Ice Gouging Characteristics: Their Changing Patterns from 1975-1977, Beaufort Sea, Alaska

by

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Contents

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INTRODUCTION

Sea ice, in the form of ridges and massive blocks, commonly impacts the sea floor of arctic shelves, scraping, plowing, scouring, and gouging. The characteristics of bedforms have been dealt with at some length (Rex 1955; Kovacs, 1972; Reimnitz and others, 1972; Pelletier and Shearer, 1972; Kovacs and Mellor, 1974; Reimnitz and Barnes, 1974; Reimnitz and others, 1977a,b; and Lewis, 1977). These bedforms are ubiquitous on the arctic shelves of the Chukchi and Beaufort Seas and are known to be present in many areas of the northern Bering Sea and Norton Sound (Thor and others, 1977). Less well known is the evolution of ice gouges in space and time.

A variety of terms has been applied to the micro-features and the associated processes reulting when ice in its various forms is driven along the sea floor. At present there isno agreement among workers as to nomenclature. Prior to the advent of side-scanning sonar, terms such as "gouging" (Wright and Priestley, 1922; Woodward, 1948; and U.S. Department of Commerce, 1964), "ice grounding" (Rex, 1955), and "scouring" (U.S. Department of Commerce, 1964) have been used. With the recent application of side-scan sonar equipment a plethora of terms, as discussed by Lewis (1977), has arisen. These include: "ice scores" (Kovacs, 1972), "ice scours" (Pelletier and Shearer, 1972; Brooks, 1974; Lewis, 1977), "ice gouges" (Reimnitz and others, 1972, 1973, 1977a), "iceberg plough marks: (Belderson and Wilson, 1973), and "iceberg furrow marks" (Harris and Jollymore, 1974). At the present time we have chosen to use the term "ice gouge" from a historical perspective and for its definitive character regarding the processes of ice interacting with the sea floor. The term "ice scour" is perhaps more in keeping with the evolution of geologic nomenclature (Am. Geol. Inst., 1972). However, the implication of erosion and grain by grain transport does not occur with the processes of ice gouging. Furthermore, scour features resulting from currents are often associated with ice gouges (Reimnitz and others, 1973), and the vast difference between the two processes seems to encourage different terminology.

Background

It is important for the design and safety of offshore structures, such as pipelines, to understand the frequency and character of ice interactions with the sea floor. The rates of sediment reworking by ice can be estimated using ice gouge recurrence intervals coupled with the incision depth of ice keels. Similarly the demise of gouge features in time gives information on the rates of sediment reworking by benthic communities, storm waves, and by currents. Seasonal or annual changes in patterns of ice gouge events and their orientation are a reflection of the ice motion during gouge formation. Futhermore, the orientations and intensities of sea-floor gouges are an integration of ice motions dating back many years to the time of complete reworking of the seabed by ice.

To date there has been considerable disagreement among investigators as to the age of ice gouge features and the relative intensity of contemporary gouging as related to winter ice zonations and seasonal ice patterns (Pelletier and Shearer, 1972; Kovacs and Mellor, 1974; Reimnitz and Barnes, 1974; Reimnitz and others, 1977a,b; Lewis, 1977; and Hnatiuk and Brown, 1977).

Many of these differences have resulted from a general sparsity of data and our lack of knowledge regarding ice-seabed interactions on arctic shelves.

Utilizing data gathered for this study during repetitive surveys of the same area on the inner shelf has allowed us to further define the character of year-to-year ice gouging, and the possibility of summer gouging, and to assess the variability of gouging from one year to another. Based on these data, the probability of deep gouges and the frequency of ice impacts can be estimated.

Setting

In the area of this study (Fig. 1) sea ice can generally be divided into three zones based on bathymetry and ice character (Reimnitz and others, 1977b): 1) a bottom fast ice zone inside the 2-m isobath, where ice, at the end of the season of ice growth, rests on the sea floor; 2) the zone of floating fast ice; and 3) the stamukhi zone which forms the seaward edge of the floating fast ice, as a series of major grounded ice ridges. The stamukhi zone commonly in 15-20 m water depths, marks the boundary between the quasi-stable fast ice and the moving polar pack. It is an area of shear and pressure ridge formation and of intense ridge grounding during the winter. As a result, solidly grounded stamukhi ice ridges may remain grounded throughout one or several seasons of melting (Kovacs, 1976).The two fast ice zones remain essentially stable once the stamukhi has formed. Early in the fall, prior to the stabilization of fast ice, newly formed ice and remnant ice blocks in the fast ice zones are free to move. During the summer open water season, drifting ice of various drafts is commonly present at all water depths on the inner shelf. The area of this study (Fig. 1) is primarily located in the zone of floating fast ice.

The sea floor in the study area slopes offshore from the islands to depths of about 7 m, within about a kilometer, then more gradually seaward, remaining less than 20 m, 20 km offshore (Fig. 1). Test line 1 runs northwest

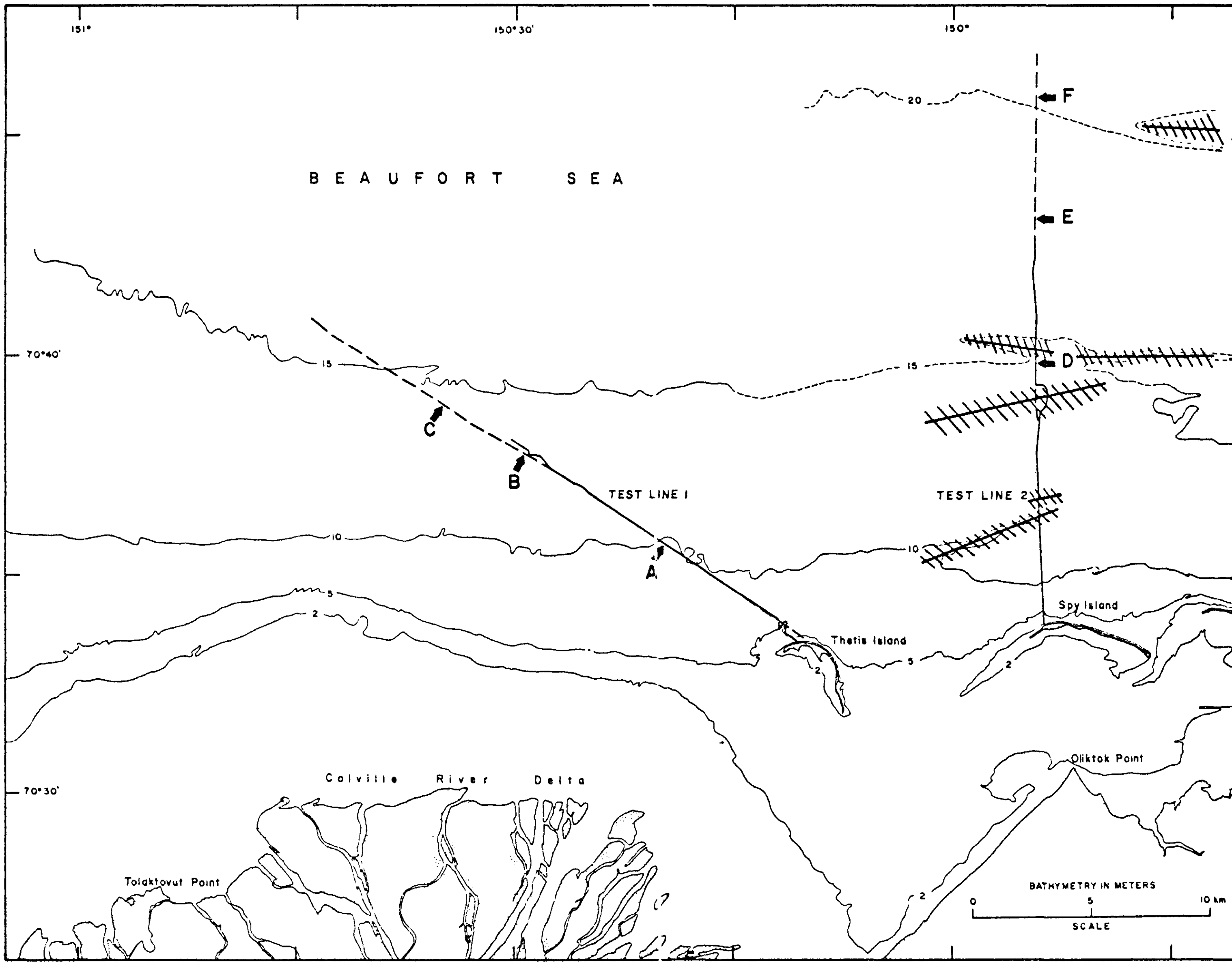


Figure 1. Location map of the study area indicating the location of test lines 1 and 2. Letters A through F designate the location of sonographs and fathograms illustrated in following figures. The hachured areas emphasize the location of submerged shoals in the vicinity of the test lines.

from Thetis Island and test line 2 heads just about due north from Spy Island. Along test line 1 no significant bathymetric features are encountered. On test line 2 several 2 to 4 m high ridges are crossed (Fig. 1). Several additional northwest-southeast trending linear shoals are present northeast of line 2 which apparently have a significant influence on the shelf ice zonation (Riemnitz and others, 1977).

Field Methods

In 1973, 1975, 1976, and 1977, a recording side-scan sonar and a precision fathometer were used on carefully navigated test lines to repeatedly obtain records over the same area of sea floor in each year. Test line 1 was surveyed twice during the summer of 1977, once in early August and once in early September. A comparison of gouging on test line 1 between 1973 and 1975 has already been reported on (Reimnitz and others, 1977a). The 1975, and 1977 side-scan sonar records cover a 125 m swath on each side of the ship's track whereas the 1976 survey obtained side-scan records that covered only 100 m on either side. Depending on sea state, bottom reflectivity, and system tuning the sonographs produced by the sidescan can resolve features less than 10 cm high. The 200kHz fathometer used in this survey was also capable of resolving bottom relief of less than 10 cm.

Navigation along the test lines was accomplished by ranging on landmarks onshore and by a precision range-range navigation system which can be read to the nearest meter and is accurate to $\pm$ 3 m. With these techniques the test lines were renavigated within 50 m from year to year and overlapping sonographs were obtained of the sea floor except in areas where detours were made to avoid ice.

Sonographs from the side-scan sonar were the key data used to define the presence of gouge features and to locate and characterize new gouges from one year to the next (Fig. 2). The analysis of ice gouge character was separated into two parts. First the character of all gouges along the test lines was assessed. The test lines were marked off in 500 m segments from the base of the line on Thetis and Spy Islands seaward (Fig.1), and the trend, density, maximum incision depth and the maximum disruption width were determined from the 1975 records and again for the longer 1977 tracklines to extend and verify the measurements on the 1975 records. Secondly, the new gouge features formed between the summers of 1975 and 1976 (Fig. 2) and between the summers of 1976 and 1977 were tabulated for the same characteristics, using the sonographs and fathograms from 1976 and 1977. The techniques used in determining gouge character are given in greater detail along with the results in the section below. A comparison of gouging on test line 1 between 1973 and 1975 has already been reported on (Reimnitz and others, 1977a).

Terminology

An idealized gouge cross section is shown in Figure 3 as an aid in clarifying the terminology used in this report (Reimnitz and others, 1977a). The keel of an ice projection is depicted bulldozing or plowing though the bottom sediments (Fig. 3A) displacing material. The ice keel is presumed to dig below the prevailing sea-floor depth and to pile materials to the side forming flanking ridges. After the ice keel has passed (Fig. 3B), the flanking ridges and the incision remain to the extent that they are modified by slumping, current and biological reworking, and subsequent ice bulldozing and sedimentation. It should be noted that: a) "incision depth" is generally less than the gouge relief and may be measured less than the actual

