ATTACHMENT I

ICE GOUGE INFILLING AND SHALLOW SHELF DEPOSITS IN EASTERN HARRISON BAY, BEAUFORT SEA, ALASKA

by

Edward W. Kempema

INTRODUCTION

Approximately 25% of the sea surface over the world's continental shelf area is seasonally covered by ice. Through the formation of pressure ridges and shear ridges this ice can gouge the seafloor, disrupting and reworking sediments on the shelf. Thus, ice processes are important to sedimentation on high latitude shelves, in addition to all the normal processes that affect lower latitude shelves. The discovery of oil off the North Slope of Alaska has generated interest in the ice gouging process on the shallow shelf of the Alaskan Beaufort Sea - the ice keels that disrupt the seafloor could be a major threat to oil pipelines transporting oil from offshore platforms to the mainland. However, most of these studies have focused on ice related processes: how the ice gouges form, ice gouge morphology and ice gouge recurrence rates, and the density of ice gouges on various parts of the shelf. Very little work has been done on the sedimentary processes that work to fill in ice gouges and the type of sedimentary structures formed in ice gouged terrain. Papers by Barnes and Reimnitz (1974), Reimnitz and Barnes (1974), and Barnes et al. (in press) review much of the available information on sedimentary processes and ice gouging on the Alaskan Beaufort Sea shelf. This paper describes 4 cores collected on a single gouge on the shallow shelf of the Beaufort Sea, and speculates on the method of ice gouge infilling and the types of sedimentary structures formed in ice gouged areas. The terminology used in this paper conforms to that used by Barnes et al. (in press).

METHODS and RESULTS

In 1980 an ice gouge in eastern Harrison Bay, about 40 kilometers west of Prudhoe Bay, was marked with an acoustical pinger for later study (Fig. 1). This gouge, called Gouge #1, lies on Test Line 1, a line that has been repetitively surveyed with side-scanning-sonar and fathometer since 1973 in order to determine ice gouge recurrence rates (Reimnitz et al., 1977, Barnes et al, 1978, Barnes et al, 1979, Barnes and Reimnitz, 1979, and Rearic, in preparation). Test Line 1 is run on a range and bearing from a fixed location, and is repeatable to less than +25 meters on repetitive surveys. Gouge #1 crosses Test Line 1 at about right angles, and was first seen in the summer of 1976. Gouge #1 lies inside a zone of offshore shoals that are subjected to intense ice gouging (the Stamukhi Zone, Reimnitz et al., 1978), in the floating fast ice zone (Barnes et al., 1978) - an area where there is little movement of the ice sheet during the winter. The sea surface in the area of Gouge #1 is ice covered 9 months a year, but in the summer time the sea is open and shelf sediments are subject to normal shelf sedimentary processes.

In 1982 we returned to Gouge #1 to collect cores to determine ice gouge infilling processes and the type of sediments that collected in the gouge. We relocated the pinger we had left 2 years before; this gave us positive proof that we had returned to the same gouge we had picked out in 1980.

