Ice Gouge Obliteration and Sediment Redistribution Event; 1977-1978, Beaufort Sea, Alaska

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ABSTRACT

In 1978 major changes in shelf morphology were observed during a routine re-survey of part of the inner shelf region of the central Beaufort Sea. Regional observations are coupled with a detailed diving and side-scan study of a single ice gouge of known age to develop a detailed description of the altered seabed conditions. Hydrodynamic activity has caused extensive sediment reworking, obliterating ice gouges to water depths of at least 13 m and has caused ponding of sediment in ice gouge terrain in deeper waters. Ponded sediment is characterized as a soft, sometimes very poorly consolidated, mud unit underlain by a stiffer, more consolidated, silty clay. In places, stiff silty clay is exposed in windows in the sediment pond and displays a fine-textured ice gouge morphology. Rates of sediment reworking and redisposition from apparently episodic events are an order of magnitude greater than the average sediment accumulation rates on the Beaufort Sea shelf. Reported maximum ice gouge incision depths are not representative of maximum ice keel penetrations into the seabed because these sedimentation events preferentially infill gouges. Furthermore, because these sedimentation events concentrate sediments in gouge troughs, a series of overlapping and interfingering "shoestring" deposits is developed which should characterize the ice gouge stratigraphy. The specific hydraulic mechanisms for sediment redistribution and sediment compaction observed in this study are only poorly understood.

1977 to 1978--in Beaufort Sea, Alaska
Part A: General Characteristics

by Peter Barnes

INTRODUCTION

Knowledge of where, how often, and how deep the processes of ice gouging affect the Beaufort Sea shelf is of critical importance for the development of the Beaufort Sea inner shelf. Subsea completions, pipeline burial depths, and structure protections must take these factors into account. Dredging or trenching activities either for pipeline installations or for gravel mining are influenced by ice gouging as this process determines the stability and physical character of the bottom sediments. The observations reported on here show that ice gouge obliteration along with the actual formation of gouges are both processes that are much more dynamic than was previously known. Episodic sediment redistribution and sediment compaction indicate that maximum incision depths have been too conservative, and that speculations on sediment strengths may have been underestimated.

BACKGROUND

Since 1973 we have been monitoring segments of the sea bed in the eastern part of Harrison Bay for morphologic changes on a year to year basis. Our observations have been in the form of repetitive side-scan sonar and fathometer tracks in water depths from 0 to 15 or 20 meters, precisely navigated (± 25 m) along a visual range and for distances of 10 to 20 km offshore of the coastline or islands (Barnes and others, 1978;

Reimnitz and others, 1977). The location of these tracklines is shown in Figure 1.

Repetitive surveys, for a period of three years (Barnes and others, 1978), have shown that 2 percent of the bottom is randomly impacted by ice along the test lines from one year to the next. These studies also show the changing character of ice gouging from one year to the next depending on the preceding winter's ice conditions. Barnes and others, (1978) used statistical estimates to predict over half of the bottom would be reworked to a depth of about 20 cm within fifty years or less. The study further concluded that there was no pronounced relationship between ice gouging and water depth, at least within the area of study (Barnes and others, 1978).

Bottom sediments in the area of repetitive ice gouge observations, and indeed over most of the inner shelf, are characterized by lateral and vertical variability (Barnes and Reimnitz, 1974). In general, the inner shelf sediments are sandy muds. Cores taken from ice gouge terrain are typically alternate layers of sand and mud. A marked feature of these cores is an absence of lateral continuity over distances of a few tens of meters, although the vertical character can be remarkably similar: alternating beds of slightly sandy muds with the well-laminated clean sands (Barnes and others, 1978). One characteristic of the cores is of special significance to the following discussion: the upper contacts of the mud units are generally erosional, while the lower contacts appear bioturbated and are possibly depositional contacts with the sand units.

Unusually ice-free conditions prevailed on the Beaufort Sea shelf in the late summer of 1977, resulting in long fetches and the formation of abnormally large waves. These open water conditions, coupled with wind-generated shelf currents are apparently responsible for the changes in bed morphology reported on here. Part B of this report, emphasizing diving observations, considers the effects of the 1977 open water condition on the environment of a single gouge. In Part B we discuss the regional change in character along our test lines and the relationship of these changes to water depth, sediment character, sediment dynamics, ice gouge recurrence interval, and the general implications regarding ice gouging.

OBSERVATIONS

Yearly monitoring of ice gouge character and the formation of new gouges has been done on two test lines extending from the coast to distances of 10 to 20 km offshore. The background information on these test lines and navigational techniques used to re-occupy the same segments of the sea bed year after year have been outlined by Barnes and others (1978). The location of these two lines and significant bathymetric information is given in Figure 1. Two primary forms of data were obtained - side-scanning sonar records (sonographs), and precision bathymetric records (fathograms).