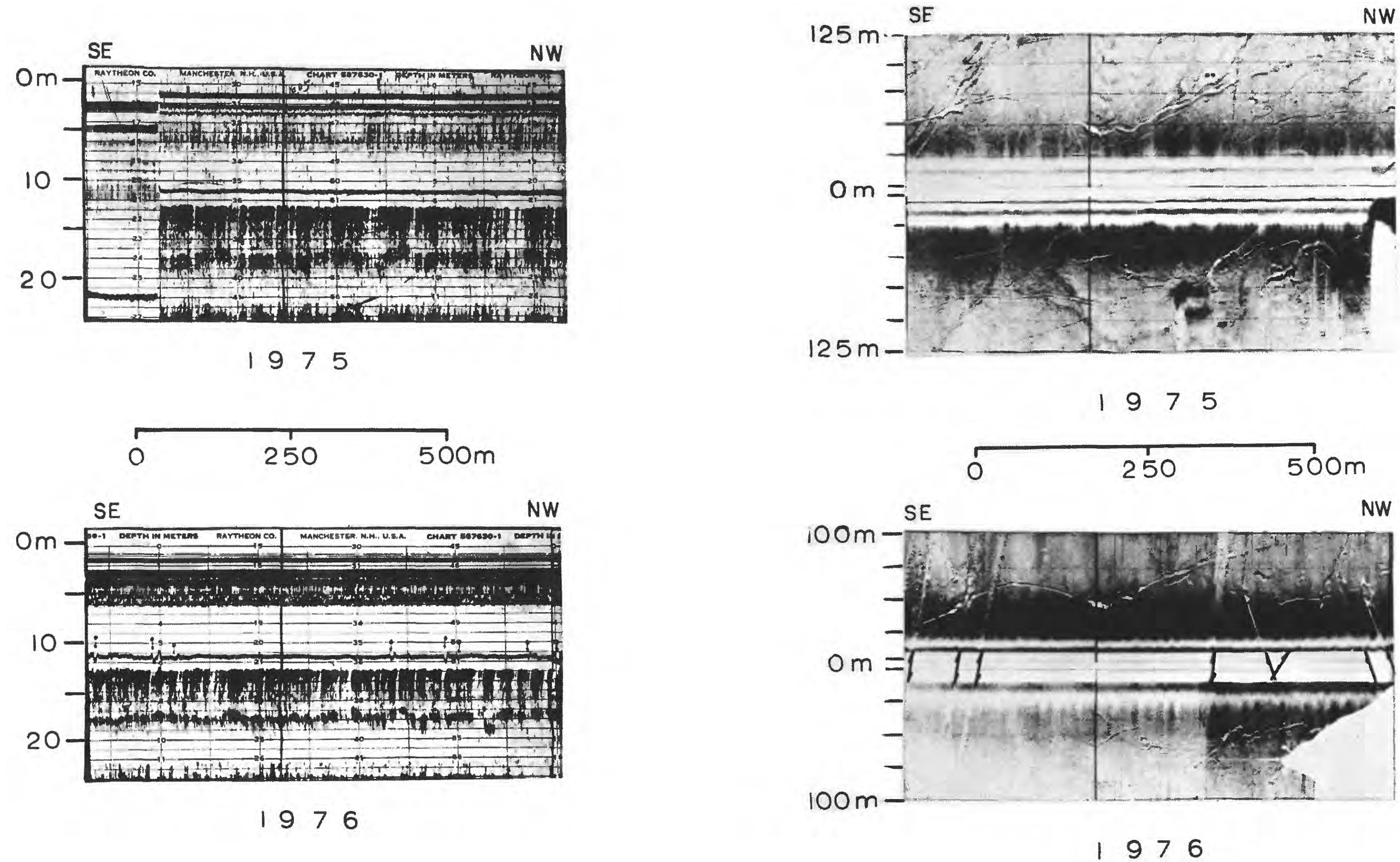


Figure 2. Comparison of 1975 and 1976 fathograms (left) and sonographs (right) at location A (Figure 1) showing new gouges which have formed between September 1975 and August 1976 (arrows). Eight gouges from three ice events can be distinguished on the 1976 sonograph; a) an event forming the series of three parallel gouges on the left side of the record and one gouge right of center with the same trend, b) the set of three parallel gouges on the right side of the sonograph which terminate near the NW corner, and c) a single gouge which weaves across the record toward the upper right hand corner. Note the variability of new gouge incision depths seen on the 1976 fathogram (dotted arrows).

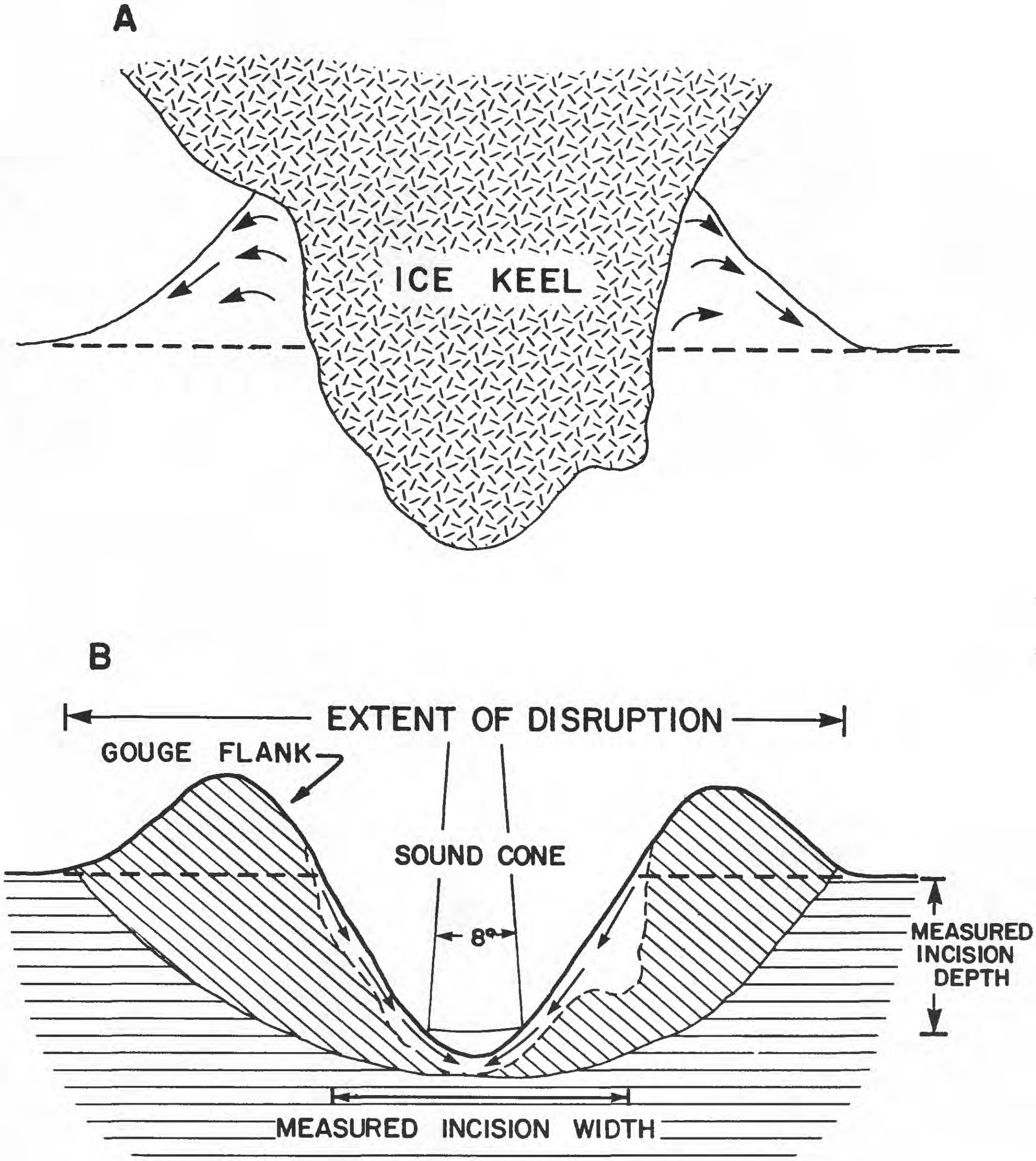


Figure 3. Drawing of an idealized ice gouge cross section. A) Gouge being plowed by an ice keel. B) The same gouge after the ice keel has passed and slumping of the flanks of the gouge has occurred (after Reimnitz, and others, 1977).

depth due to sound-cone geometry of the fathometer, b) the final gouge depression (even "fresh" gouges) may be shallower than the ice incision due to sedimentation and slumping, and c) the "extent of disruption" probably often extended laterally and vertically beyond the original incision.

RESULTS

Summary Gouge Character

All gouges, new and old were examined. The dominant gouge trend, density, maximum incision depth, and maximum disruption width were determined for 1/2 km segments of the test lines. We have tried to standardize as many of the admittedly subjective observatons (Hnatiuk and Brown, 1977) in an effort to make them comparable from one area to another and from year to year. As the reader proceeds through the various characteristics discussed below, it might be helpful to refer to the 500 m data segment depicted in Figure 4 along with a listing of the characteristics determined from this segment.

Gouge Trend

Most ice gouge features are linear. The gouge trend is the orientation of the major portion of the linear features within a given segment. As both the boat speed and paper speed are variable, the sonographs exhibit horizontal exaggeration. By removing the exaggeration and computing the true orientation relative to the ship's course, the gouge trends may be determined(Fig. 4). A dominant trend was computed each 1/2 km segment. Occasionally subordinant trends were evident, or the variability and non-linearity of orientation were so pronounced that it was not possible to plot a representative trend.

On test line 1 the dominant trend is nearly east-west, which is essentially parallel to the depth contours in this area (Figs. 1 and 5). Furthermore, the trend is uniform on both the inner and outer portions of the survey line and similar on both the 1975 and 1977 data sets. Intervals where no dominant trend was established occur at several locations along the test line but are concentrated on the inner half.

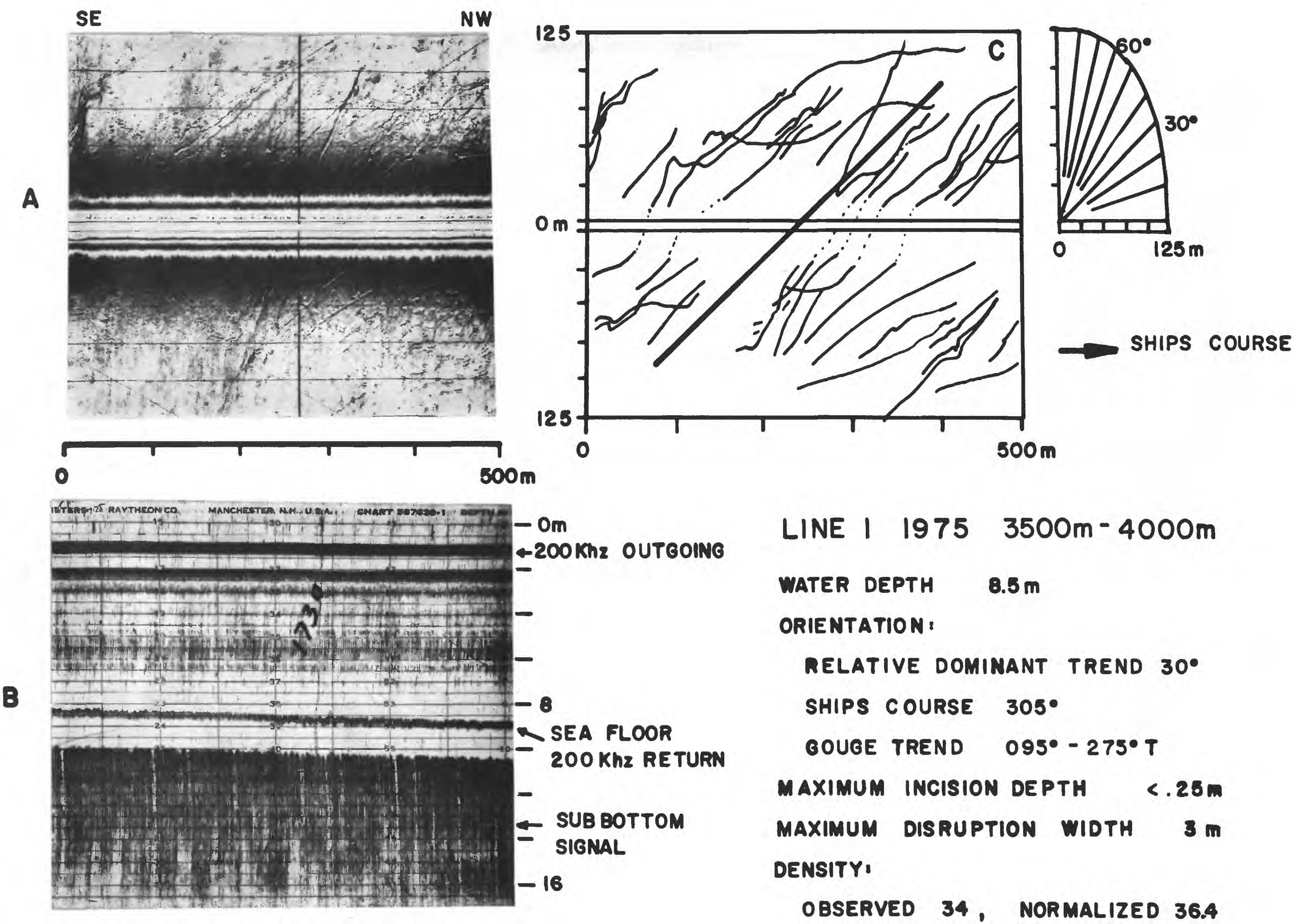


Figure 4. Representative 500 meter segment of seafloor on test line 1 illustrating how ice gouge characteristics were determined from sonograph and fathogram records; a) side scan record used to determine gouge trend, density, and maximum disruption width, b) fathogram used to determine water depth, gouge incision depth and incision width, and c) sonograph overlay shows gouge trend and relative dominant trend.

In contrast the dominant orientation of gouges on test line 2 (Fig. 6) swings clockwise from northeast-southwest on the inner 7 km of the line to northwest-southeast on the outer part of the line, beyond about 12 km. The submerged ridges and isobaths along this test line also demonstrate the shift in orientation noted in the ice gouges (Fig. 1). The ridge crests are characterized by numerous rather short gouges of various orientations so dominant trend can not be determined (Fig. 7).

Gouge Density

To determine the density of gouges, every linear feature resulting from ice contact with the bottom was counted, including each individual scratch produced by multi-keeled ridges, as we wished to assess the effects of ice on the bottom rather than ice events. Thus, when a multipronged ice ridge keel plows the bottom, many ice gouges may disrupt a section of the sea floor much wider than any individual gouge.