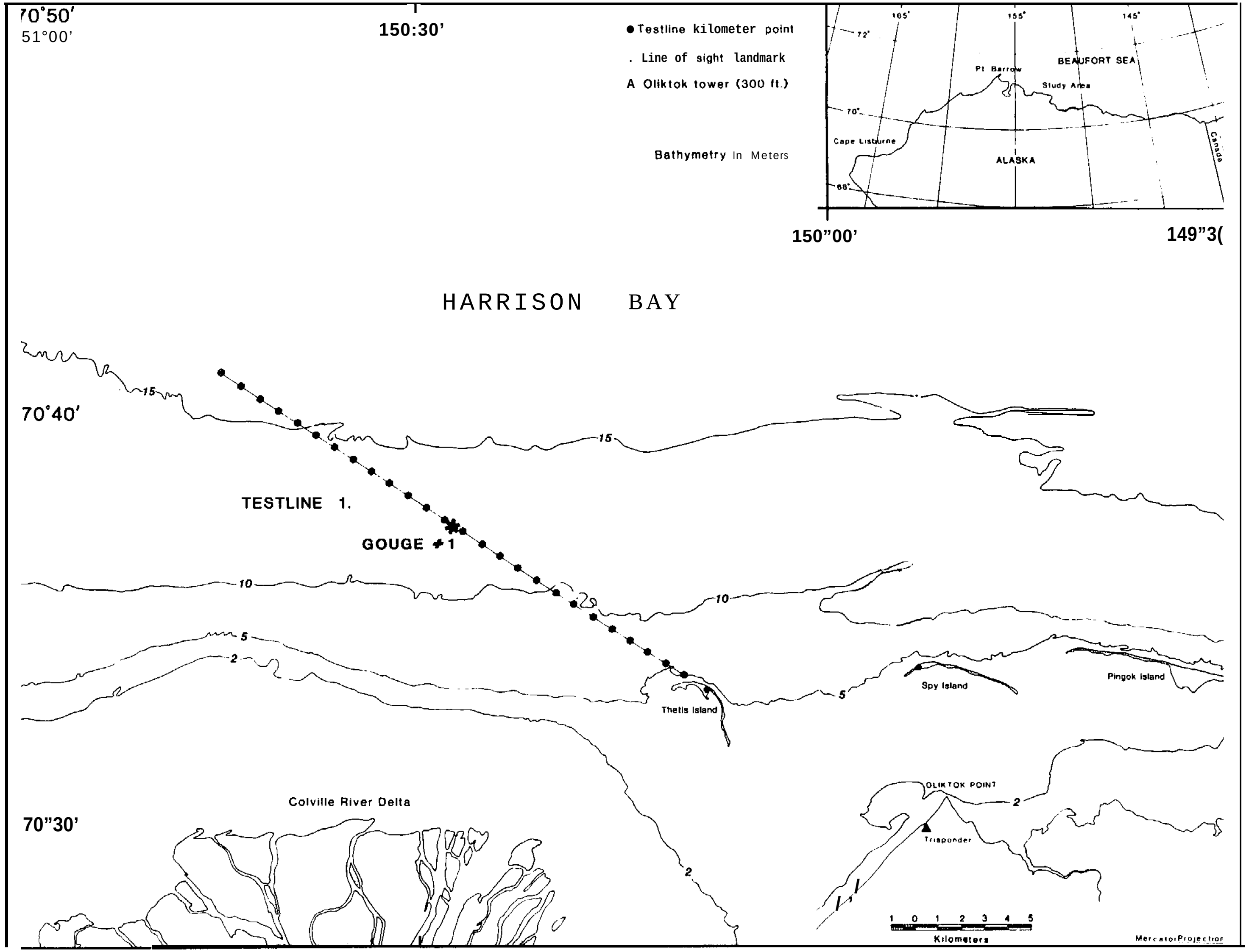


Figure 1. Location map of Gouge #1 and Test Line 1 in eastern Harrison Bay, Beaufort Sea, Alaska.

