ATTACHMENT J

SIXTY-METER-DEEP PRESSURE-RIDGE KEELS IN THE ARCTIC OCEAN SUGGESTED FROM GEOLOGICAL EVIDENCE

by

Erk Reimnitz, Peter W. Barnes, and R. Lawrence Phillips

Abstract

Ice gouge patterns on the Alaskan Beaufort Sea shelf extend from the coast seaward to water depths of 64 m. The maximum measured draft of sea ice in the Arctic Ocean is only 47 m. Thus the numerous gouges seaward of the 47 m isobath might be relict, cut during times of lower sealevel many thousand years ago. Sedimentation rates along the shelf break are very low, and a rain of particles settling vertically in a quiet environment on these bedforms would not obliterate them soon.

Several lines of evidence suggest, however, that the gouges at their seaward limit of occurrence are modern features. Continuous, 380-day current records at a representative site show that the environment is dynamic, with long-period current pulses capable of transporting medium to coarse sand as bedload and fine sand in intermittent suspension. Added to hydraulic reworking are the effects of a rich benthic fauna, reworking the upper 20 cm of sediment and providing sedimentary particles for current transport. The seaward limit of the ice gouged shelf surface does not follow a water depth pattern consistent with a relict origin, warped by known vertical crustal movement from tectonism and isostatic rebound after deglaciation. This depth limit instead shows variations one would expect from an interaction of sporadic ice reworking to 64 m depth during the last 200 years, and continuous reworking by currents and organisms. This interpretation **has** important implications for offshore petroleum development.

Introduction

Numerous efforts have been made during the last two decades to determine the ice thickness distribution in the Arctic Ocean, and in particular to learn the keel depth of the largest modern pressure ridges. With the discovery of oil and gas in the arctic offshore, and the trend to extend exploration into deeper water and increasing distance from shore, knowledge of the maximum ice thickness on the continental shelf is becoming increasingly important.

Various approaches have been used to obtain keel depth data in the Arctic, but as yet no satisfactory technique for water depths of less than 100 m exists. In the deep sea, upward-looking sonar profiles obtained from submarines are nearly ideal for measuring two-dimensional under-ice profiles along single tracks. One 3,900 km long profile from an area northeast of Greenland, for example, has been analyzed by Wadhams (1977), who reported 44 ridge keels between 30 and 40 m, and one slightly over 40 m deep. Other data sets have been reported on and the deepest keel measured by this technique to date is 47 m (Lyons, 1967). Laser profiles of ice surface relief, obtained by aircraft, together with established ratios between sail height and keel depths of pressure ridges, give an estimate of under-ice relief. In one application the two types of profiles were used together (Wadhams, 1981).

Attempts of applying the above techniques to continental shelves, however, face two serious problems: a) The shelf is the boundary between the moving arctic ice pack and the continent, and resists its pressures, resulting in bigger and more numerous ridges than over the deep basin (Tucker, 1981). These ridges and the shallow water prevent access by submarines, b) Application of the ratio between sail height and keel depths requires that ice ridges be free-floating and in isostatic equilibrium, which is not necessarily the case on the continental shelf.

For continental shelves, virtually all public data on ridge keel configuration stems from spot measurements made with horizontally held sonar transducers lowered through the ice adjacent to ridges, and from cores of ridges (for example, Weeks et al., 1971; Kovacs, 1976). Because these techniques are time-consuming, the depth of only few ride keels have been determined by such methods. Fixed upward-looking sonar devices have been used with limited success in several applications to record under-ice relief and movement, but any data so obtained is not public.

Where the seafloor is sediment covered and is shallow enough to intercept the deepest keels, these mark their paths by drawing patterns of ice gouges. Such records, however, are not permanent, because of various kinds of sedimentary and erosive processes. Distinctive internal sedimentary structures, bedding discontinuities, and non-sequential ages in sediment cores of fomerly ice gouged terrane may hold a record of sediment disruption and mixing by ice keels, but on present shelves such records cannot be deciphered and dated with available techniques. Attempts to interpret the history of deep keels from the geologic record therefore are restricted to gouges on the shelf surface, and are limited by our understanding of processes that erase shelf relief. This report is an attempt to interpret the age of deep-water gouges seen on the Alaskan Arctic shelf in light of these processes.