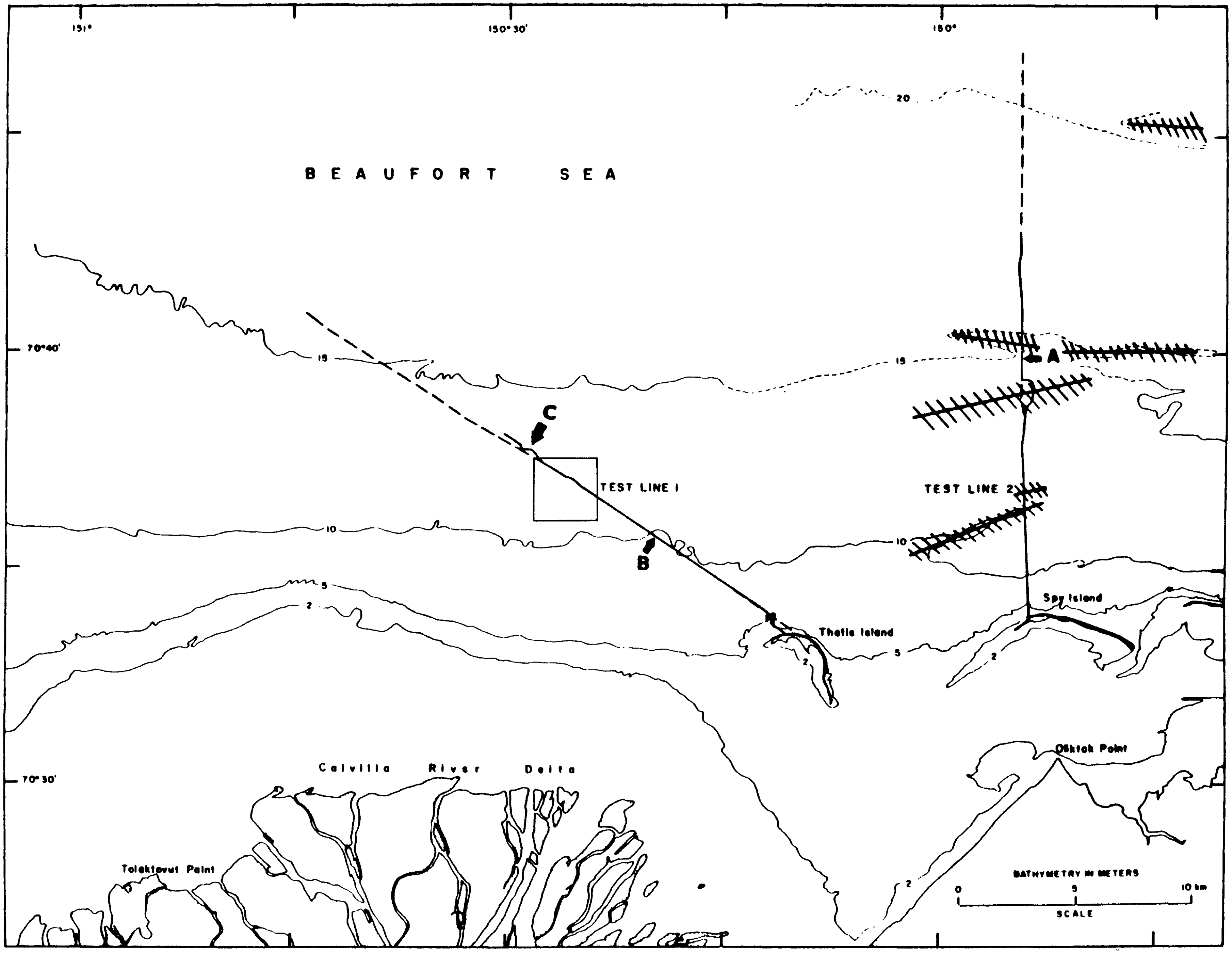


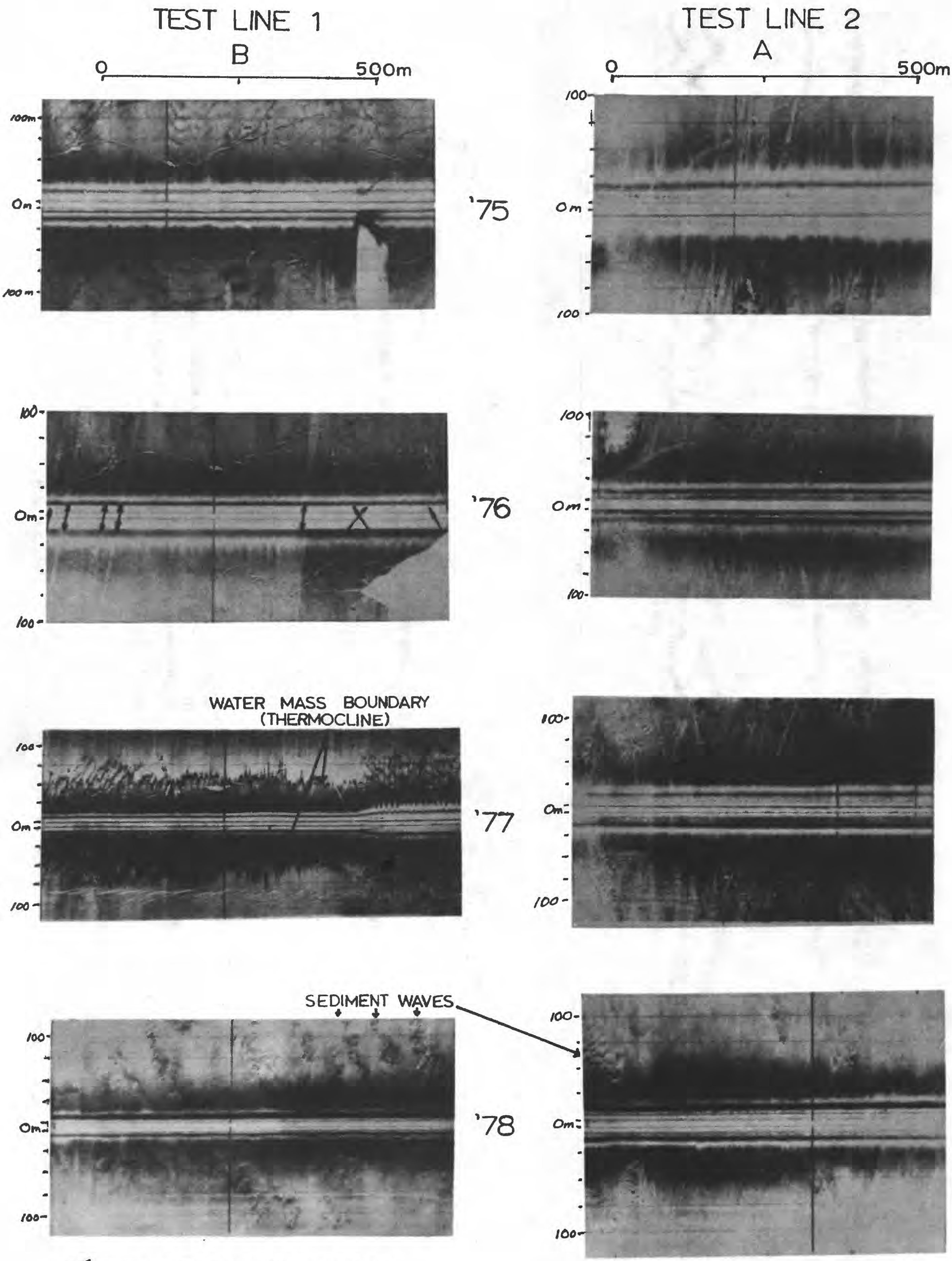
Figure 1. Location map of the study area indicating the location of test lines 1 and 2 reoccupied 1973-1978. Letters A through C designate the location of sonographs and fathograms illustrated in following figures. The location of the particular gouge cut during the 1976/77 period lies within rectangle on test line 1. The hachured areas emphasize the location of submerged shoals in the vicinity of the test lines.

A change in seabed character from 1977 and 1978, documented by comparisons of sonographs and fathograms, is widespread and shows significant sediment reworking. On test line 2 north of Spy Island (Fig. 1) the sea bed has changed so significantly that we are unable to correlate morphologic features in the 1978 records with those of earlier records, even though we feel confident that our navigation is not in error. In fact, gouge features that had been used for correlating records of several earlier years are simply not in evidence on the 1978 records, as shown in Figure 2a. Ice gouges are present but occupy only a very minor part of the sea bed and apparently represent ice gouge events that occurred since the fall of 1977, when wave-reworking took place. On test line 1 we also are unable to correlate morphologic features along the inner 10 km of the test line out to 13 m depth between 1977 and 1978 (Fig. 2b). However, seaward of this point, older gouges are still visible and correlate with our earlier records, further convincing us that our inshore navigation is not in error. The transition from the inshore area with no correlations to the seaward area with good ice gouge correlations occurs within a 1-km-wide transition zone on test line 1. Inshore of the transition zone two types of morphologic forms are seen on the new sea bed: a) sediment waves with wavelengths of about 100 m, and long crests extending beyond the swath covered by sonar, alternating with b) zones of irregular, sharp relief features in the troughs, that are similar to "funny bottom" (Barnes and others, 1977). These belts are suggestive of an older ice-gouged surface preserved in stiff, cohesive sediments (see Fig. 2b, 1978).

The change in character of fathograms from 1977 to 1978 shows significant redistribution of sediment. By the summer of 1978 the small-scale, sharp, micro-relief characteristic of ice gouges in the 1977 record has been transformed into smooth, positive relief features of 1 to 2 m amplitude and a 100 m wavelength, interspersed or broken by surfaces of sharp relief, as shown in Figure 3. Seaward of about 13 m depth, where the 1978 side-scan records show ice gouge correlations with 1977 records, fathograms illustrate a character similar to that of the 1977 records, but many of the deeper gouges clearly have been infilled with sediment and ridges have been beveled off between 1977 and 1978. A comparison of the overall depth profiles on test lines 1 and 2 shows no regional change in the inner shelf profile (± .25 m) suggesting that no significant onshore-offshore bulk transfer of sediment has occurred.