More gouges would be seen when the ship's track is perpendicular to the trend of gouges over a given distance than when the track is parallel to the features, (due to scan width of the sonar, e.g. Figure 8). To compensate for this record artifact, gouge counts were normalized to represent the number of gouges that could be seen if all gouges were at right angles to the ship's track using the following equation:

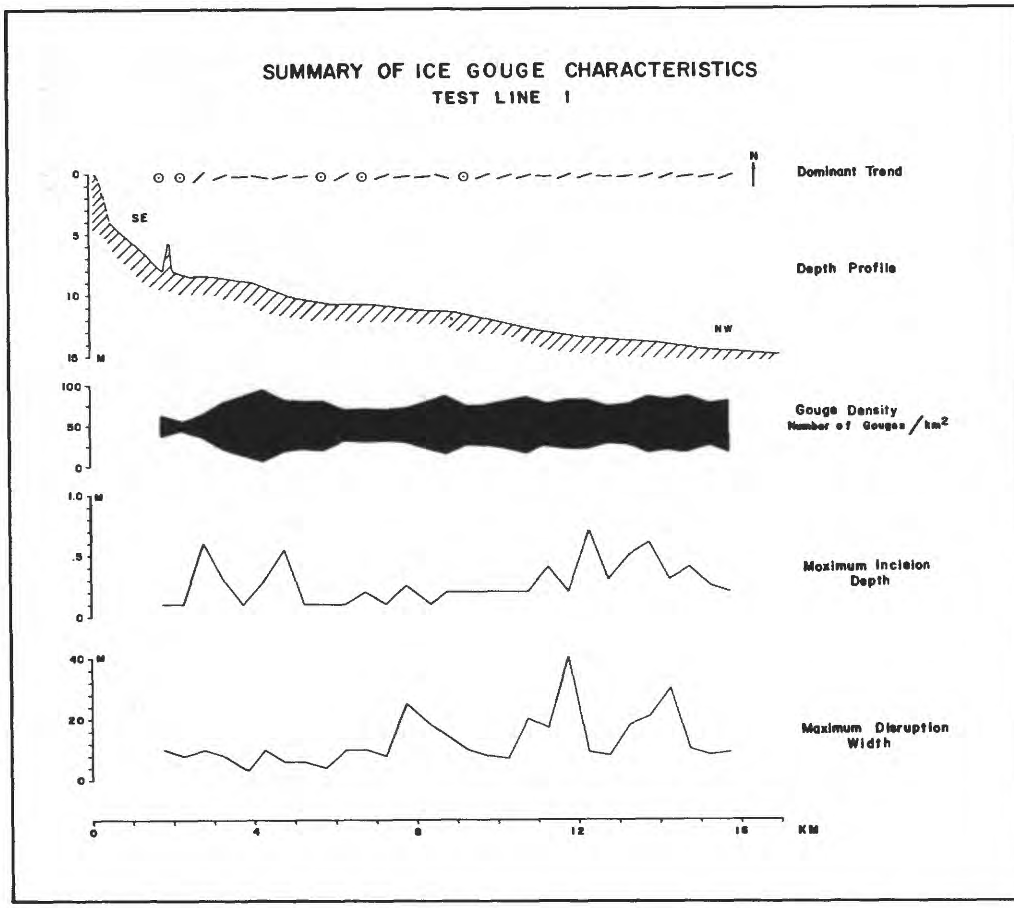
$$N = \frac{i}{i \text{ Sin } \emptyset + R \text{ Cos } \emptyset} (N_{obs})$$

where: N = corrected number of gouges in counting interval

N_{obs} = observed gouges in interval

R = recorded width of sonograph - meters

(both sides of record i.e. 125 m scale = 250 m record width)



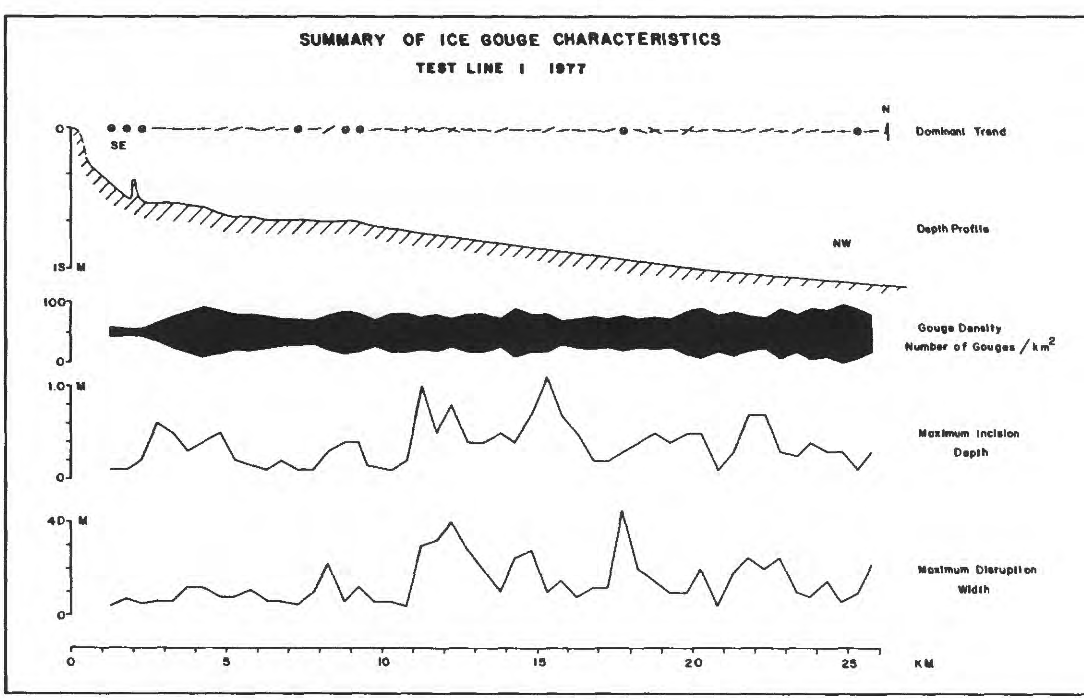
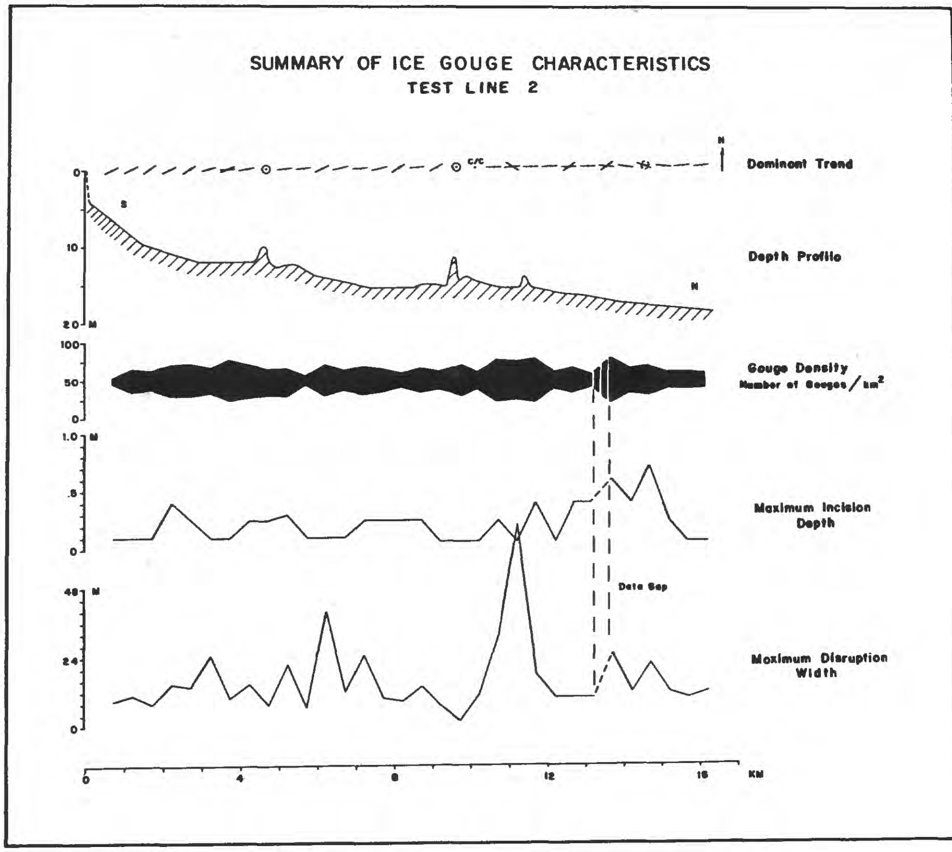


Figure 5. Summary of ice gouge characteristics on test line 1 determined from data taken in 1975 (A) and in 1977 (B). Values were determined from 500 m segments along the test line.



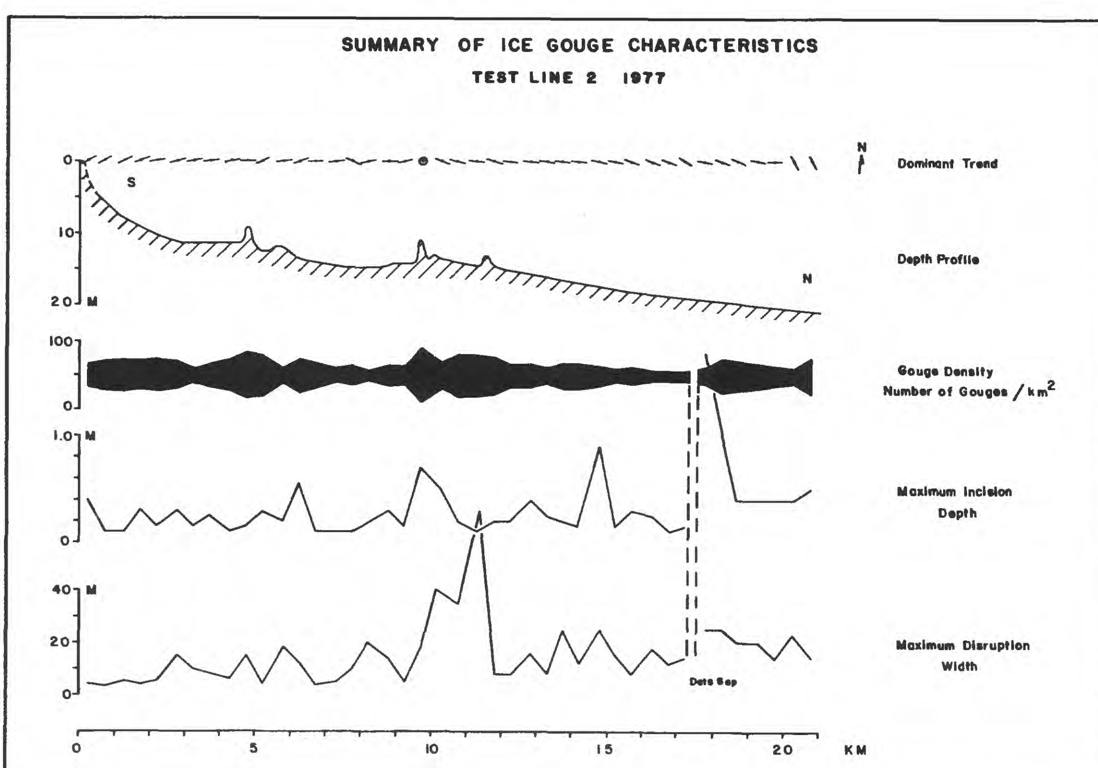


Figure 6. Summary of ice gouge characteristics on test line 2 determined from data taken in 1976 (A) and in 1977 (B).