Background Information

The crisscrossing patterns drawn by ice keels on the Beaufort Sea Shelf have been mapped and interpreted since the introduction of side scan sonar techniques to marine geological studies of the Arctic in 1970. The existence of gouges in water depths greater than 47 m was recognized, and attributed to the past action of glacial ice, or to sea ice gouging at times of lower sea level 10-12 thousand years ago (Kovacs, 1972; Pelletier and Shearer, 1972; Hnatiuk and Brown, 1977; Lewis et al., 1982). Pelletier and Shearer (1972) based their interpretation on a sedimentation rate of 1 m yr , by vertical settling of particles, resulting in an even blanket draped over ridge crests and gouge floors alike. According to this model, 12 to 16 m of sediment is required to completely bury a gouge with 3 to 4 m original relief (Pelletier and Shearer, 1972). Reimnitz and Barnes (1974) cast doubt upon this model and upon the presumed relict nature of gouges along the shelf edge. In Alaska they felt that gouges can be traced to 75 m (Reimnitz, et al. 1972), or to 100 m or deeper (Reimnitz and Barnes, 1974). Reimnitz et al. (1977) restated their doubt of the presumed old deep-water gouges in the Beaufort Sea with new data from the Chukchi Sea, and in light of high current velocities measured near the shelf edge. Lewis (1977) conducted a thorough statistical evaluation of ice gouge measurements in the Canadian Beaufort Sea, and proposed that the break in ice gouge parameters he observes at 50 m depth marks the outer limit of modern "ice scouring." But his model again assumes uniform blanketing of seafloor relief by sediment. Wadhams (1980) supported this concept, and stated that gouges at least 1000 years old are still visible on the shelf surface today. For this reason, he believed that knowledge of the rate of shelf submergence (transgression) within the last few thousand years is important for relating the ice gouge distribution to that of keel depths in the Arctic.

Methods of study

The seaward margin of the ice-gouged shelf in the Beaufort Sea from Point Barrow to Barter Island was determined from 10 available survey tracks (Fig. 1). Along 4 of these tracks, both side scan sonar and precision fathometer were operated. The side scan records show identifiable gouges when gouges are no longer discernible on the fathometer records. The maximum water depth to which ice gouge relief can be recognized using fathometer records only, therefore is about 10 m shallower than when both systems were operated together.

The seaward margin of the ice gouged shelf surface

The intensity of ice gouging decreases from the midshelf toward the outer shelf and with increasing water depth. Various ice gouge parameters, such as maximum gouge depth, ridge height, total gouge relief, and 'gouge intensity show peaks at about 38 m water depths, and decrease to zero at about 65 m (Barnes, et ale, in press). Along the 10 available survey tracks, features clearly identifiable as ice gouges are seen to depths between 49 and 64 m. At these water depths the relief of ice gouges is somehat subdued, probably due to their advanced stages of sediment filling, compared to those of the mid-shelf. Furthermore, almost all transects at these depths are associated with isobath-parallel rythmic bedforms, spaced between 3 and 10 m apart and with amplitudes of less than 20 cm. We suspect that these bedforms are produced by currents flowing parallel to the shelf edge. Figures 2A and B are side scan sonar example records of the outer limit of ice gouges obtained near Barter Island. Clearly defined ice gouges are present at 56 m water depths on Fig. 2A while Fig. 2B shows signs of current-produced bedforms with indistinct traces of gouges only 1200 m to seaward. A tracing of the fathometer record obtained along the same survey track, but shifted slightly upslope (Fig. 2C), demonstrates the change from ragged ice gouge morphology to smoother bottom farther seaward.

Relief-leveling processes at the shelf edge

Sedimentary processes affecting ice gouge relief along the outer shelf include sedimentation, winnowing by currents, and the activities of bottom dwellers. The processes will be discussed in this order.