A detailed comparison of 1977 and 1978 fathograms over a 1 km section of the sea bed (Figs. 4 and 5), illustrates several of the morphologic changes that have occurred. A 50 cm gouge incision on the 1977 fathogram is infilled with 20 cm of sediment in the 1978 records, while the deeper gouge (.9 m in 1977) is only 30 cm deep in 1978 records, indicating an infilling of 60 cm of sediment (Fig. 4). The ridges flanking these two gouges indicate erosion although their morphologic expression is preserved. The flanking ridges of the smaller gouge have decreased in height by 40 cm; those of the large gouge by only 20 cm. The 1977 and 1978 fathograms do not cross these two gouges in exactly the same location, thus changes in ridge heights may be due to height variations along the ridge of the gouge as observed by divers and discussed in Part B. However, in comparing an overall cross section of the morphology of the sea bed, between 1977 and 1978 one sees an overall decrease in ridge height and subduing by infilling of gouge incisions as shown in Figure 5.

Figure 2. Sonographs of the same area of the seabed in four different years. Locations A and B on Figure 1. Note that individual gouges can be seen and traced from the 1975 records through the 1977 records, but in 1978 hydraulic bedforms dominate. On test line 2 sand waves are seen in the 1978 record. On test line 1 the trackline parallels a meandering gouge in the 1975 through 1977 records but only smooth bedforms almost transverse to the trackline are seen in the 1978 records. The boundary with the ragged edges in the 1977 record is due to a density layer in the water column and does not relate to seabed conditions. Note the rough bottom relief in the windows between the smooth bedforms in the 1978 record.



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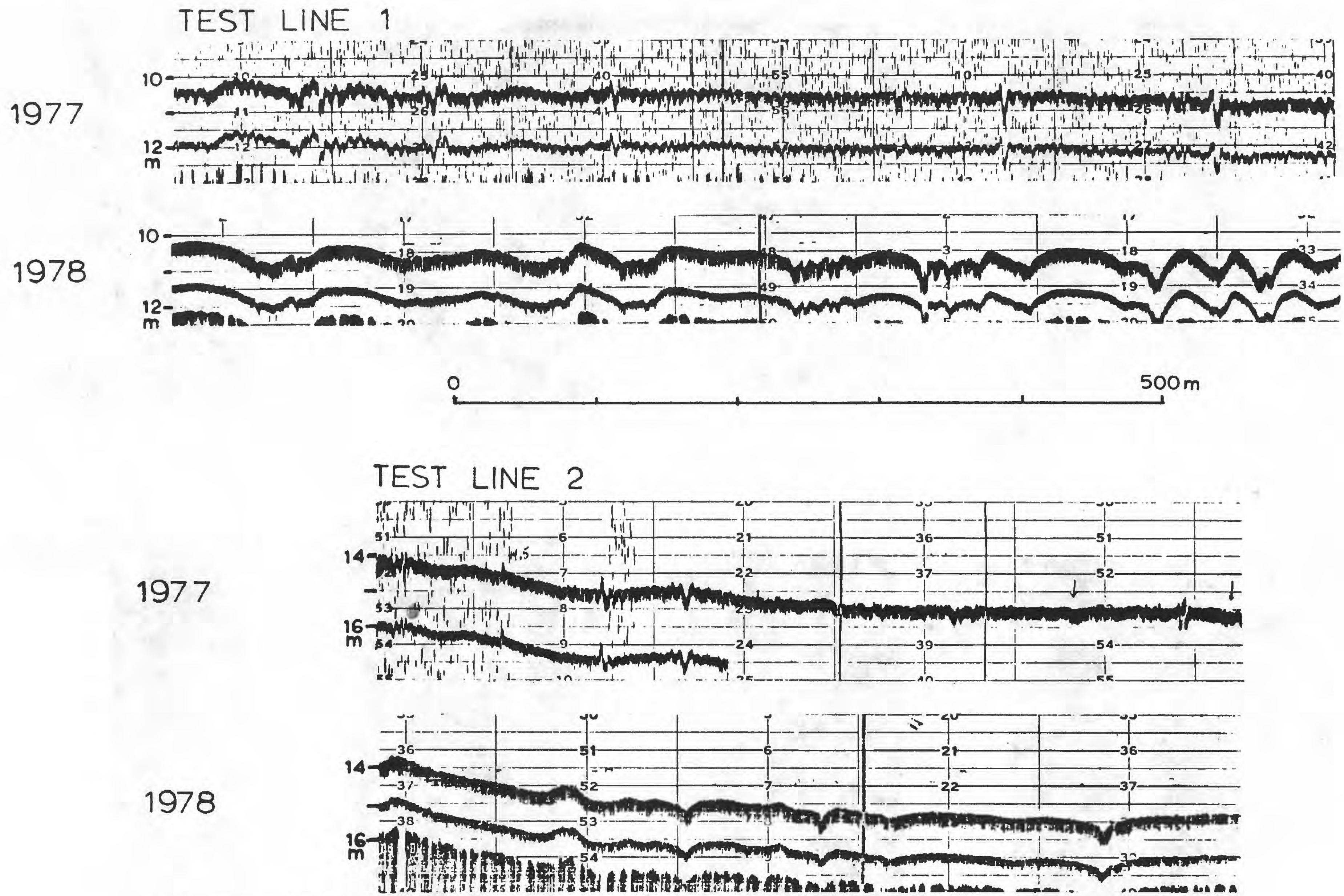

Figure 3. Fathograms of the seabed corresponding to the sonographs in Figure 2 for 1977 and 1978 on test lines 1 and 2. On test line 1 the positive relief features on the 1978 fathogram correspond to the smooth areas on the sonograph and the rough relief to the irregular bottom on the sonograph.