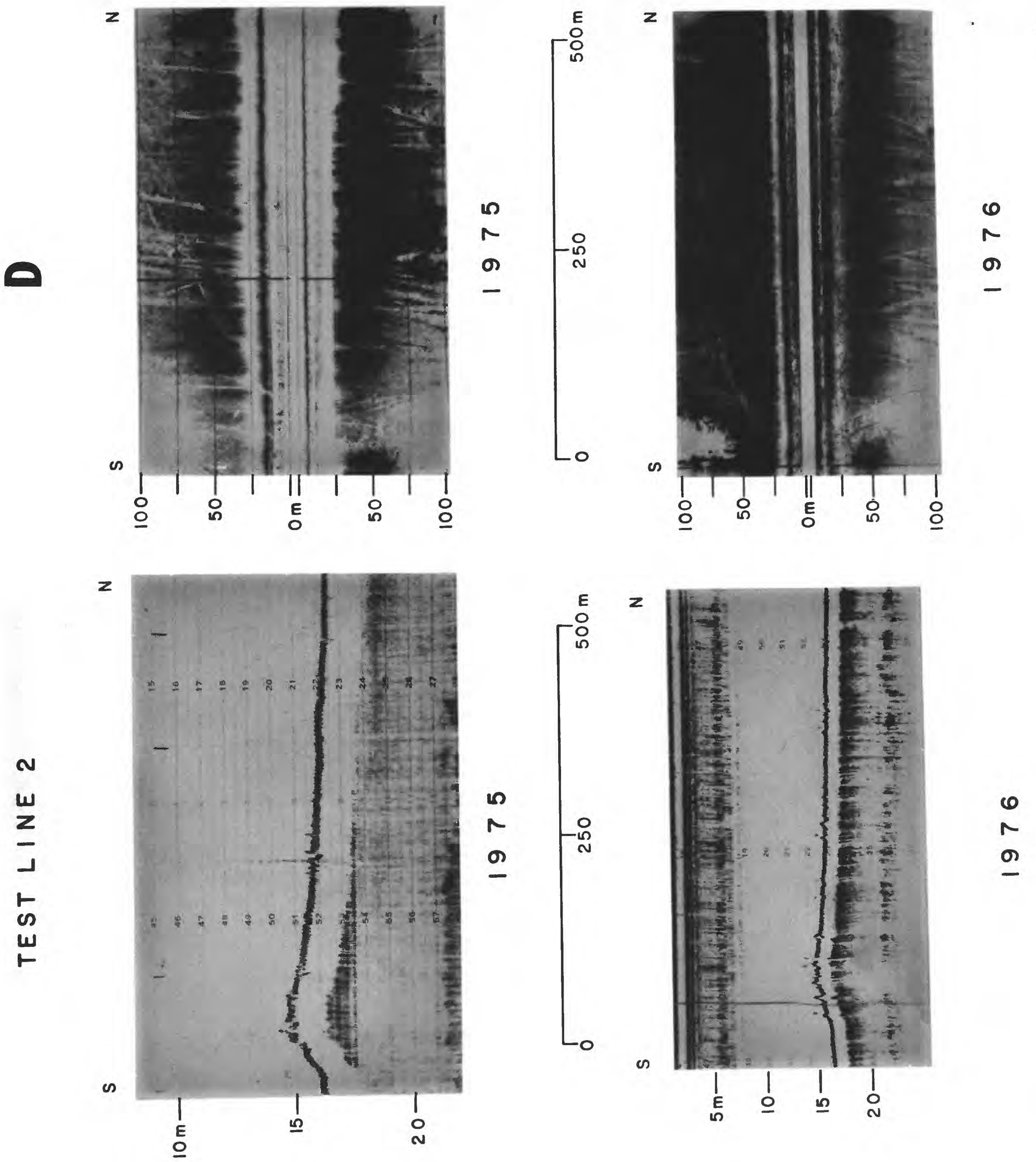


Figure 7. Comparison of 1975 and 1976 sonographs and fathograms at location D (Figure 1) illustrating the change in bottom morphology due to ice gouging. Note vertical scale difference between the 1975 and 1976 fathograms. Of significance is the high density of gouges on the ridge top and seaward flank, and the lack of a dominant trend of the gouging on the ridge crest.

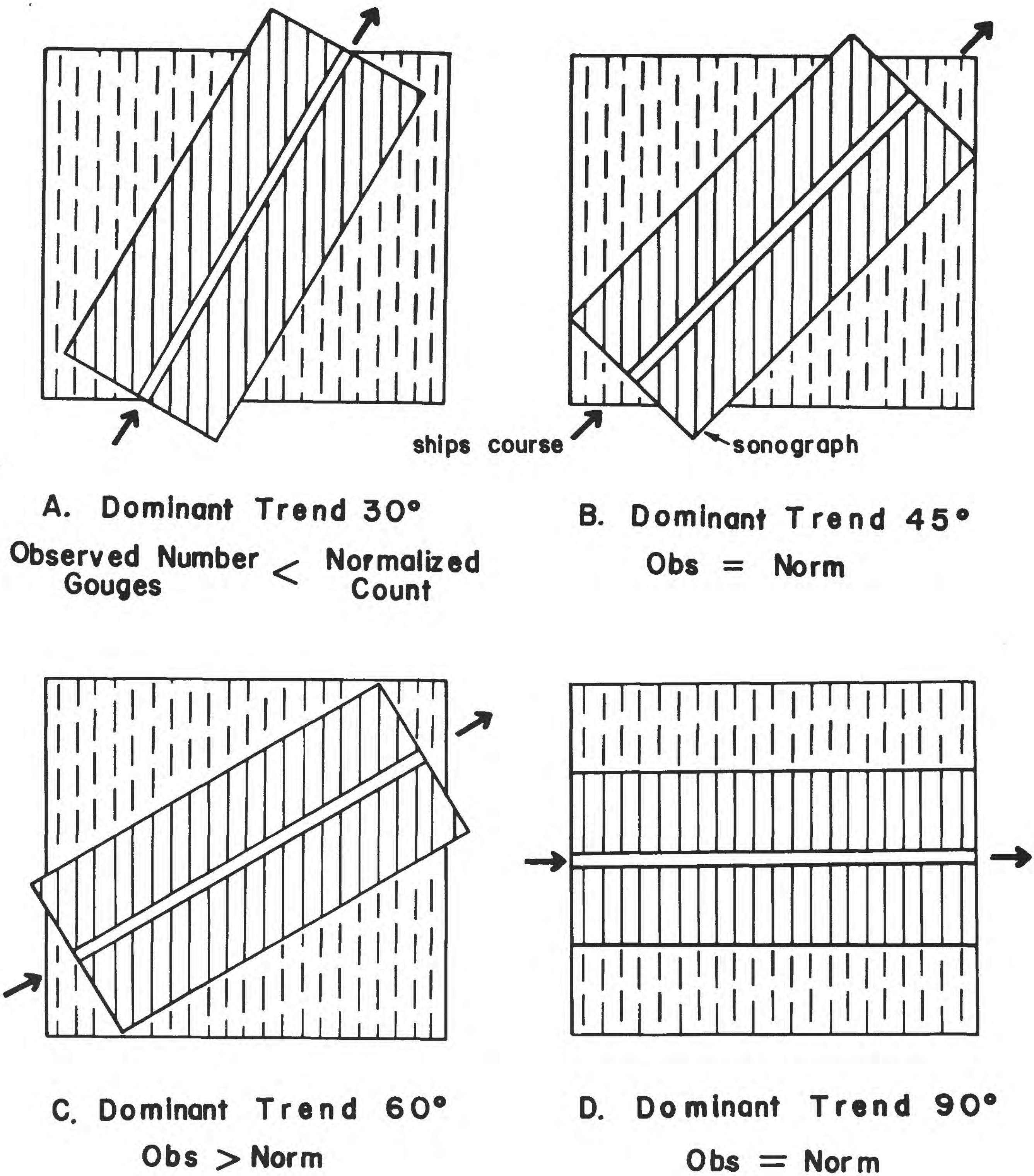


Figure 8. Normalized gouge density showing variance between observed number of gouges on sonograph and normalized density per unit area when the dominant gouge trend varies with ships course. See text for computations. The vertical solid and dashed lines represent dominant trend of ice gouges. If all of the ice gouges in a line segment are assumed to be aligned with the dominant trend and normalized, then gouge density may be extrapolated to areas beyond the sonograph, as in D.

i = length of counting interval in meters

$\emptyset$ = dominant trend angle of gouges relative to ship's track

(90° = perpendicular to track).

Utilizing the 1975 and 1977 records, with a sonograph record width of 250 m and a 500 m counting interval, this formula reduces to:

$$N = \frac{500}{500 \text{ Sin } \emptyset + 250 \text{ Cos } \emptyset} (N_{obs})$$

Thus, a count of 34 gouges in a 1/2 km segment of track, oriented with a dominant trend of 30° to the ship's track, calculates to 36.4 gouges per 1/2 km of track 1/4 km wide(Fig. 4).

Assuming that the distribution and orientation of gouges immediately adjacent to the zone scanned with the sonar is similar to that on the sonograph, the density of gouges per unit area may be calculated. This is only possible because the gouge count has been normalized at right angles to the ship's track and the assumption made that all gouges have the same trend and that they are linear. In this case, the number of gouges calculated for a kilometer segment of trackline should be the same as the number in a kilometer square bisected by that trackline segment (Fig. 8D). Thus, in the above example 36.4 gouges per 1/2 km of trackline, is equivalent to 72.8 (73) gouges per km^2 where gouges are at right angles to the track. These assumptions, of course, are not strictly correct, (Figs. 2 and 4), they simply allow a standardization of the data for comparison.

On both test lines 1 and 2, the gouge densities correlate with bottom slope; portions with steeper slopes have higher density values (Figs. 5 and 6). The highest densities on test line 1 ($88/km^2$) occur at the upper edge of a slope in the bottom profile (Fig. 5). The seaward facing slopes of the ridges on test line 2 also show a sharp rise in the density of gouge events (Fig. 6). The longer trackline segment run in 1977 shows that the gouge density tends to increase with increasing water depth although the trend is not clear cut (Fig. 5). The increase in gouge density is very apparent when examining sonographs and fathograms from the outermost portions of the test lines (Fig. 9). The lowest values of gouge densities are associated with areas of low slope, areas inshore of submerged ridges, and in shallow water (Figs. 5 and 6).

Incision Depth

Vertical distance to the gouge floor below the surrounding sea bed, exclusive of ridges, is measured as the incision depth rather than the overall vertical relief of the ridges and furrow (Fig. 3). This depth, depending on the gouge history since inception, where slumping, erosion, and/or sediment deposition may have taken place, may or may not be the depth to which ice penetrated below the sea floor. The incision depth is a minimum measure of the depth of sediment reworking. For each 500 m segment the prevailing sea-floor elevation was determined, then the maximum depth of incision below this elevation was scaled from the fathograms.

The maximum incision depths shown in Figures 4 and 5 do not correlate with the other summary characteristics. Deep incisions are spread out along the line showing no clear relation to water depth. The deepest gouge (180 cm) was observed at the outer end of line 1, although respectable gouges (50-70 cm) occur on the inner 5 km of both test lines (Fig. 5A and 6A). A greater number of ice gouge events is expected in shallow water due to the greater abundance of shallow ice keels thereby increasing the probability of a deep gouge. However, the possiblity of having a deep gouge in shallow water areas is offset by the fact that deep incision depths are unlikely inshore due to the limited size and mass of the cutting tools.

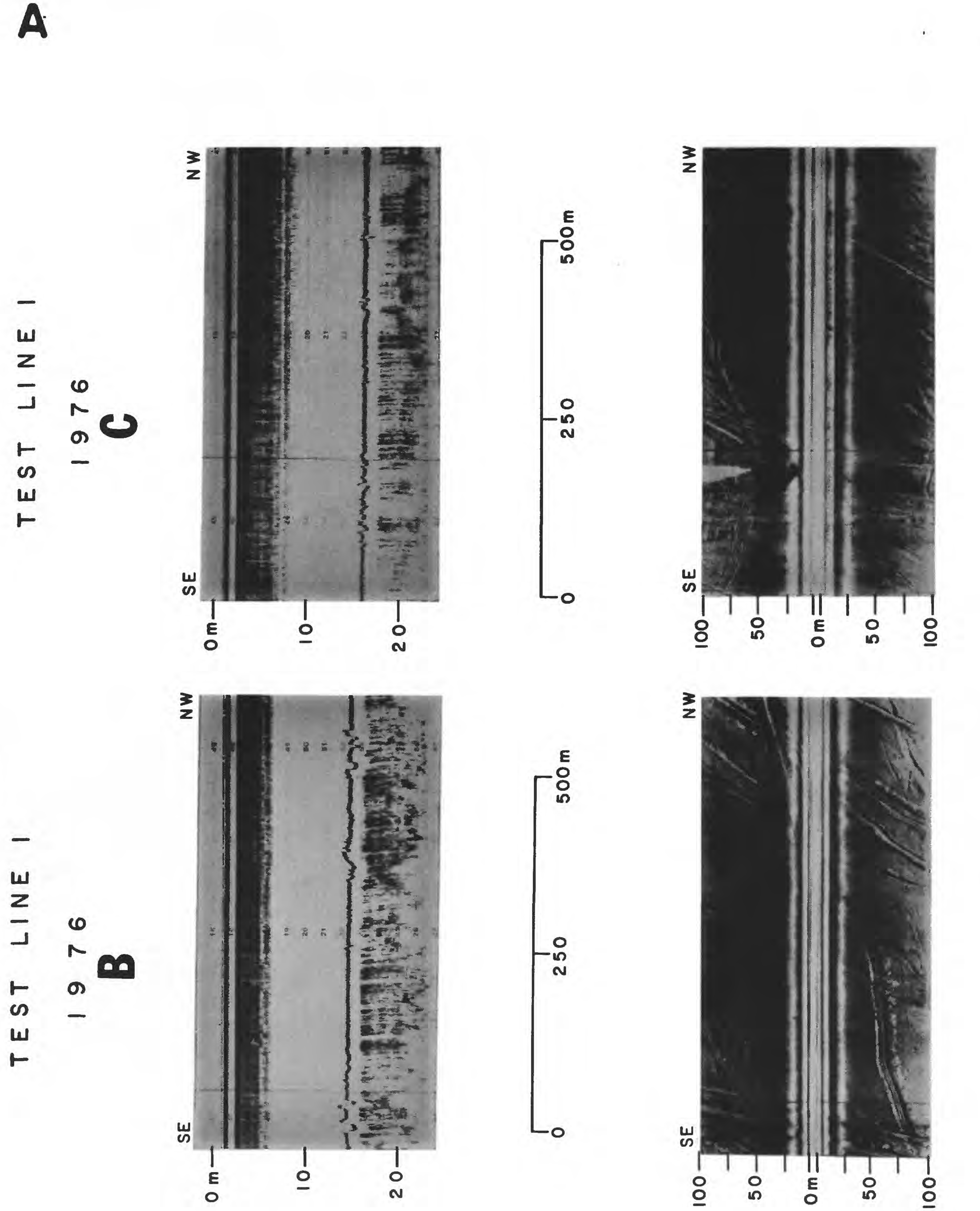


Figure 9. Fathogram and sonographs of 1976 records demonstrating the increase in density of gouging on the outer portions of test line 1 (A) and test line 2 (B). Location of trackline segments shown in figure 1.