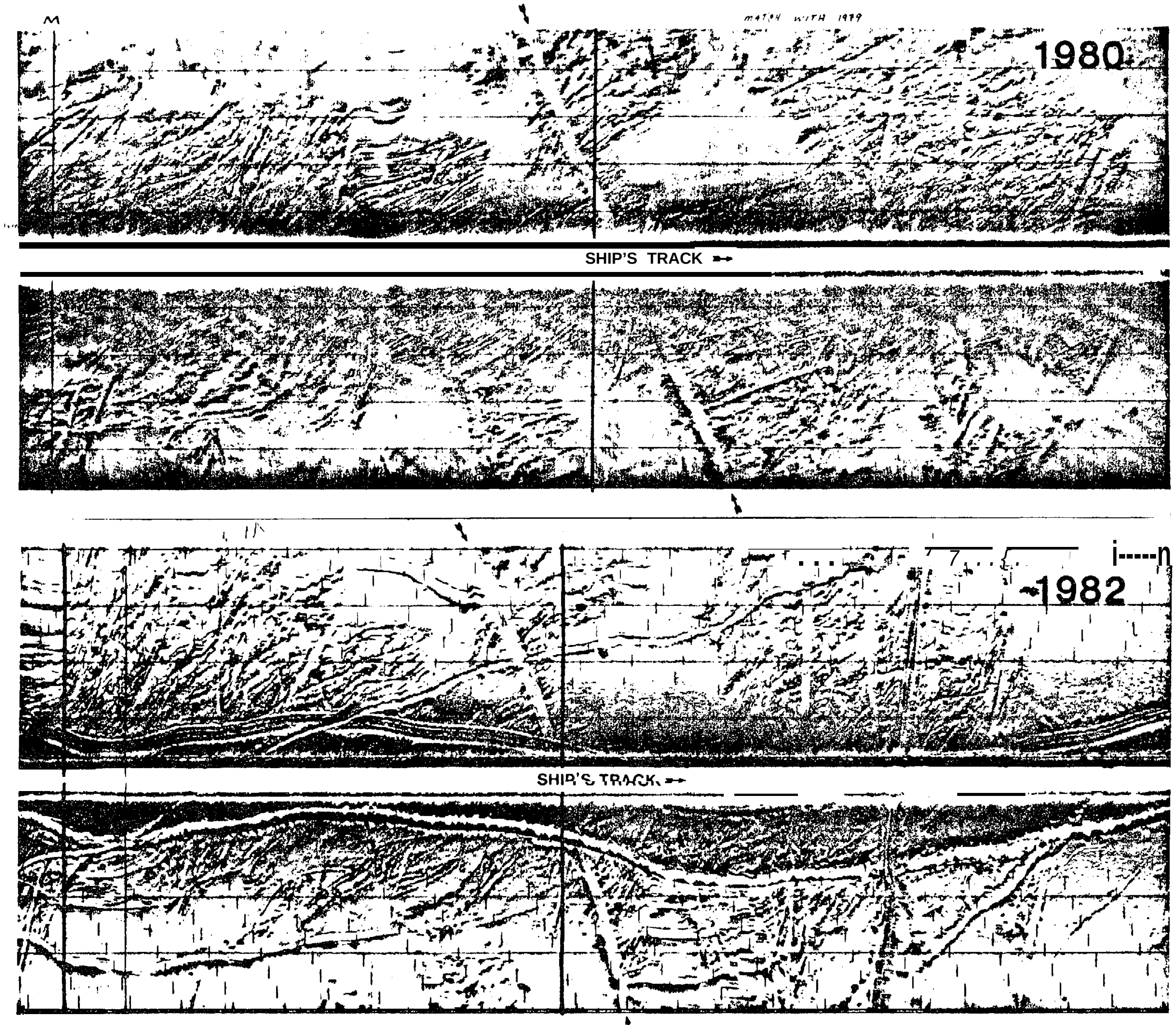
Gouge #1 formed during the winter of 1975/76 and trends roughly north/south. It lies in 13.5 meters of water, is 8 meters wide, and when it was first seen crossing Test Line 1 in the summer of 1976 it was 50 cm deep and had a flanking ridge 30 cm high as measured on a precision fathometer. The 1980 crossing of Gouge #1 on Test Line 1 is essentially identical to the 1976 crossing on the fathogram and sonargraph. When we reran Test Line 1 in 1982 there was no evidence of Gouge #1 on the fathogram although the gouge is still clearly visible on the sonargraph. Figure 2 shows that we crossed the gouge in almost exactly the same place in 1976, 1980 and 1982. The 1982 sonargraph shows a number of new gouges that formed since the 1980 crossing of Gouge #1. One of these gouges passes directly under the ship's track at Gouge #1. The area where this new gouge crosses Gouge #1 is the area studied in detail. In this area divers reported up to 60 cm of relief on the gouge in 1982. The divers also reported cracks along the crest of the flanking ridge. A crossing of Gouge #1 a few meters north of Test Line 1 in 1982 has a fathogram identical to those seen in 1976 and 1980.