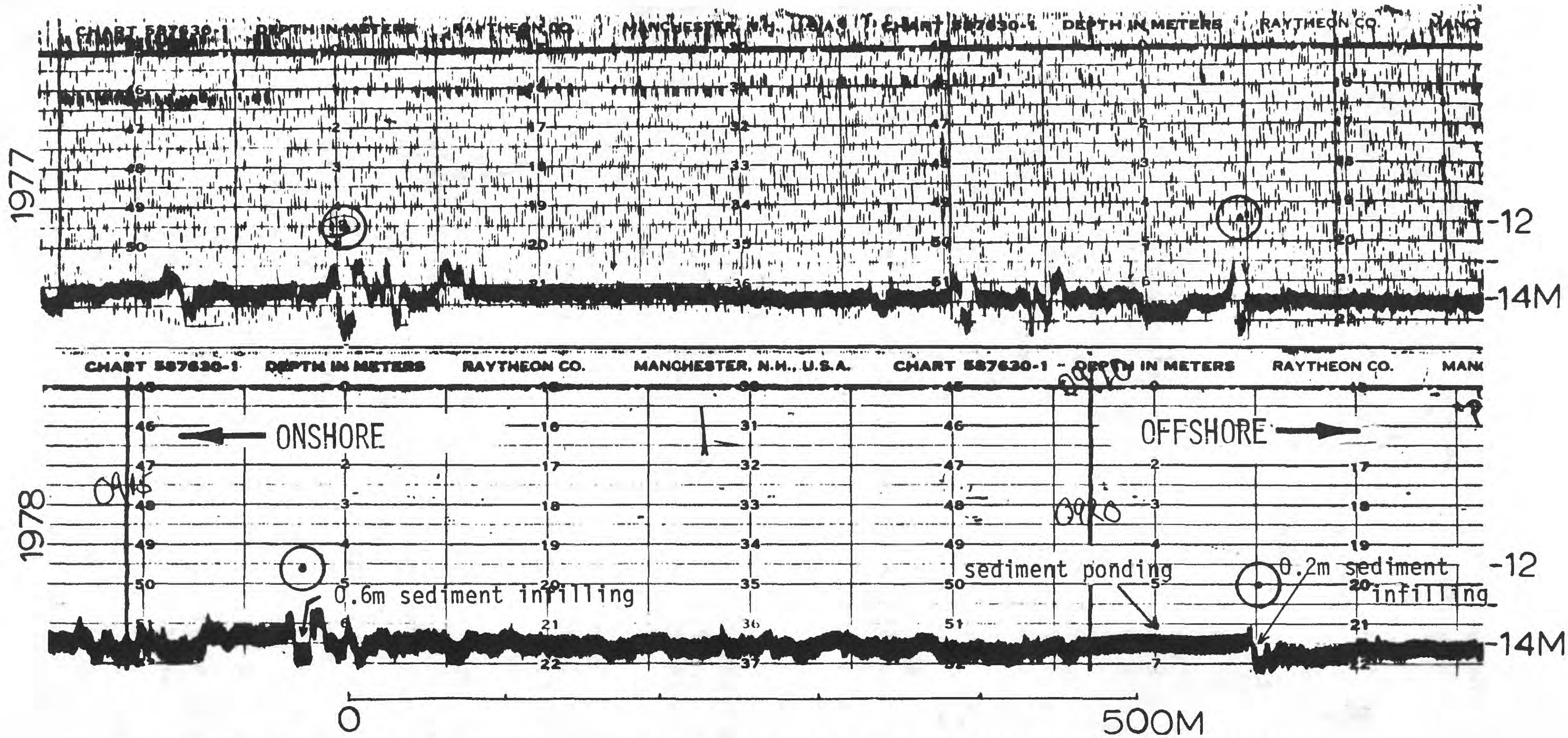

Figure 4. Fathograms of the seabed at location C (Figure 1) illustrating the infilling of gouges during the interval between 1977 and 1978. The bull's-eyes are over the gouges mentioned in the text. Note the decrease in ridge height in the 1978 records and the pronounced ponding on the onshore (left) side of the gouge ridge under the seaward bull's-eye.

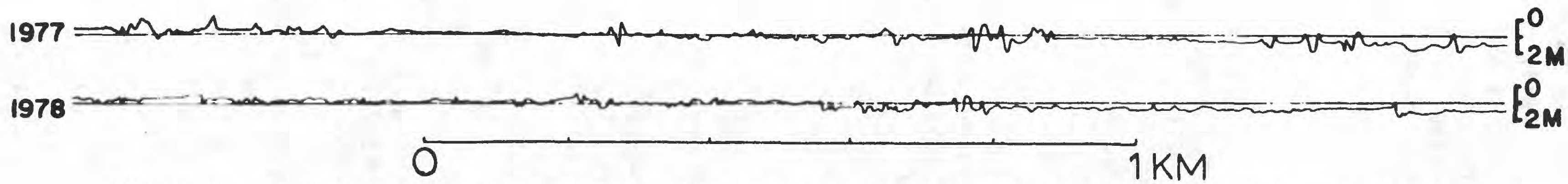

Figure 5. Tracing of fathograms from 1977 and 1978 records illustrating the overall decrease in seabed relief yet minimal change in absolute depth between the survey interval.

On test line 1 in the area where 1977 gouge morphology was only partially obliterated, sediments appeared to be ponding on the shoreward side of major ridge features. The seaward side of these major ridge features was often free of sediment ponding as illustrated by rough bottom relief on the fathograms and by more clearly defined ice gouge features on the sonographs (see Figure 4 and Part B of this report).

DISCUSSION

Sediment reworking

Our data show that sediment reworking by waves and currents is a major though episodic influence on ice gouge character of the inner Beaufort Sea shelf. The reworking events move material from relief highs such as gouge ridges into troughs, thereby causing more rapid infilling of gouge depressions than occurs on the shelf surface as a whole. Measurements of gouge incision depths as an indicator of maximum sea bed penetration by ice is greatly influenced by the recency of a sediment redistribution event. Measured incision depths of gouges of unknown age have the potential of greatly under-rating the true ice incision depth, due to sediment infilling subsequent to the formation of the gouge. This implies that maximum incision depths measured for the shelf are considerably greater than have been reported in the literature (Reimnitz and Barnes, 1974; Reimnitz and others, 1977; Barnes and others, 1978).

Inner Shelf Sedimentary Regime

The occurrence of episodic events documented here, along with the clearly wave and/or current-produced sedimentary units observed in our vibracores, suggests that the inner shelf sedimentary environment is a complex mixture involving both ice and current reworking. The morphologic character of the bottom on test line 1 suggests that a surface layer of readily reworkable sediments, on the order of 50 cm or less in thickness, overlies a more consolidated unit. In the fall of 1977 this" mobile" surface layer was reworked by currents and waves on the inner part of the test line to such an extent that all ice gouge morphology present earlier was obliterated by erosion and/or burial.

Further offshore, waves and/or currents aligned this more mobile sediment in coast-parallel ribbons with zones of consolidated, cohesive, underlying material exposed in intervening troughs. The positive relief ribbons may have formed in response to westerly longshore currents generated from the prevailing northeast winds that dominated the storm events of the fall of 1977. A coastal jet of the form described by Scott and Csanady (1976) also may be responsible for the observed bedforms. The erosional character of the upper surfaces of mud units in vibracores may represent preserved indicators of episodic events in the past.

Still further offshore the effects of waves and currents were apparently less pronounced, although an offshore component of the longshore currents or the coastal jet apparently carried material seaward as a near-bottom sediment layer which preferentially settled on the landward sides of positive morphological features, such as the flanking ridges of ice gouges, forming sediment ponds (Fig. 4).

The recurrence interval between episodic erosional events of this magnitude is difficult to estimate. To create the extreme wave and coastal current climate postulated for this event, or series of events, two things must occur simultaneously. Open water must exist over a sufficient area of the Beaufort Sea to permit generation of large waves, and storms with accompanying winds must be present. In 1974 we suggested that gouges on the inner shelf might have been smoothed by a storm event in 1972 (Reimnitz and Barnes, 1974). But, in a later paper (Reimnitz and others, 1977), we attributed the change to poor quality of records following the storm event. Thus the periodicity is probably greater than five years. Furthermore, we have shown (Barnes and others, 1978) that the overall number of gouges along the test lines do not increase over a two-year period, suggesting that the rate of gouge infilling equals the rate of gouging and that reworking and infilling is slow.

In the area of study we have determined that ice gouges about 2 percent of the bottom each year rather uniformly. If gouging were to proceed without major reworking events, the bottom would be saturated with gouges over a period of fifty to one hundred years (Barnes and others, 1978). As this is not the case, particularly on the inner part of the test lines, the recurrence interval of major sediment reworking episodes must be less than fifty to one hundred years in these water depths. We don't know the effects of major storm surges, such as the one of 1970. These surges occur at 50 to 100-year intervals, but are generally associated with short fetches (Reimnitz and Maurer, 1978).

SUMMARY AND CONCLUSIONS

A major oceanographic episode in the fall of 1977 accompanied by abnormal currents and waves caused extensive sediment reworking and gouge obliteration to a water depth of at least thirteen meters, and caused infilling and ponding of sediment in ice gouge terrain in deeper water. The rates of gouge infilling from these episodic events are an order of magnitude greater than the normal rates of sedimentation on the Beaufort Sea shelf. As a result, reported maximum gouge incisions are not representative of ice keel penetrations into the sea bed. Furthermore, ice gouge incisions will serve to concentrate sediments in the troughs forming a series of overlapping and interfingering shoestring deposits on the shelf.