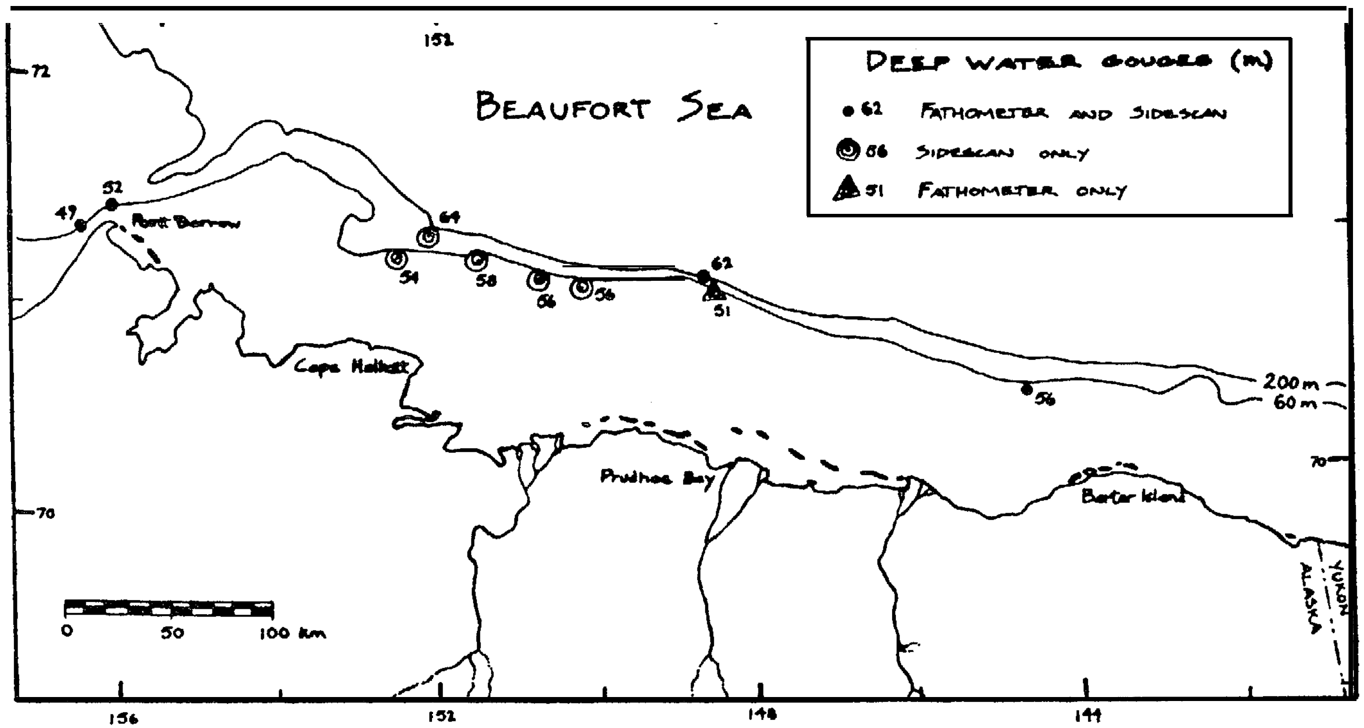

Figure 1. Map of study area, roughly defining the shelf break between the 60 and 200 m isobaths, and points marking the greatest water depths to which ice gouges can be traced with different combination of survey tools.