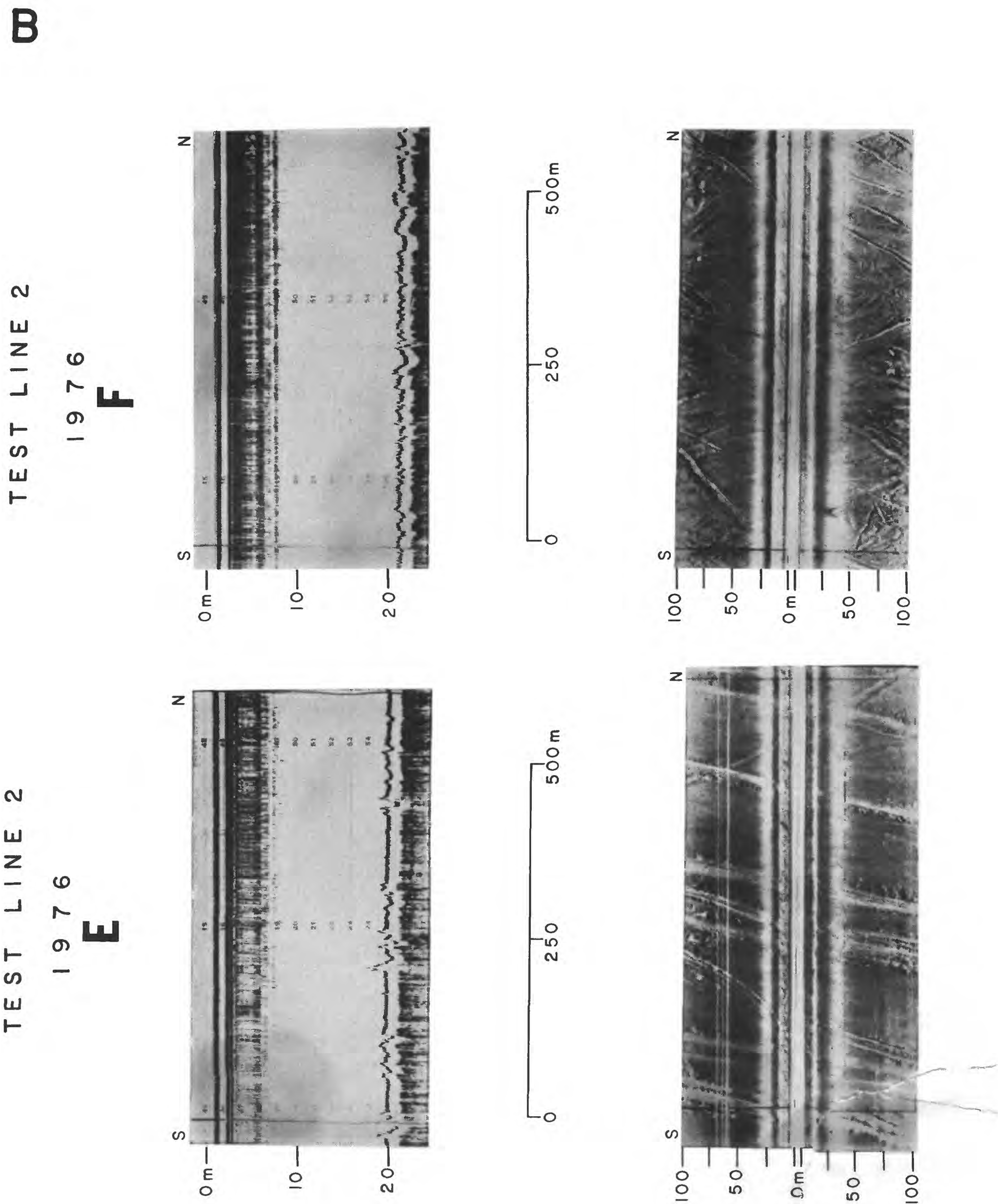

B
TEST LINE 2
1976
F
TEST LINE 2
1976
E
S
N
0m
10
20
0
250
500m
100
50
0m
50
100

Figure 9 B.

Disruption Width

Within each 500 m trackline segment the widest transverse section of the bottom disrupted by a single ice event was measured on the sonographs. This "disruption width" (Fig. 3B) does not necessarily correlate with the deepest keel incision depth. In fact, the reverse may be true. Deep gouges commonly are narrow. The sonographs were used to make width measurement as in some cases the widest feature was not crossed by the trackline and thus not recorded on the fathograms. Furthermore it was easier to identify a single event on the sonographs. The widths measured were graphically corrected for the horizontal exaggeration.

In all cases maximum disruption widths tended to increase in an offshore direction(Figs. 5 and 6). Perhaps more significantly, the inner 8-10 km of the test lines show gouge events generally less than 15 m wide. The maximum observed width on test line 1 was 45 m and on test line 2 it was 70 m. Ice gouges more than 15 m wide are almost always the result of the action of multi-pronged ice keels (Reimnitz and others, 1973).

New Gouges, 1976, 1977

By comparing the 1975, 1976, and 1977 sonographs for the same morphologic traits such as intersections of lineations, characteristic angles, and notable debris piles (Reimnitz and others, 1977), sea floor areas from each year could be compared from year to year (Fig. 2). Analysis of the 1976 and 1977 sonographs in the matched areas revealed new ice gouge features (Figs. 2 and 7).

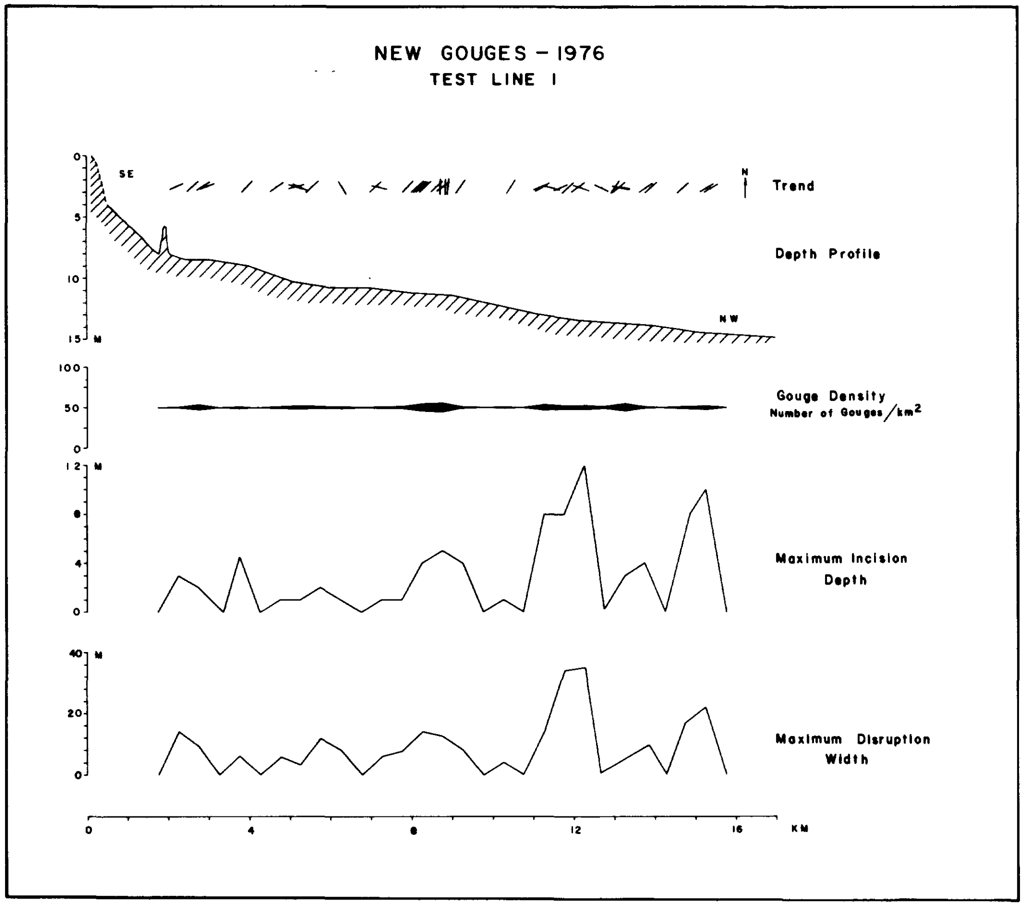
The 1975 survey was run on 16 September, shortly before freeze-up, whereas in 1976 the reoccupation of the test line took place on 10 August, shortly after sea ice break-up in late July. Thus most of the new gouges seen in the 1976 records probably occurred during the arctic winter when a full ice cover was present. In 1977 two surveys were run. The first was run a year after the 1976 study on 1 August. Test line 1 was repeated a month later on 3 September, 1977 in an attempt to learn what changes might have occurred during the open water season.

Using the same techniques and terminology discussed above, the trend, incision depth, incision width and disruption width were determined for each of the new gouges identified in the 1976 and 1977 records. Notes were also made regarding the morphologic character and symmetry of the gouge flank ridges and gouge floor. Gouge densities, maximum incision depths and maximum disruption widths were then determined for the same 500 m intervals used for the summary characterization.

New Gouge Trends

The trend of each new gouge on both test lines was plotted (Fig. 10 & 11) for comparison with the dominant trends noted in figures 5 and 6. On test line 1 the trend of new gouges in 1976 (Fig. 10A) is more onshore than the isobath parallel trend of 1975 (Fig. 5A). Furthermore, most of the 1976 gouges are sub-parallel and very straight, (Fig. 2) suggesting that they may have formed as one event when the ice acted as a single unit. This is in contrast to the trend of new gouges in 1977 (Fig. 10B) which show a more random orientation when compared to both the 1975 and 1977 gouge summary data (Fig. 5). This might suggest that the ice conditions and ice movement patterns responsible for the 1976 and 1977 new gouge data sets differed significantly.

On test line 2, the trend of new gouges in 1976 (Fig. 11A) shows essentially the same orientation as the summary characterization (Fig. 6). Although the 1977 new gouge data (Fig. 11B), shows a dominance of east-west gouges. There are more gouges with orientations differing from the summary than in the 1976 data set (Fig. 11A).



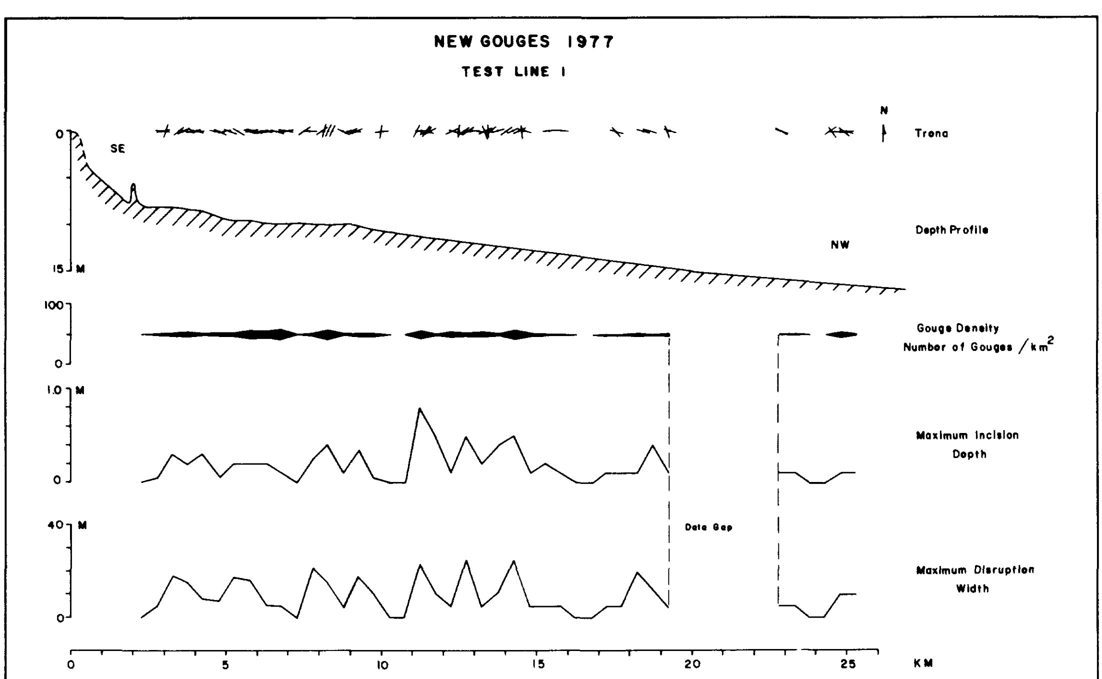
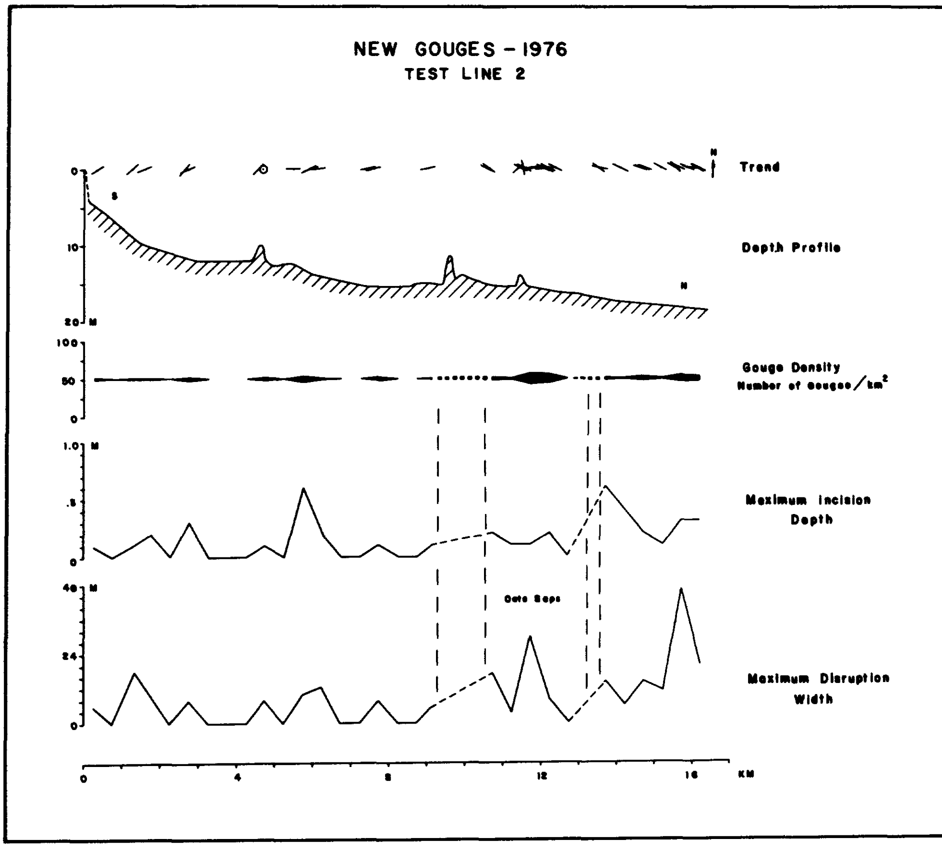