Part B: Detailed Observations of One Gouge

by Erk Reimnitz

INTRODUCTION

In order to study the dynamics of ice gouging and sedimentation of the Beaufort Sea, selected areas of the sea floor have been repetitively monitored with side-scanning sonar and fathometer since 1972. Accurate range-range positioning and bearing alignment has been used for navigational control since 1973 for frequent re-surveys. The survey results have provided reliable data on the rates of ice gouging in specific areas of the shelf, along transects 10 km to 14 km long (Reimnitz and others, 1977; Barnes and others, 1978). Additionally, our side-scan sonar data (sonographs) now contain many gouges of known age. This brief report deals with shipboard and diving observations made in September, 1978 of one of these gouges. The specific gouge was first encountered during the summer of 1977, having formed during the previous year. The bulk of the observations reported on were made during the summer of 1978, one year after our records showed this linear furrow for the first time.

The late summer of 1977, marked by unusual, ice-free conditions on the Beaufort Sea shelf, provided long fetches for wave generation. This condition, together with strong winds, correlates with dramatic changes along the coast and on the shelf surface. Erosional embankments were formed on many barrier islands, and lake beds were exposed on beaches seaward of the larger islands. These lake beds, together with new overwash fans on the landward side of the islands, are evidence of rapid migration. Sonographs and fathograms of the shelf surface show hydraulic bedforms where ice gouges existed prior to 1978. The records also show that wavelike bedforms in some areas have migrated over rough surfaces which diving observations revealed to be a stiff, silty clay. The striking changes in sea bed character prompted us to make detailed observations at a specific gouge.

SIDE-SCAN SONAR AND FATHOMETER OBSERVATIONS

The ice gouge under investigation lies on our test line 1 in the central portion of Harrison Bay, at a water depth of 10.5 m (see Fig. 1). The 1978 records of the gouge and surrounding sea-floor features show greatly subdued relief as compared to 1977 records. Fathograms demonstrate that the gouge became shallower, compared to the adjacent sea floor, and that relief of the flanking ridges became lower in 1978 (Fig. 6 inset). However, the 1978 side-scan sonar record still shows the gouge to be the same feature first observed in 1977. The side-scan sonar was used to determine gouge configuration and alignment by tracking the gouge northeastward from test line 1 to the point where the ice first touched the sea floor, and then southwestward to the point where the gouging ice apparently became stuck, and the gouge feature ended (Fig. 6). The depths of these two points on the shelf surface differ by 4 meters.

The sonographs can be used to characterize the flanking gouge ridges and the gouge fill. The flanking gouge ridges in the vicinity of our dives are in reality made up of discontinuous, irregularly spaced mounds (Fig. 7) up to 80 cm high (Fig. 6 inset). This ridge-form is characteristic for the length of the gouge (see also Figs. 8 and 9). The trough of the gouge has a homogenous, light appearance on the sonographs, suggesting a smooth, almost soupy fill.

Sonographs show that the gouge ridges and fill have been dissected by numerous, still younger gouges (Fig. 8). The younger gouges are characterized by multiple furrows probably caused by the raking action of fresh pressure-ridge ice (Reimnitz and others, 1973). Furthermore, these younger gouges were made at a time when the new gouge fill had settled sufficiently so that its surface preserved the rake marks which crossed them.

The cross-sectional shape of the gouge remains remarkably constant, even though the ice responsible for the gouging traveled through a depth range of about 4 m. Change in shape of the gouge is seen only along the first few hundred meters of gouge track, where the ice initially set down on the sea floor (Figs. 7,8, and 9).

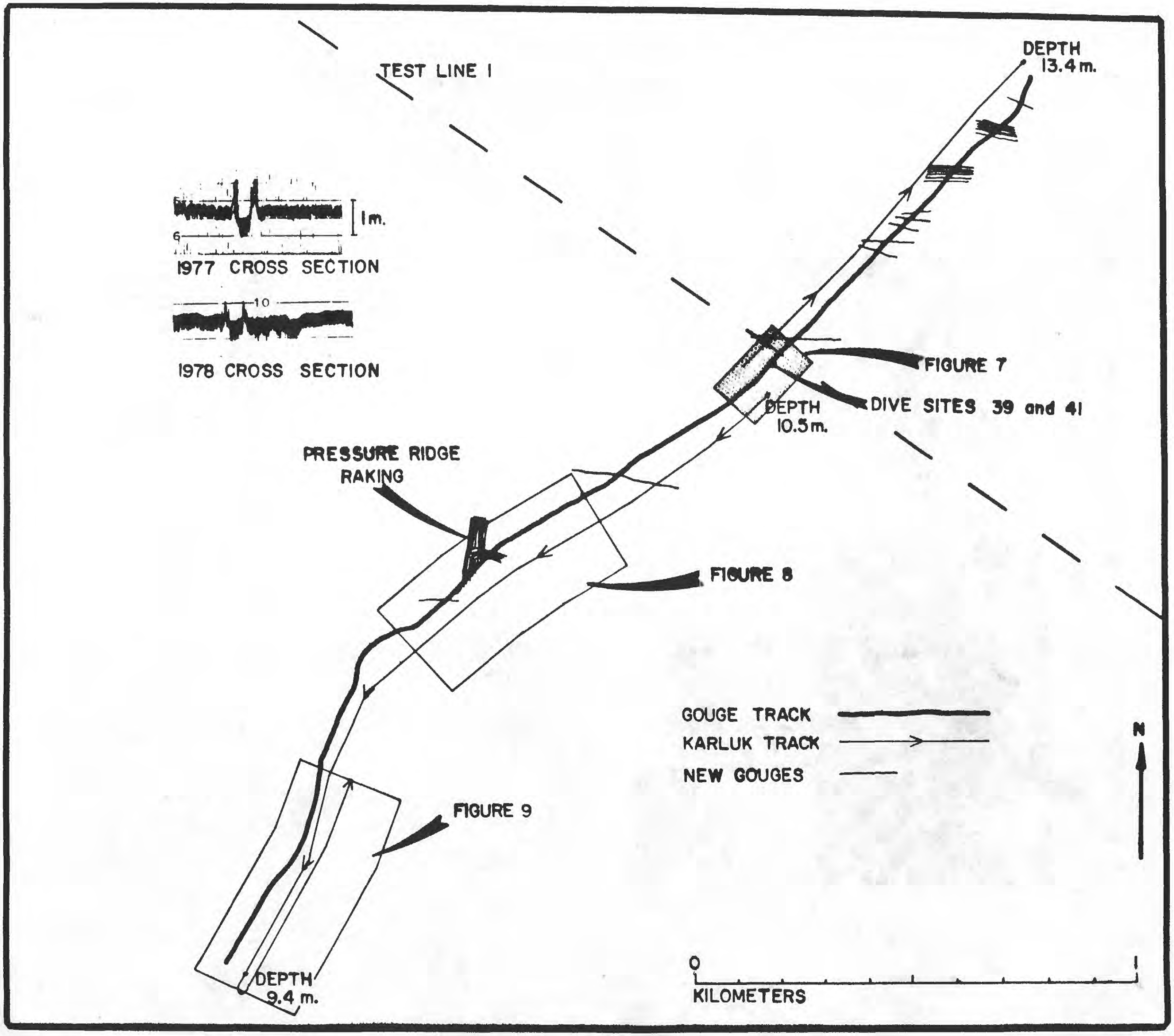

Figure 6. Details of the "1977-gouge" track, track of the R/V KARLUK following the gouge, of the dive sites, of gouge cross sections in 1977 and 1978, and of new gouges cut across the "1977-gouge".