Diving operations on Gouge #1 in 1982 consisted of collection of 4 cores in a 10 meter area around the pinger placed in 1980 and bottom observations over the same area. Three cores (Cores 2,4, and 5) were collected inside the gouge and one core was collected outside the gouge beyond the flanking ridge (Core 3) (Fig. 3). Using divers to collect the cores resulted in good positioning of the cores relative to each other and to the gouge. Divers collected the cores using 2 different methods: Cores 2 and 3 were collected using a 18 kilogram sliding hammer to drive one meter lengths of 7.5 cm diameter plastic core tube as far as possible into the bottom, and Cores 4 and 5 were collected by pushing 7.5 cm diameter core tubes into the bottom as far as possible by hand. Core 2 was driven in to 50 cm depth fairly easily, but after that could be driven no further. Core 3, outside of the flanking ridge of Gouge #1, was driven in to its full length, approximately 90 cm, with very little effort, unfortunately some of the sediment leaked out when the core barrel was removed from the bottom.

The cores were sealed in the field and shipped back to the lab for analysis. Core analysis consisted of splitting the core barrel and making a detailed description of the sediments in the core. Grain size was determined by comparing the core sediments to a grain size card containing sediments of known size. A slab 1 cm thick was cut from half of the split core and x-rayed. A resin peel of the slab was then made, using the method described by Burger et al. (1969). Unfortunately, most of the sediments in the cores contained a high percentage of mud, so the resins did not penetrate, and very little structure was preserved in the resin peels.

Figure 4 shows the results of of the lab analysis. The 4 cores are predominately mottled sandy mud. There is a high degree of lateral variability in the cores, the only units that can be correlated between the cores is the soupy grey-green sandy mud found at the tops of Cores 2,4, and 5. All of the cores have a number of sharp, irregular unconformities. There is usually a significant change in grain size across the unconformity. Most of the bedding found in the cores is irregular, notable exceptions are Core 2 from 30 to 35 cm where there is bedded sand and mud and Core 5 from 3 to 13 cm where there are clean ripple crossbedded sands. An unusual feature in the cores is in the areas of contorted sands and muds, these contorted beds are almost a midpoint between true mottled sediment and undisturbed sediments. Areas that exhibit this structure are Core 2 from 35 to 50 cm, Core 3 from 28 to 37 cm, and Core 4 from 20 to 23 cm. There is little hard evidence of biological activity in the cores. There are a few scattered

Figure 2. Side-scanning monographs of Test Line 1 crossing Gouge #1 in 1976, 1980, and 1982. Gouge #1, marked by arrows, is easy to identify on the 3 monographs. The number of new gouges that formed in the area between 1976 and 1982 is a graphic example of the high rate of reworking of seafloor sediments by ice gouging. The scale is the same for all 3 monographs.



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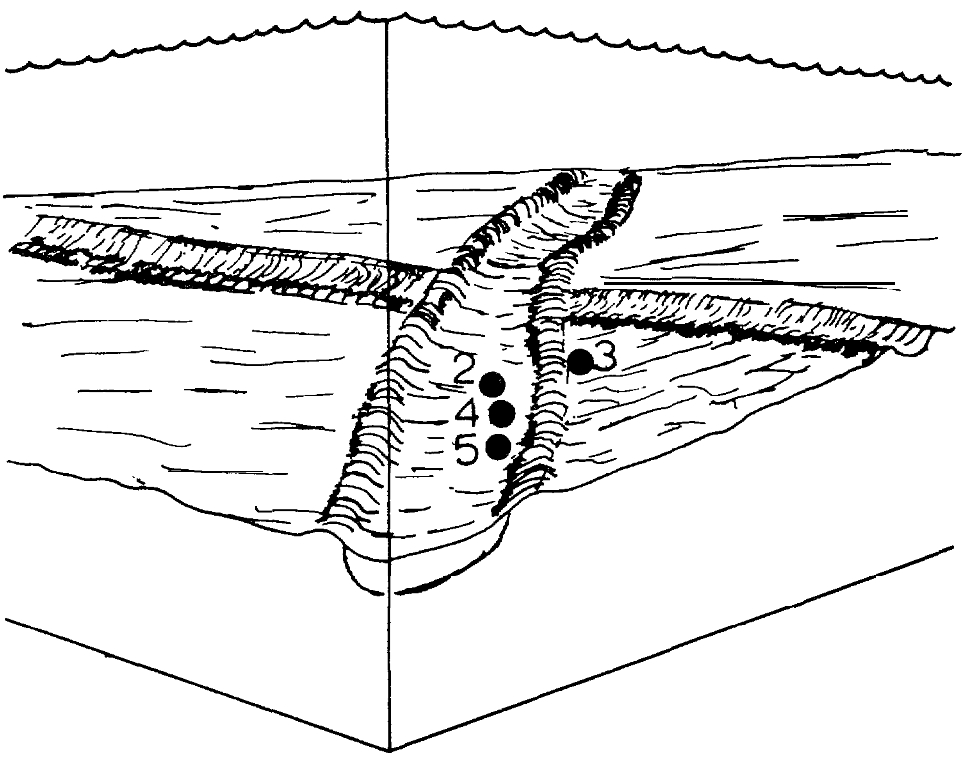