Figure 10. New gouge characteristics on test line 1 determined from data taken in 1976 (A) and in 1977 (B). Trend data is shown for each new gouge feature, while density, depth, and width data were determined for 500 m segments of trackline. Data gaps resulted when overlaping records were not obtained due to trackline detours around ice or equipment malfunctions.



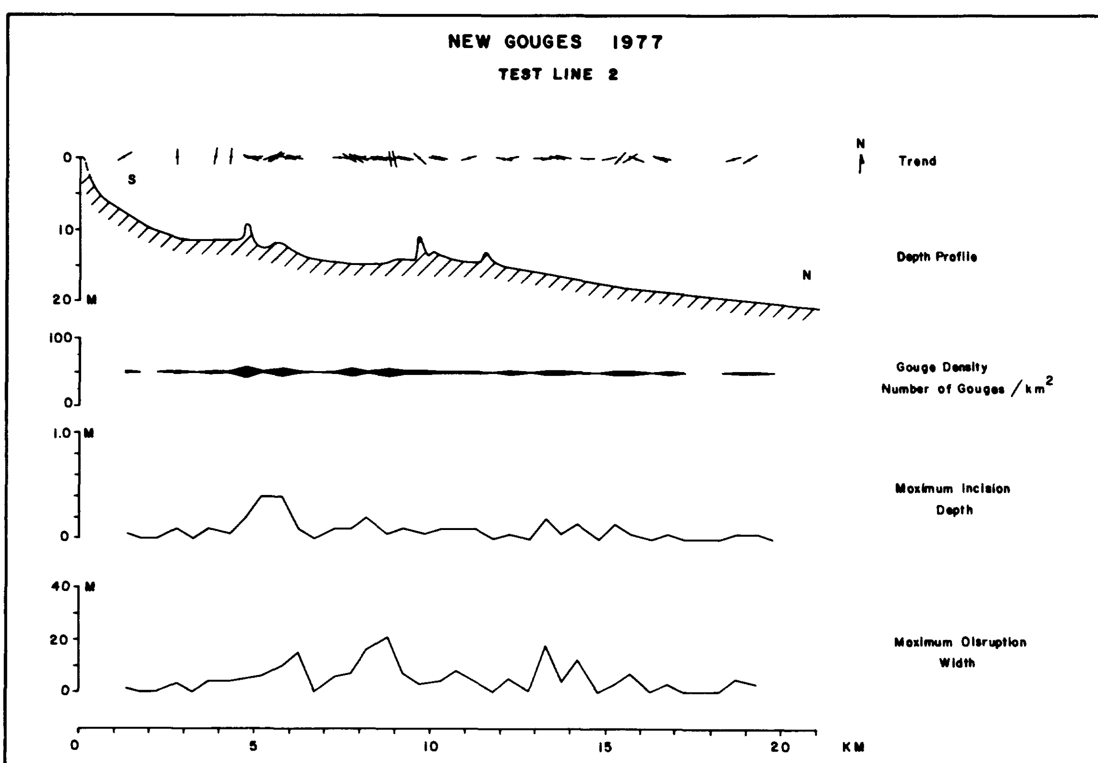


Figure 11. New gouge characteristics on test line 2 determined from data taken in 1976 (A) and in 1977 (B).

When comparing trends of new gouges as yearly data sets, the events which formed the 1976 set were found to be apparently more "normal", i.e., more similar to the summary characteristics, than were those gouges that occurred during formation of the 1977 data set.

New Gouge Densities

The densities of new gouges are remarkably evenly distributed over the length of test line 1 in both years of the study (Fig. 10,). On test line 2 the density appears to be greatest on the line segment seaward of the ridges in 1976 (Fig. 11A), but concentrated landward of the ridges in 1977 (Fig. 11B). The densities do not reflect the character of increased gouge densities offshore as suggested in Fig. 9.

New Gouge Depths

As with density distribution, the maximum incision depths of new ice gouges on both test lines are rather evenly distributed. Depths tend to increase seaward only in the 1976 data for test line 1. It should be remembered that the maximum incision depth is measured only where the ship crosses the gouge and it would be logical to assume that there is variance in incision depth along the length of a gouge. Thus the maximum values might have been different if the test lines had been run several meters to one side or the other. A scatter plot of incision depths versus water depth for ice gouges (Fig. 12) suggest that there is a concentration of deeper gouges in water depths between 11 and 15 m, although the population between 15 and 20 m may be under-represented because fewer data points were obtained in these water depths (Figs. 10 and 11). The maximum new incision depth on test line 1 was 120 cm in 1976 and only 60 cm in 1977. Similarly, on test line 2 the 1976 maximum value (80 cm) was greater than that observed in 1977 (40 cm).

Further problems exist in distinguishing the quantity and incision depth of small gouges which cannot be detected on the side-scan sonar and the

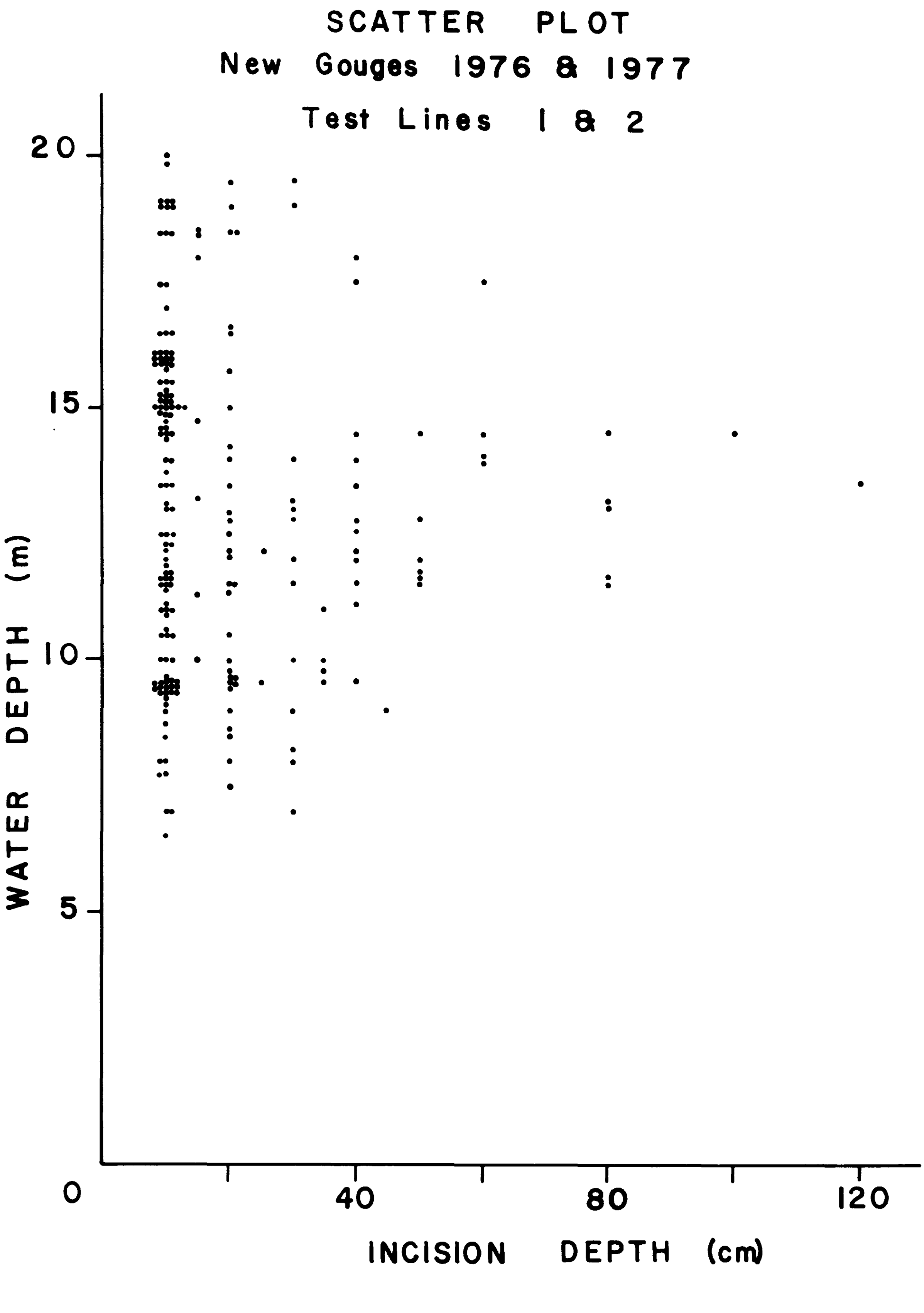


Figure 12. Scatter plot of new gouge incision depths versus water depth. The absence of deep incisions in water depths greater than 16 meters may relate to the fact that this depth interval is under-represented (see figures 10 and 11).

fathometer due to the system's resolving power. We assumed a depth of 5 cm for those gouges where the gouge did not cross the sonograph centerline and was therefore not recorded on the fathograms, and a depth of 10 cm when the gouge was crossed but indistinguishable on the fathogram. Furrows formed when ice only impacts on the projecting flanking ridges of ice gouges will probably not be recorded although they are a part of the gouge population (Fig. 3). As Lewis (1977) pointed out, the smaller gouges are underestimated. Thus, the frequency curve of new gouges (Fig. 13) does not truly represent the distribution of small gouges. Conversely, it is highly unlikely that gouges with incision depths greater than 10 cm will be missed.

The average depth of new gouge incisions over the entire length of the test lines shows a consistent pattern. On test line 1 incision depths decrease from 37 cm in 1975 (Reimnitz and others, 1977) to 19 cm in 1977 (Table I). On test line 2 the gouges also repeat the decrease from the 1976 to the 1977 data (Table II) and are lower than values for test line 1. This comparison is significant and suggests that the energy expended by the ice on the bottom was less intense during formation of the 1977 data set than it was during formation of the 1976 data set. Furthermore, the energy spent on line 2 was less than that expended on line 1.

New Gouge Widths

Two width parameters were measured for the new gouge data. The incision width (Fig. 3), as measured on fathograms, was used in calculating the rates of sediment reworking. The disruption width (Fig. 3), measured on sonographs, was used to compare new gouges with the summary gouge characteristics (Figs. 5 and 6). As most gouges were not crossed at right angles, width measurements had to be corrected for gouge trend on both the sonograph and fathogram data.