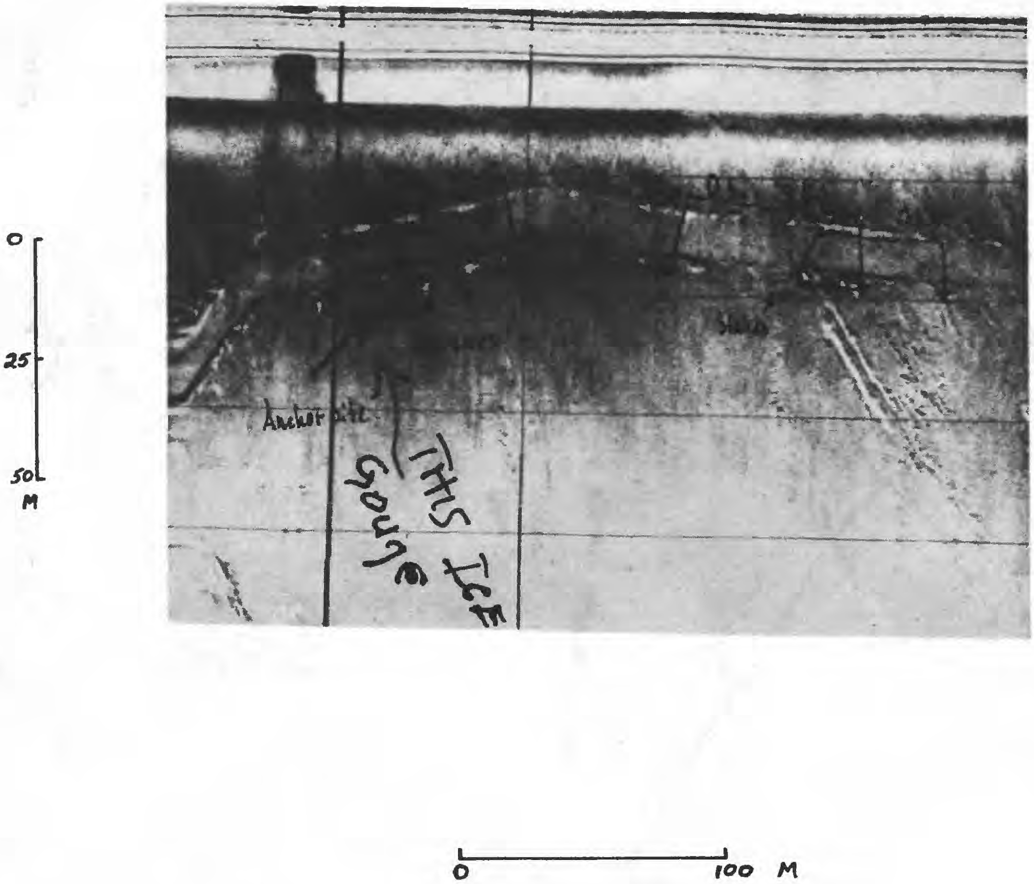

Figure 7. Sonograph of dive sites 39 and 41, showing location of box cores, stakes and bottom traverses. The small new gouge crossing the "1977-gouge" was noted by us as an "80-cm wide gouge". Note that flanking ridges are not continuous, but hummocky and intermittent. (See Fig. 6 for location).

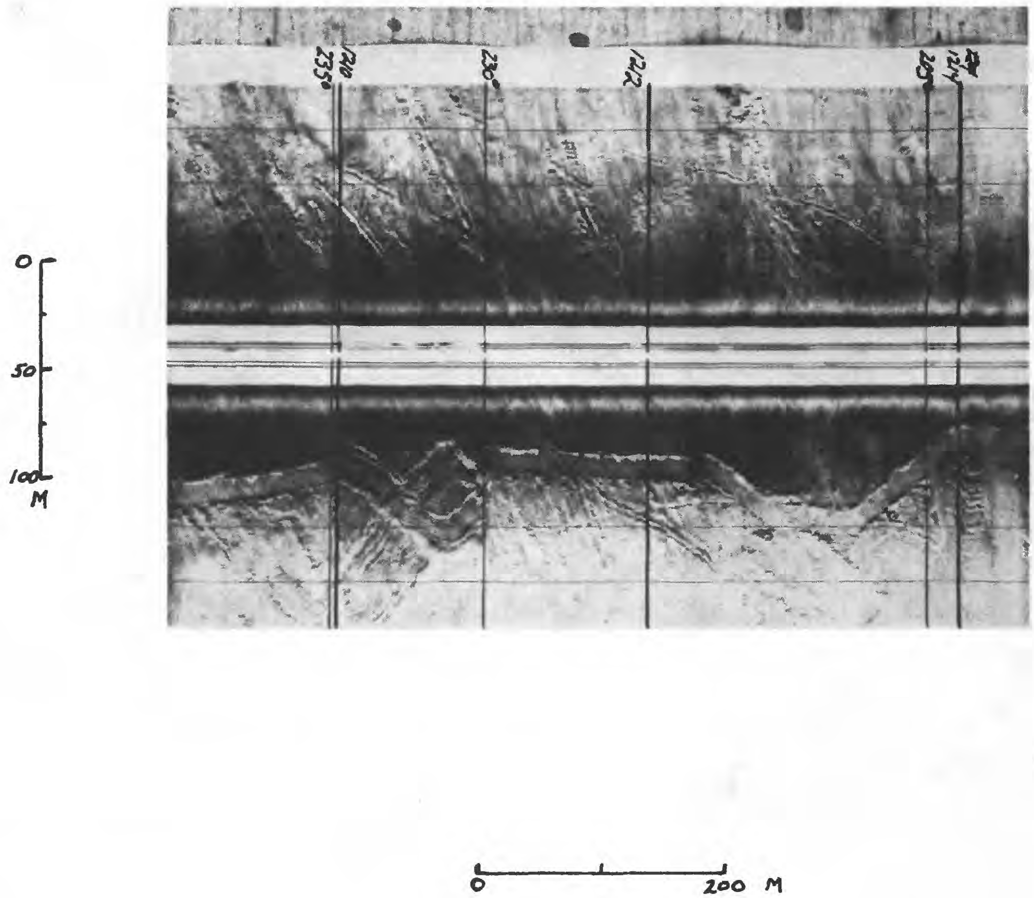

Figure 8. Sonograph of 1977 vintage gouge as seen in 1978, cut by numerous new gouges (in part by pressure ridge keels) after 25 to 40 cm of new soft sediment had smoothed the 8-m wide floor from one flank to the other. (For location refer to Fig. 6).