Figure 3. An oblique view of Gouge # 1, **showing the positions of the 4 cores** collected by divers. Cores 2,4, and 5 **were collected in the gouge trough and** Core 3 was collected outside the gouge **beyond the flanking ridge. The width** of Gouge #1 is about 8 meters, and the **cores were all collected over an area** of less than 10 meters.

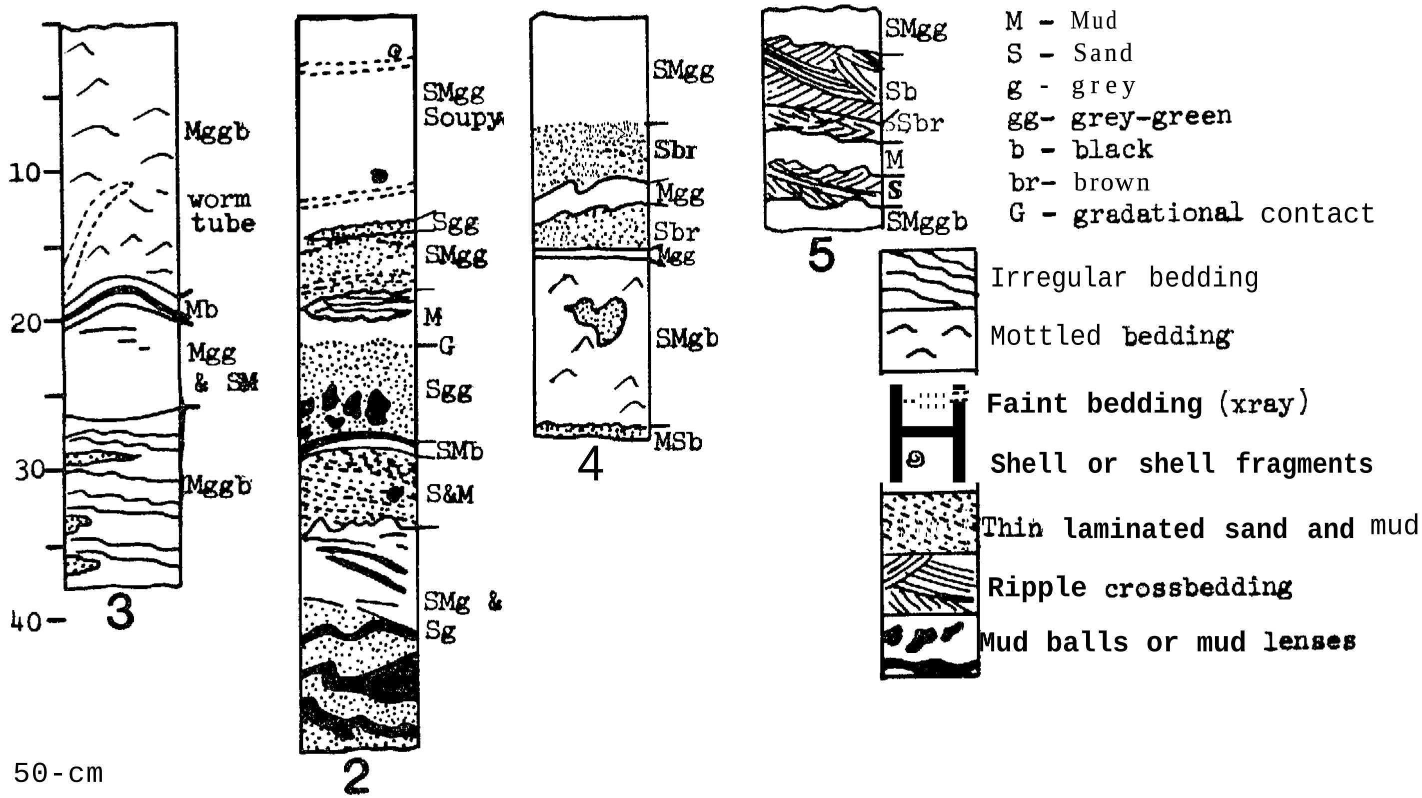

Figure 4. Sketches of the 4 cores collected at Gouge #1. The cores are a mixture of mottled sandy mud and clean sands. The only units that can be correlated are the grey-green sandy muds at the tops of Cores 2,4, and 5, the 3 cores that were collected in the gouge.

bivalves in Core 2 and a well preserved burrow in Core 3 from 10 to 18 cm. The cores were not examined for microfauna.

DISCUSSION

Cores. The high lateral variability in the cores was not totally unexpected but it was a bit surprising. Barnes et al. (1979) report high lateral variability in 3 vibracores taken within 40 meters of each other in an area very near Gouge #1 . These cores showed similar deposistional units (alternating beds of slightly sandy muds and well laminated clean sands), but core stratigraphy could not be correlated from one core to another. However, there was no way to determine if all three cores were collected in the same gouge, so the cores probably reflect fill from different gouge events. By using diving techniques on Gouge 1 we were able to assure that the samples were all collected on the same gouge. Since the cores were all collected on the same gouge, the sediments in the cores should have similar depositional histories, and sediments should correlate from core to core. The soupy grey-green sandy mud at the top of Cores 2,4, and 5 is the only unit that can be correlated from core to core, and probably represents all of the sediment that has collected in Gouge #1 since