The maximum disruption width from new gouges on test line 1 in 1976

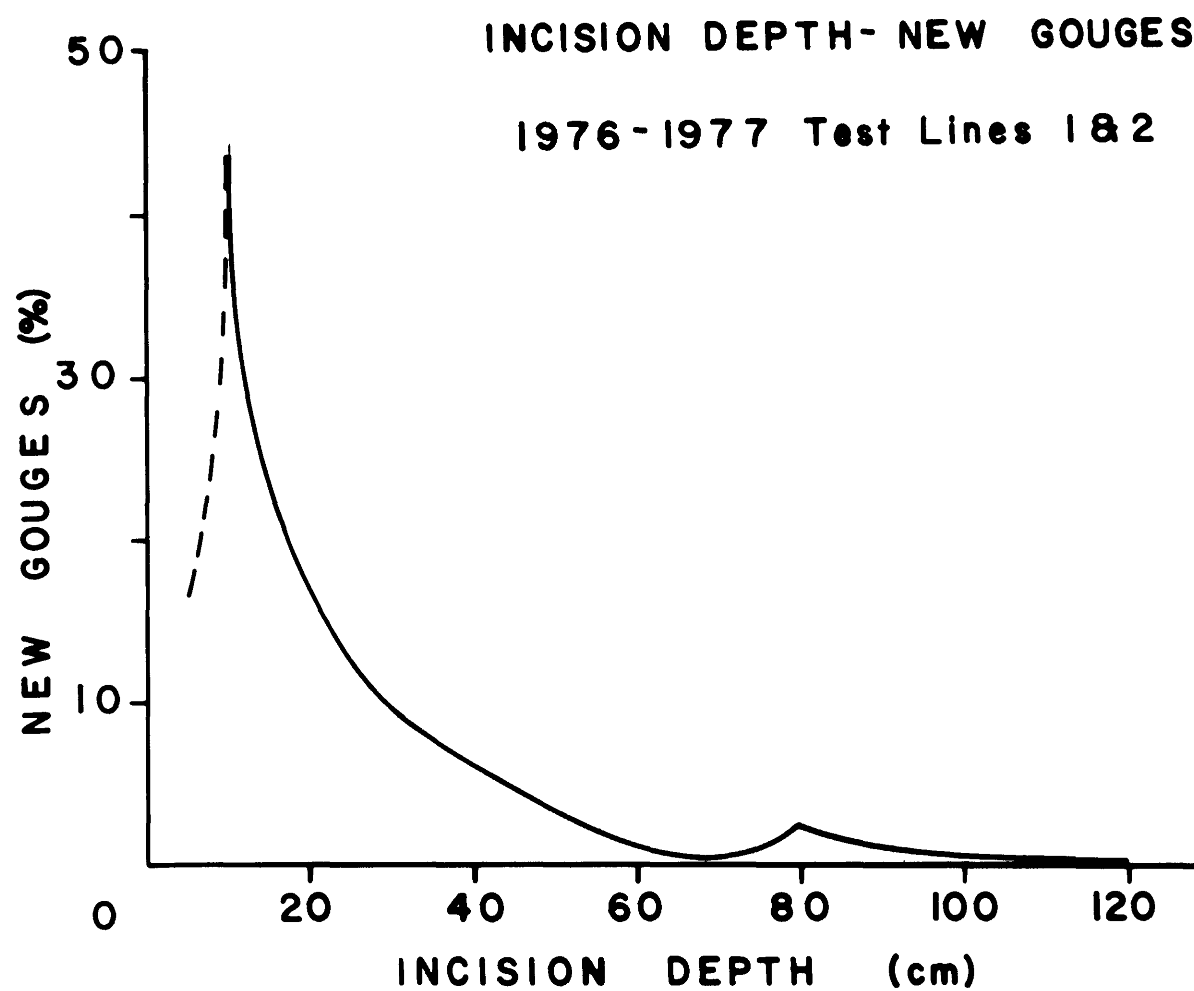


Figure 13. Frequency distribution of new gouge incision depths. Gouges less than 10 cm deep (dashed line) are underestimated due to the resolution limitations of the sonograph and fathogram records.

Table I - ICE GOUGE DATA - New Gouges

Interval on Test Line 1 (km)

	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	Total Average	16-18	18-20	20-26
Water Depth (Meters)	Too shallow no data	7.6	9.7	10.5	11.3	12.6	13.1	13.7	---	14.0	14.5	16.0
Number of new gouges												
1973-1975		2	4.5	0	1	0.5	1	1.5	10.5			
1975-1976		5	5	3	10	6	8	3	39			
1976-1977		7	9	13	10	5	12	7	63	1	4	6
Incision Width (m)												
1973-1975		17	79	0	7	45	105	12	263			
1975-1976		13	10	9	40	43	25	24	161			
1976-1977		36	34	32	54	34	46	35	271	1.4	21.3	16
Average Incision Depth (cm)												
1973-1975		40	37	0	45	30	45	27	37			
1975-1976		35	12	10	31	40	31	80	31			
1976-1977		14	14	12	21	50	18	22	19	10	29	10
Amount of Trackline Gouged (m/km/yr)												
1973-1975		8	40	0	4	22	53	6	19			
1975-1976		6	5	4	26	21	12	12	12			
1976-1977		18	17	16	27	17	23	17.5	19			
Fraction of Bottom Impacted Each Year ((k) x 10^{-3}												
1973-1975		8.5	40	0	4	22	53	6	19			
1975-1976		6.5	5	4	26	21	12	12	12			
1976-1977		18	17	16	27	17	23	17.5	19			
Total Number of Gouges (Old and New, Figure 5)												
1975		83	134	77	111	119	110	118	752			
1977		81	139	99	114	124	112	119	788			

Table II - IGE GOUGE DATA - New Gouges

Interval on Test Line 2 (km)

	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	Total Average	16-18
Water Depth (Meters)	7	11.5	12	14	15	15	16.5	18		18
					(Data gap 9.0-10.5 km)					
Number of new gouges										
1975-1976	3	2	5	3	1	10	8	9	41	
1976-1977	1	2	10	7	8	13	6	5	42	2
Incision Width (m)										
1925-1976	30	11	21	13	2	7.1	36	81	268	
1976-1977	3	6	40	27	43	10	23	17	169	6
Average Incision Depth (cm)										
1975-1976	3	15	32	17	15	15	24	21.	21	
1976-1977	10	10	21	10	9	10	8	12	12	5
Amount of Trackline Gouged (m/km/yr)										
1975-1976	15	7	11	7	2	49	21	41	19	
1976-1977	1.5	3	20	13.5	21.5	5	11.5	8.5	10.5	
Fraction of Bottom Impacted Each Year (k) x 10^{-3}										
1975-1976	15	7	11	7	2	49	21	41	19	
1976-1977	1.5	3	20	13.5	21.5	5	11.5	8.5	10.5	
Total Number of Gouges (Old and New, Figure 6)										
1975	47	84	71	65	60	94	72	56	549	
1977	86	75	100	68	75	107	67	48	626	

shows a positive correlation with segments where maximum incision widths were observed (Fig. 10A). The new gouges observed in 1977 on test line 1 and in both years on test line 2 do not repreat this correlation. Wider gouges correlated with deeper water depths in 1976 (Figs. 10A and 11A) but not in 1977 data (Figs. 10B and 11B).

DISCUSSION

The above characterizaton of new gouges from the two test line environments suggests that the gouging process varies from area to area and also from year to year. In an attempt to evaluate the randomness of the processes, the data on new gouges was summarized for 2 km segments of each test line (Tables I and II) including data from our earlier study (Reimnitz and others, 1977a). Although the range of values for the numbers of gouges, incision widths, average incision depths are roughly of the same order of magnitude for both the 1976 and 1977 data, significant differences between test lines 1 and 2 and between the 1975 and 1977 data were found to exist. The most relavent are: 1) The increase in the number of new gouge events observed on line 1 (from 10.5 gouges/yr in 1975 to 63 gouges/yr. in 1977); 2) The sum of the incision widths on line 1 has decreased from 1975 to 1976, then increased in 1977, while on test line 2 the opposite occurred between 1976 and 1977; 3) The average depths of incision on test line 1 are greater by about 10 cm than those computed for test line 2, although both test lines show a decrease in average depth from 1975 to 1977; and 4) Gouging was concentrated on the inner and outer sections of both test lines in 1976 but was more intense on the central section in 1977.

The above discussion suggests that the ice events leading to the gouges recorded by each yearly data set differed from one another. A few wide and deep gouges are recorded in the 1975 data set (Table I) from ice events in the winters from 1973 to 1975. New gouge data from 1976 regarding the ice event in the winter of 1975-1976 suggest that one or two major ice movements took place in a southwesterly direction which produced straight, deep gouges where keels contacted the sea floor (Figs. 2, 10 and 11). This gouging tend to follow bathymetric contours. Where shoals were present, as in the vicinity of test line 2, (Fig. 1) their elongate axis determined direction of movement of the ice keels. In the winter of 1976-1977 ice movements were more random (frequent?) and were less intense, producing shallow gouges with less well-defined orientaions (Figs. 10 and 11). We do not have detailed data available on sea ice climate in the arctic to test this hypothesis, except to note that ice conditions in 1975 were notably extreme (Barnett, 1976) and ice ridging in the Prudhoe Bay area was less intense in 1977 than in 1976 (Kovacs pers. commun.). In any event, the widely differing character of gouging during the three periods suggests that gouging is a sporadic process dependent on storm and ice conditions of the preceding fall and winter. It is interesting to note that an estimation of the gouge "intensity" could result from a knowledge of previous ice events.

The abundance of grounded ice in summer has led us to suspect that some gouging must occur during this season particulary when there is considerable open water as in 1977; allowing waves and currents to develop and fostering ice movement. Data from test line 1, taken one month apart in the summer of 1977, revealed that a single gouge event occurred during the month of August (Fig. 14). The gouge (in 12 m water depth) was a linear feature, more than 400 m long, oriented east-west and composed of three furrows on the eastern portion of the sonograph and a single furrow on the west. The incision was 10 cm deep on the fathogram. The direction of ice motion is not apparent. This summer gouge does not differ significantly in orientation, incision

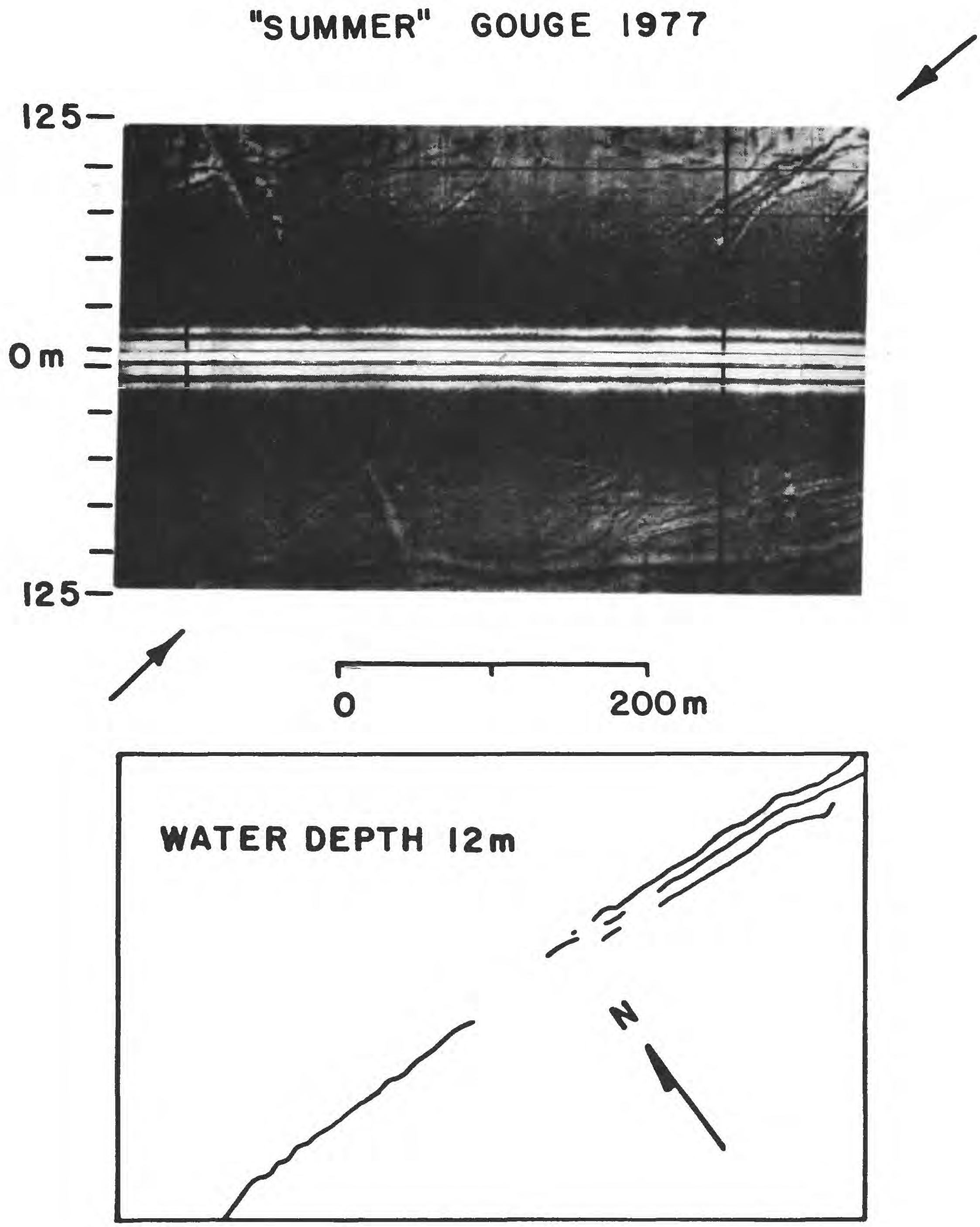


Figure 14. Sonograph and line drawing of a summer gouge event that occured between 1 August and 3 September, 1977. Compare this gouge with the new gouges in Figure 2.

depth, length or width from most gouges seen (Figs. 2, 7, and 9, Table I and II). The only unique feature is the wavy character of the gouge and the change from multiple furrows to a single furrow. Most of the ice motion in winter must be rather uniform in direction as ice blocks and ice keels will be "locked" into a larger ice sheet, whereas in summer ice blocks are free to rotate in the currents. Thus, the character of the summer gouge described above might be typical of gouges occurring from grounded ice keels in open water and the varied form resulting from different faces of the ice keel impacting the bottom as the ice block swings or rotates in the current field (Reimnitz and others, 1973).