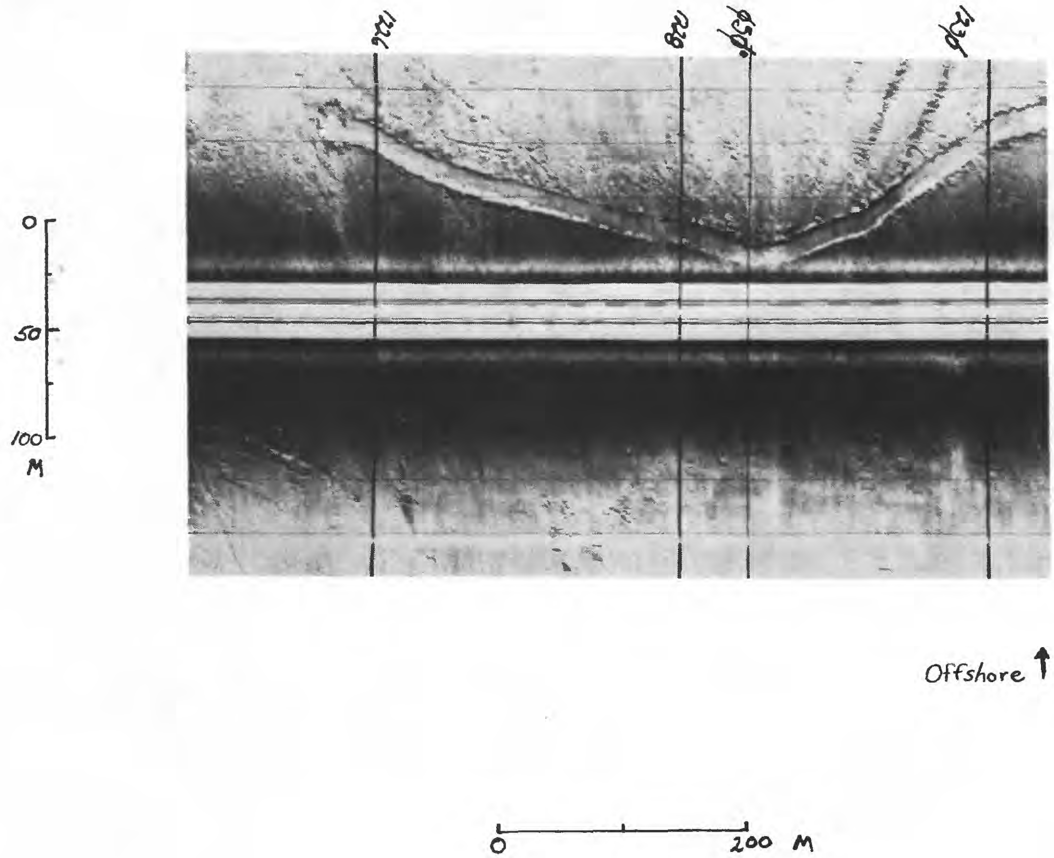

Figure 9. Southwest terminus of 1977 vintage gouge as seen on sonographs. Note that ice-gouge related microrelief, preserved in firm, cohesive sediments, is exposed on the seaward side of the gouge, but is largely blanketed and hidden by transient layer on landward side of the gouge. (For location refer to Fig. 6).

The most striking observation on regional sea bed character revealed by the most recent (1978) sonographs is the ponding of new, smooth-surface sediment. Sediment ponding occurs in gouge troughs and where major gouges serve as dams for the offshore movement of sediment (Fig. 9). Thus, the shelf surface adjacent to, but seaward of the gouge, is marked by a continuous, dense pattern of irregularly linear relief features that reflect many ice-gouge events. On the landward side, however, most of the sea floor sonograph is marked by smooth, even texture, similar to that within the gouge. This smooth texture suggests that the area is mantled by a 10 cm to 20 cm thick, soft soupy layer, observed in many of our dives (Reimnitz and Toimil, 1977). This layer is only broken in a few places landward of the gouge, where "windows" are formed, exposing a firmer, rough surface.

DIVING STUDIES

SCUBA dives were made on two different days along the gouge in the vicinity of the test line as shown on the sonograph in Figure 7. Observations made at the dive sites are briefly summarized below:

The underwater visibilities varied between 1 and 1.5 m; restricted by a snow of largely translucent organic floccules. The sea floor was covered by a layer of brownish ooze, principally of organic origin with an admixture of fine, clastic detritus. Because the ooze layer was easily disturbed, our diving activities reduced visibility to zero.

The floor of the gouge was about 8 m wide and appeared to be completely smooth from one flanking ridge to the other. Only a small number of open burrows (0.5 cm in diameter) were seen in the soft fill. These burrows were surrounded by excrement or excavation material. When we hit the gouge fill with our hands, a closely spaced turbid plume arose, indicating a rich fauna of burrowing organisms. During the six gouge traverses (Fig. 7), we pushed our hands into a very soft gouge fill, generally 20 to 25 cm deep, but extending to 40 cm deep in some areas. The lower portion of the gouge fill was noticeably firmer than the upper portion. Below the soft gouge fill there was a very firm, slick, impenetrable floor with grooved micro-relief trending parallel to the gouge.

Segments of the bottom traverses followed the 50 to 70 cm high flanking ridges on either side of the gouge (Fig. 8). The upper portions of the ridges were steep, and their slightly rough forms protruded from the ooze blanket that covered everything else. These flanking ridges were not continuous, levee-like features but were instead irregularly spaced mounds of cohesive, soft, grey mud. These mounds were not well aligned along the gouge but irregularly distributed in a 2- to 3-m wide zone flanking the gouge. When mound crests were displaced sideways, they would spring back elastically. The slightly rough crests of the mounds did not show obvious signs of current erosion but did have obvious extension cracks. Some of these cracks were partially infilled.

Small scale ice gouge events post-dating the formation of the 1977 gouge and post-dating the sediment redistribution event were also observed. Sharply defined, steep-sided, linear ice gouge incisions, 10-cm to 20-cm wide, crossed several of the mounds. A fresh-looking ice gouge 80-cm wide incised the main gouge fill near the east end of the dive-site 14 traverse (Fig. 7).

Considerable effort was required to insert stakes and box corers in the seabed onshore from the gouge, (Fig. 7). The 1 cm x 5 cm x 100 cm pointed stakes were easily pushed into the ridge by hand, but were difficult to drive into the firm floor below the gouge fill even with the aid of a hammer. The stakes driven on September 6 were observed again on September 9. All of the stakes had snagged large brown kelp fronds, which had apparently drifted in from the east, although no current was noted at the time of the dives. Box cores (Fig. 7) penetrated 20 to 30 cm of highly mottled, bioturbated, firm, cohesive mud, with irregular, discontiuous lenses of muddy sand up to 10 cm long.

DISCUSSION OF RESULTS

The data demonstrate that sediment infilling of large and small negative relief features is a dynamic process. A few ice-free, stormy seasons, such as occurred in 1977, could cause total obliteration of ice gouges. The large volume of soft fill ponded in local depressions, when compared with an overall low (6 cm/100 years) sedimentation rate, suggests local deposition at the expense of local erosion (Reimnitz and others, 1977). This deposition is demonstrated by comparison of 1977/78 gouge cross sections in Figure 7 (inset), where the height of the flanking ridges and the depth of the gouges was reduced--the first by erosion, the second by deposition.

RATES OF GOUGING AND SEDIMENTATION

On test line 1, three closely spaced (within 40 m) vibracores, were taken in 1977 which contain alternating beds of mottled, sandy mud and clean, laminated sand. In these cases individual beds can not be correlated from one core to another (Barnes and others, 1979) suggesting that sand and mud are deposited in lenses of less than 20-m in length. Observations at dive sites 39 and 41 demonstrate that mud units are deposited in the form of irregularly sinuous "shoe-string deposits" in the troughs of existing gouges. Thus individual mud stringers of existing gouges may be kilometers long, sub-parallel to the dominant trend of the gouges, and crisscrossing them. Evidence of a large number of burrowing organisms in the fill or the 1977 gouge, suggests that the fill is nutrient rich, and will become bioturbated or mottled.