it formed. This mud was so soupy that it flowed out as a smooth even cover across the bottom of the gouge. It was easy for divers to push their hands up to 40 cm deep through this soupy layer and feel the rough relief of the original gouge floor underneath. Therefore the difference in the amount of this grey-green sandy mud in Cores 2,4, and 5 probably represents roughness of the original gouge floor rather than differential sedimentation in the gouge. Assuming that the grey-green sandy mud represents all of the gouge fill collected since Gouge #1 formed, and that it is 5 to 40 cm deep, as reported by divers, the rate of sedimentation in the gouge trough is at least 1 to 2 cm per year. This gouge fill contains a high percentage of interstitial water and considerable compression of the gouge fill may occur as more sediment is added to the gouge.

If the grey-green sandy mud represents all of the fill in Gouge #1, everything below this mud in Cores 2,4, and 5 and all of Core 3 represents pre-Gouge #1 sedimentation, but still represents gouge fill. (A discussion of sediment reworking by ice gouging and sedimentation rate follows below.) During the formation of Gouge #1 the keel forming the gouge exerted a shear stress on the sediments below it. This shear stress could have caused the contorted sediments that are found in the cores. Highly contorted beds below less contorted beds, as seen in the bottom of Core 2 ,for example, could result from distortion by ice keels previous to the deposition of the less contorted beds above. In the extreme case, where the shear stress is very great, or where the bottom has been reworked by a number of ice keels, the contorted bedding could actually change into mottled sediments. Alternately, Barnes and Reimnitz (1979) report high rates of biological activity in ice gouge fill that could result in mottling.

