	0	53	0	18	0	4														358
1979-1980	0	0	0	82	0	3	15	3	48	0	4	1	15														171
1980-1981	11	13	5	121	21	14	4	0	64	28	49	88	88	34													540

Total No. of New Gouges: 447 **Deepest New Gouge:** 1.4m **Total Disruption Width:** 1895

Table 2

Testline	Year	Total Disruption Width (m)	Testline Length (x 1000m)	Percent Seafloor Disrupted
1.	1978	609	25	2.4
2.	1978	826	15	5.5
1.	1979	563	21	2.7
2.	1979	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 3

Water Depth (m)	TESTLINE 1. X (depth) (m)	Y (width) (m)	Z (length) (m)	V (volumn) (m^3)	TESTLINE 2. X (depth) (m)	Y (width) (m)	Z (length) (m)	V (volumn) (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
9-10	.15	61	>209	>1912.4	.12	79	>130	>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 4

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.	1979	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
		TOTALS		
1.	all	1159	171	14.8
2.	all	188	112	59.6

Table 5

Testline	Year	Single Gouge Events	Multiplet Gouge Events	Percent Multiplet Events	Number of Gouges From Single Events	Number of Gouges From Multiplet Events	Percent of Gouges From Multiplet 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
Both	all	460	182	28	460	832	65

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

Table 6

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 7

	survey line length (km)		number of new gouges		maximum gouge depth (cm)		mean gouge depth (cm)		total gouge width (m)		percent of seafloor disturbed	
	TL1	TL2	TL1	TL2	TL1	TL2	TL1	TL2	TL1	TL2	TL1	TL2
Reimnitz et al (1977)												
1973-1975	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	358	2.7	2.8
1979-1980	21	13	278	46	40	30	15	11	1164	171	6.1	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 unresolveable, whereas 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 8

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%