We suggest that the 3-m thick sheet of Holocene marine deposits found on the shelf along test line 1 must consist of such crisscrossing "shoe-string deposits," or that sedimentation is restricted largely to gouge troughs. Assuming a general rate of sediment build-up of 0.6 mm/yr (Reimnitz and others, 1977), about 8.5 m^3 of sediment would accumulate in a 1-m wide strip along the test line (14 km long) each year. Additionally, four years of data indicate (Barnes and others, 1978) that 40 to 75 m^3 new gouge excavations are made each year in the same 1-m wide zone, depending on whether we assume triangular or rectangular shapes for the gouge cross sections. The gouge shapes are intermediate between the two extremes. We can assume that the total number of gouges on the shelf does not increase with time (Barnes and others, 1978). This implies that gouges are being removed from the population by infilling at the same rate at which they form. In this case 40 to 75 m^3 of sediment would have to be reworked and deposited in existing and new gouges along the 1 m wide zone in the average year. This volume is almost an order of magnitude greater than the general rate of sediment build-up on the shelf 5mm/yr vs. 0.6 mm/yr).

CHARACTER OF SEDIMENTS

Sand units observed in the vibracores result from local erosion and winnowing on high spots of the shelf surface. Thus we anticipated that the box cores we took might contain surficial sand units. However none of the nine box cores taken in the area contained a surficial sand layer which suggests that the 1977 season of winnowing is not recorded in the sedimentation record of the shelf.

At dive site 41 the flanking gouge ridge consisted of discontinuous very soft mud mounds created during the process of ice gouging. The process suggests a mechanism of sediment extrusion which is accompanied by the formation of tension cracks in the caps of the mounds. We have observed similar mounds of soft mud, 60 to 80 cm high, with tension cracks, on the borders of gouges in other areas of the inner shelf. Similar mounds even occur within the gouges.

A firm surface layer underlain by softer muds is required in order to form soft mud extrusion mounds. Firm mud deposits are believed to be formed in the gouge troughs from ice pressures during the gouge event. High shear strengths in gouge troughs have been observed and measured in numerous dives (Reimnitz and Toimil, 1977). The very firm to overconsolidated, fine, cohesive sediments on the Beaufort Sea shelf may be due to frequent ice override compression although other mechanisms are possible (Chamberlain and others, 1978). A source for a soft, unconsolidated unit underlying the stiffer surface unit remains an enigma.

REGIONAL PROCESSES OF SEDIMENTATION

Firm surface sediments are widespread in the region as shown by the difficulty encountered in driving stakes and box cores into the bottom and by the rough relief forming windows in the regional morphologic character of sonographs. The cohesive mud bears a rough microrelief relict from many generations of gouges. The morphology has a finer character and a higher density of gouge features than noted when this surface is not exposed (Reimnitz and Barnes, 1974; Barnes and others, 1978).

If the overlying, soft, surficial unit were formed by settling from suspension, the unit would be continuous and of uniform thickness rather than preferentially ponded in gouges and upslope from gouge ridges (Fig. 10). The occurrence of windows in the unit, and ponding against flanking gouge ridges less than 1-m high, suggest a process of lateral transport in a layer that is thinner than the height of the flanking ridges. The predominance of recent deposition landward of gouges indicates offshore transport as sketched in Figure 10B. This offshore shift of sediment may have occurred under oscillatory water motion during the passage of waves on the gently sloping shelf surface or by processes suggested in Part A.

SUMMARY

The findings from this study and Part A, show that gouges on the inner shelf are younger than previously believed, and were orginally much deeper than they were during the period of the survey. The findings also indicate

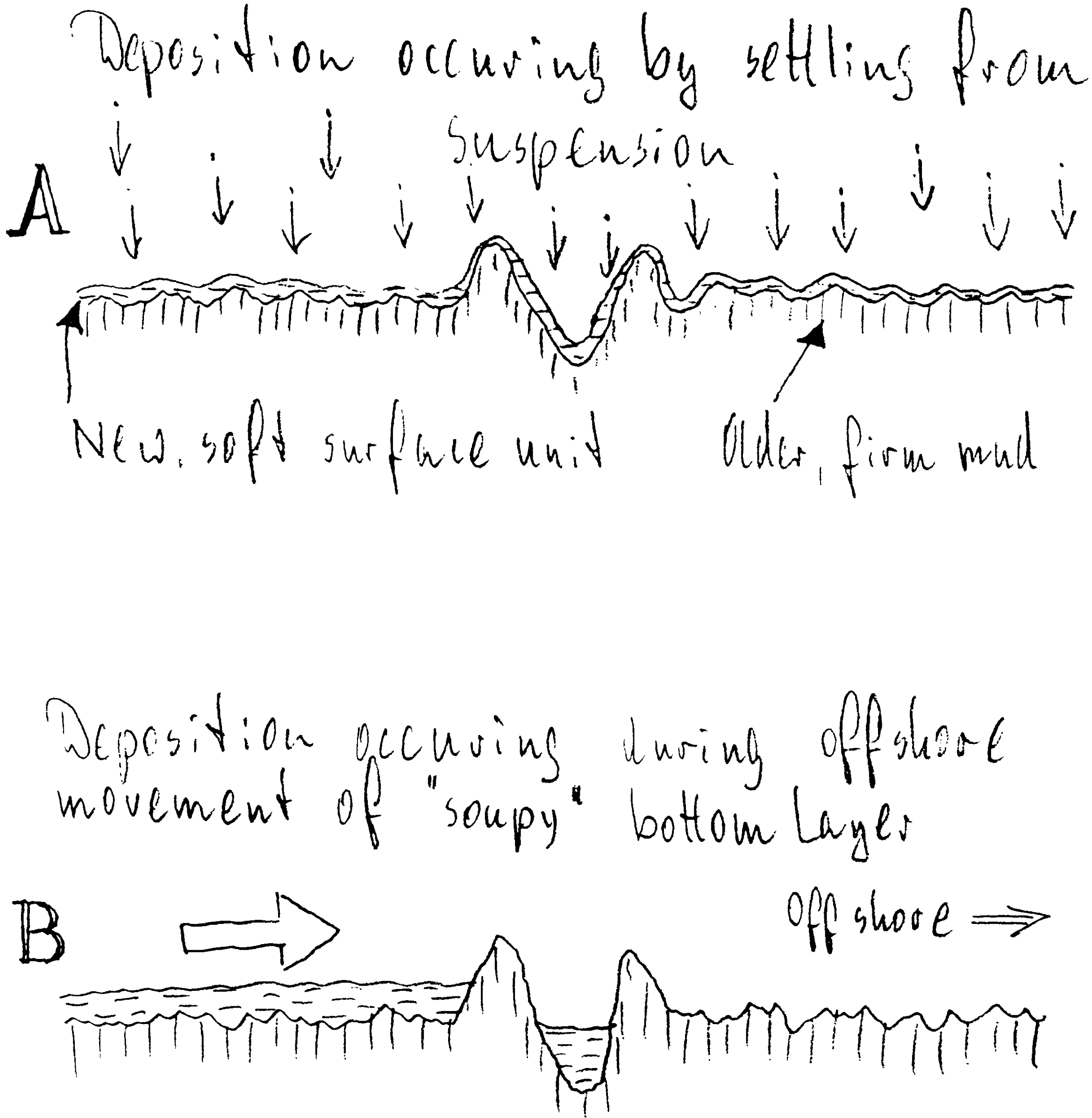

Figure 10. Sketch of two different models of mud deposition on a gouged shelf surface: A - by vertical settling from suspension, and B - by lateral movement of a thin sediment sheet. The thickness of this sheet is less than the relief of major flanking ridges bordering gouges. B is observed in sonographs.

that bottom excavations made for the purpose of laying a pipe line will infill with sediment rapidly under conditions similar to those we found in the 1977 season. Our findings also suggest that the submerged portions of sand-and-gravel islands may require protection, to a depth of at least 10 m, against erosion by water. Furthermore the hydrologic processes of lateral sediment movement causing preferential ponding are not well understood. Neither are the processes leading to the formation of sediment extrusion mounds associated with gouge events.

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