The numbers of gouges counted in 2 km intervals was compared for the summary data of both 1975 and 1976 (Tables I and II) for increase or decrease in trends in gouge densities. Assuming a steady state, gouge numbers should remain constant with time; new gouges replacing old gouges by infilling with sediment or replowed. Although the counts show a slight increase in the total number of gouges over the two year interval particularly in the 10-12 m water depth; the variability in gouge density numbers due to the subjectivity of counting and the variability in record quality may be responsible for part or all of the observed differences. The increase of 36 gouges (752 to 788) on test line 1 does not correspond with the 102 new gouges that were counted. On line 2 the increase of 77 gouges (549 to 626) is also less than the sum of the 1976 and 1977 new gouges (84). A longer time interval is needed before the ambiguities of these observations can be assessed.

Ice Gouge Recurrence

The data described above demonstrates that ice gouging is a modern process on the inner shelf. Questions now arise as to how often gouging occurs and how extensively does gouging rework the bottom sediments. Using data on the incision widths of new gouges, length of test lines, time interval between surveys, the fraction of the bottom impacted within that interval may be calculated. As:

$$k = \frac{\Sigma W_i}{L(t)}$$

where: k = fraction of the bottom impacted each year.

W_i = incision widths of new gouges (in meters)

L = total length of test line segments compared for new gouges - less data gaps (in meters)

t = time interval between compared surveys (in years)

Comparison of the data for test lines 1 and 2 (Tables I and II), indicates that the average k value varies between .0105 and .019. In other words, on the average, less than two percent of the test line was impacted with new gouges each year. Earlier we assumed that gouging would proceed in a systematic manner and would not replow* any point on the sea floor until the entire sea floor is impacted with new gouges (Reimnitz and others, 1977a). The fraction of the bottom impacted after T years would be (Fig. 15):

$$G_T = k_{(T)}$$

where: G_T = fraction of the bottom gouged

T = time in years from some arbitrary T_o.

A gouge recurrence interval was also calculated for points on the sea floor which would be the time required to completely gouge the segments. We called this the no-replow recurrence interval, where 100% (G_T=1) of the sea floor has been impacted with new gouges since T_o.

*Replow - Replow occurs when new gouges become superimposed on on older gouges. As used here we are referring to those new gouges superimposed on other 'new' gouges that have occurred since some arbitraty time T_o.

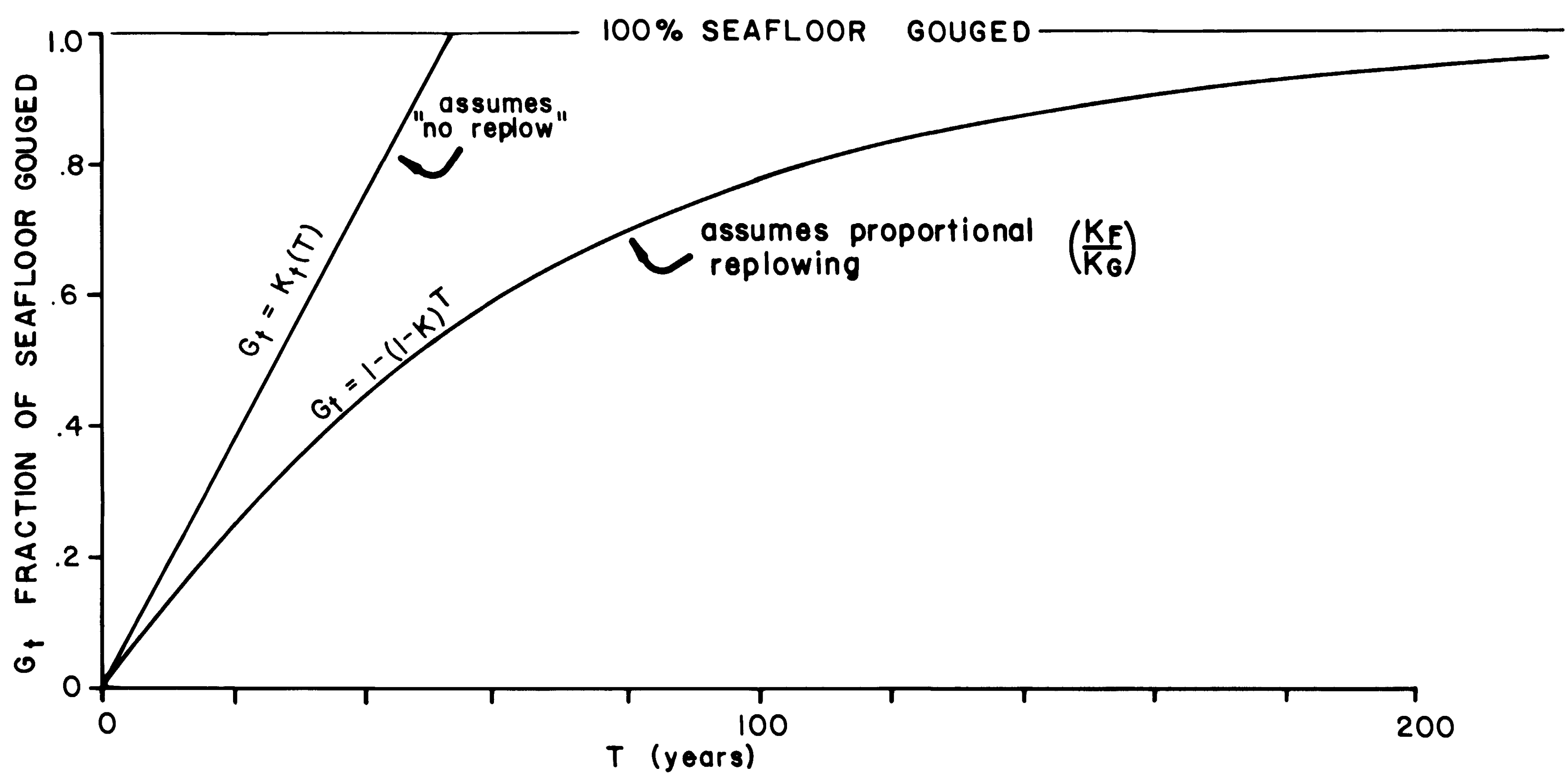


Figure 15. Fraction of the seafloor gouged after T years, assuming a) no-replow of bottom and b) proportional distribution of new gouges in year T (see text). K equal to 0.019 from test line 1 and 2.

$$\text{No-replow recurrence interval (in years)} = \frac{1}{k} \quad (1)$$

As ice interaction with the bottom does not occur in a systematic manner in our area of study, (and probably elsewhere), this approach is not a very good approximation of frequency of new gouges. A better approach, which does not involve rigorous statistics, would be to assume that each year some new gouges will replow portions of gouges extant since the start of the counting interval (T_o). For this projection we will assume that the fraction of the bottom replowed by new gouges is dependent on the area of the bottom that has been impacted by new gouges since T_o. This can be written:

$$\frac{k_f}{k_g} \quad \frac{F_T}{G_T}$$

and $k_f + k_g = K$ and $F_T + G_T = 1$

where: k_f = fraction of new gouges occuring with no replow

k_g = fraction of new gouges replowing

F_T = fraction of bottom not impacted since T_o at time T

G_T = fraction of bottom gouged since T_o at time T

For example: if 10% of the bottom is impacted each year (k =.1), then in the first year 10% (G_T) of the bottom is gouged and 90% (F_T) has not been impacted. In the second year, assuming another 10%, of the bottom is impacted, 1%, (k_g), of these new gouges will occur on the 10% of the bottom impacted the previous year and 9% (k_f) will occur in new areas. Now 19% (G_T) of the bottom is gouged since the first year. In the third year a larger fraction, (1.9%), of new impacts occurs in areas gouged in the first two years. Thus each successive year more and more replow takes place. This relationship can be expressed using the binomial theorem as follows:

$$G_T = 1 - (1-k)^T \quad (2)$$

where: G_T = fraction of the sea floor impacted after T years

T = time in years from some arbitrary T_o initiation of new gouging.

k = fraction of the bottom impacted in 1 year.

Using an average k computed from 3 years of data on test lines 1 and 2 (Tables I and II) we can determine, based on the above assmuptions, the rate at which the bottom will be impacted with new gouges (Fig. 15). This computation suggests that 50% of the bottom will be impacted in less than 40 years and 90% of the bottom will be impacted in about 150 years.

The incorporation of average depth of incision data (Tables I and II), along with the gouge recurrence, makes it possible to estimate the rate of sediment reworking of the sea floor by ice. The average gouge depth of the almost 200 new gouges observed was 21 cm. Assuming a 'no-replow' reccurrence interval (Eq. 1), the sea floor was reworked to an average depth of 21 cm in about 50 years. Assuming a proportional replow (Eq. 2), in 50 years only a little over 50% of the bottom would be reworked.

Repetitive sonograph studies in two 14 km^2 areas of the Canadian Beaufort Sea have been conducted in 15-20 m water depths, slightly greater than our own studies (Lewis and others, 1976). Their data indicates that the fraction of the bottom impacted each year (k) was 0.17% in one case and 2.0% in the other, an order of magnitude difference. The higher value is very similar to the impact rate that we determined for the Alaskan Beaufort Sea in shallower water. No data is given on the incision depths of new gouges. The Canadian workers noted, as we have, that there can be considerable variability between subsequent data sets and record interpretation is often highly subjective. Thus, a rigorous comparison betwee the Canadian and Alaskan data seems inappropriate at this time.

In considering the rates of sediment reworking, incision depths and the amount of bottom disturbed by gouging, our estimates are very conservative. Gouge incision depths do not include the height of the flanking debris ridges, nor do they include a correcion for the cone angle of the fathometer which will give conservative depth values for narrow deep gouges (Fig. 3). The "extent of disruption" by ice keels often includes a considerable area on one or both sides of the incision(Fig. 3). Measurement of the 1976 gouges on test lines 1 and 2 indicates that disruption widths were 1 1/2 to 3 times wider than the incision widths. If these widths are used to determine rates of reworking, the values we report above would have to be increased by 30 to 60%.

The rates of sedimentation on the inner shelf in the study area have been estimated at about 10 cm per hundred years (Reimnitz and Barnes, 1974).

The proportional replow curve for sediment reworking rates (Fig. 15) suggests that in 100 years about 20% of the bottom still remains undisturbed by gouging since T_o. This suggests that on the average, gouges less than 10 cm deep in the 20% of the "undisturbed" bottom would be filled in. Carrying this line of reasoning one step further, in 2,000 yr (Fig.15),when the average gouge incision (21 cm) would have been essentially filled with new sedimentation (20 cm) there is still a portion of the bottom yet to be gouged (5%). The average gouge occurring in this yet ungouged area in subsequent years would not reach to the bottom of the sediments deposited since T_o and thus deposition reflective of hydraulic processes would be preserved.

Vibracores taken in the viciity of test line 1 (Barnes and others, 1977a) are dominated by sedimentary structures related to ice gouging (Barnes and Reimnitz, 1974). However, they do show a surprising amount of horizontal bedding one would ascribe to hydraulic sedimentation. The fact that sediment reworking by ice gouging seen in the vibracores is not as intense as would be suggested either by the no-replow or proportional replow rates of reworking indicates that we do not have a complete understanding of the processes. Our rates of shelf sedimentation might be too low or contrary to our data. The pattern of ice gouging may not be random with areas that become reworked many times while other areas are infrequently gouged. More likely, local sedimentation rates are high due to the redistribution of materials in the vicinity of a recently formed ice gouge as a function of sediment type, gouge morphology and flank stability, bottom currents, sedimentation, and biologic activity.

The character of ice gouging elsewhere on the Beaufort Sea shelf could differ considerably. The segments of test lines 1 and 2 as reported here are partially protected from ice gouging by updrift shoals (Fig. 1). Furthermore these segments are located inside the major stamukhi zone, within the zone of floating fast ice (Reimnitz and others, 1977b). As the stamukhi zone is the site of the most intense winter ice deformation, we would expect rates of gouging and sediment reworking to be greater further seaward along the test lines (see Fig. 9). To date the presence of stamukhi in summer has kept us from obtaining usable repetitive surveys in this area.

SUMMARY

Ice gouging has been shown to be the dominant process influencing the sediments in the area of study. Several generalities regarding the process can be listed:

1)Higher rates of ice gouging and ice-bottom interaction are related to steeper bottom slopes, local topographic highs such as ridges, the stamukhi zone, and geographic exposure to drifting ice.

2) The dominant trend of gouges parallels the bottom topography and submerged ridges tend to 'steer' gouges parallel to their elongate trend.

3) The character of gouging can vary significantly from year to year and is probably a reflection of the intensity and direction of motion of local segments of the ice canopy during the previous winter.

4) Ice gouge recurrence data suggest that the bottom is essentially completely reworked to depths greater than than 20 cm in less than 200 years.

5) The intensity of gouging is expected to be much greater within the stamukhi zone, as this zone experiences the most intense ice deformation.

6) In the area studied, the maximum depth of ice gouge incision is less than 2 m and the maximum width of the bottom gouged by a single ice event is less than 100 m.

7) Between 1 and 2% of the bottom is gouged in any one year along the test line.

8) Gouges are formed both in the open water and the ice-covered periods of the year.

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