Filling of Ice Gouges. Barnes and Reimnitz (1979) report a change in sea bed morphology from 1977 to 1978 along Test Line 1 out to a depth of 13 meters. This change in morphology was the result of strong fall storms with large waves that reworked the sediments on the shallow shelf and erased all of the ice gouges on the inner part of Test Line 1 and replaced them with hydraulic formed features. This study shows that gouge filling can be a sudden, cataclysmic event, when large area of the shelf are wiped clean of gouges at one time. It seems strange that Barnes and Reimnitz could trace the change in sea bed morpholgy out to 13 meters along Test Line 1 and yet there is little evidence of hydraulic reworking of sediments at Gouge #1 at 13.5 meter water depth. If the ripple cross bedded sediments in Core 5 represent pre-Gouge 1 deposition they could not have formed during the 1977 storm. It is hard to believe that this ripple bedded sand could have been formed at the site of Core 5 and no ripple bedding shows up in any of the other cores, all collected within 10 meters of Core 5. I think the explanation is that the ripple bedded sand in Core 5 was deposited before the formation of Gouge #1, and Gouge #1 wa below the wave base for the 1977 fall storm, so it didn't fill in with materials transported by tractive currents. However, the presence of clean sand beds in all of the cores is evidence that tractive currents are active in the area around Gouge #1 at least part of the time.

Ice gouges fill by a combination of tractive currents moving sand during storms, and by settling of muds out of suspension during calm periods. The bottom of Core 2, from 33 to 55 cm, probably records a number of storm events with sand deposition and intervening quiet periods with deposition of sandy muds. Repeated gouging of the area has contorted the sand and mud beds.

Ice Gouging and Sedimentation Rates. There is a 3 meter thick sheet of Holocene marine sediments on the shelf along Test Line 1 (Barnes and Reimnitz, 1979). The sediment accumulation rate on the shelf is estimated to be 6 cm per 100 years (Reimnitz et al., 1977), roughly 20 to 30 times less than the infilling rate measured on Gouge #1. This suggests that most of the sediment that goes to fill in ice gouges is reworked local sediment. The most logical source of sediment to fill a gouge is the flanking ridge on either side of it. Reimnitz and Barnes (1974), from observations made during 40 dives on ice gouges, report that the flanking ridges of ice gouges have steep side slopes, up to the angle of repose, and are highly unstable compared to the surrounding seafloor. (Unstable, as used here, means that the sediments are resting at a high angle and are not as consolidated as as the surrounding sea floor - Erk Reimnitz, personnal communication.) This sediment would be readily reworked by hydraulic or biological processes, and it wouldn't have to be transported far to fill in the gouge. New sediment settling out from suspension or brought out to the area by tractive currents associated with storms would be mixed in with these older reworked sediments.

Rearic (in preparation) estimates that the whole sea floor along Test Line 1 is reworked to an average depth of 20 cm every 50 to 100 years, assuming proportional replowing. In this time 3 to 6 cm of new sediment is deposited on the shelf. Thus , all the new sediment being deposited on the shelf is being mixed in with older, reworked sediments by the ice gouging process, and all of the shelf should consist of ice gouged sediments. Barnes and Reimnitz (1979) suggest that the Holocene marine deposits on the shelf consist of criss-crossing "shoestring deposits" of gouge fill, since the sediments are reworked by ice gouging and preferrentially fill in the low gouge troughs. This is a somewhat simplistic view of what the shelf deposits would actually look like. The sediment reworking rates are so rapid compared to the sediment accumulation rate that the "shoestring deposits" would be destroyed before they could be preserved. For example, 250 meters of Gouge #1 are visible along Test Line 1 in 1980 and 1982 (Fig. 2). Between 1980 and 1982 three gouges have cut across Gouge #1, disrupting a total width of about 20 meters of the 250 meters of Gouge #1 that we can see. This has effectively snipped the "shoestring deposits" of Gouge #1 into several short pieces, and disrupted the fill that has collected in the gouge trough. As time passes Gouge 1 will be cut by more and more gouges so the chances of preservation of any significant part of Gouge #1 (or any other gouge) will be extremely small. It is possible that extremely deep gouge events would be preserved as "shoestring deposits" however, The shelf in an ice dominated environment consists of an extremely complex set of sediments that exhibit a very high degree of lateral variability. Clean sand beds deposited by storms may be interbedded with muds deposited during quiet periods, but these beds will be disrupted and contorted by subsequent ice gouging. There are a great number of unconformities in the sediments caused by the passage of ice keels, and it is very hard to correlate bedding in ice gouge terrain, even over distances of a few meters.

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