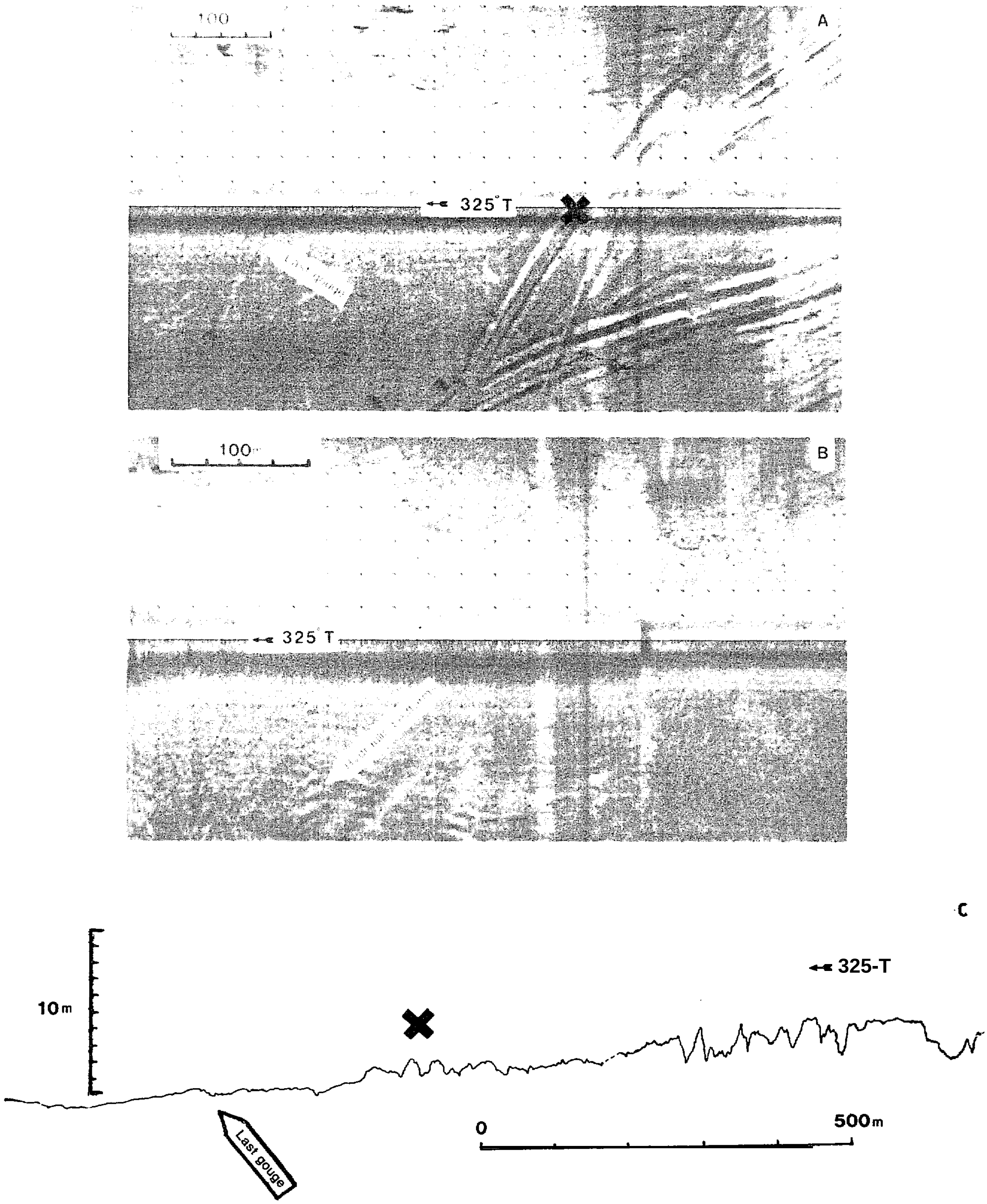

Figure 2.(A&B) Adjoining segments of monographs recorded near the shelf edge crossing northwest of Barter Island. The 'last gouge' is at a water depth of 56 m in 2A, signs of hydraulic bedforms with traces of possible gouges are recorded about one km farther seaward in 2B. (C) Tracing of the fathometer record obtained along with the sonograph, with the two corresponding gouges marked.

Sedimentation. - The outer continents 1 shelf of the Beaufort Sea has been an area of little or no sedimentation during Holocene time. Supporting evidence for this interpretation was summarized by Reimnitz et al. (1982) , who argued against Dinter's (1982) model of a wedge of Holocene marine muds thickening from the midshelf seaward to a maximum thickness of 45 m at the shelf edge.

Barnes and Reimnitz (1974) defined a "shelf edge sediment facies" between 50 and 130 m water depths, characterized as a hi-modal, poorly sorted, gravelly mud with high textural variability. The mean particle size of surface sediments in this facies is medium grain sand to silt, but gravel percentages of 60% (Barnes and Reimnitz, 1974) and nearly 100% (Reimnitz et al., 1982) canbe found. Foraminifera from a box core, raised from a depth of 123 m (70°57'N. 14°06'W.), were studiedby Ronald J. Echols. He assigned a paleo-depth of 15-35 m to a horizon 40 cm below the seafloor (written communication with Barnes, 1974). Two C^{14} whole-sample dates of sediment 2 cm and 10 cm below the surface at this site are 9,565 ± 215 yrs. and 14,980 ± 200 yrs HP, respectively. A relict age for the surface sediments of the outer shelf, particularly east of Prudhoe Bay, has also been indicated by the distribution of clay minerals (Naidu and Mowatt, 1983). Figure 3 shows typical bottom photos from a station at 53 m depth, showing the high textural variability over short distances common for ice gouged terrain. Numerous stalked anemones living here on the rocky substrate are suspension feeders, and their presence indicates an abundant supply of fine particulate matter is periodically transiting the area. The ice-rafted relict gravel along the shelf edge (Mowatt and Naidu, 1974; Rodeick, 1979; Barnes and Reimnitz, 1974) , suggests that little or no sediment has accreted during Holocene time. This is in line with the concept that the shelf-break surface generally serves only as a temporary resting place for sediment moving from terrigenous sources to ultimate depositional sites in deep marine environments (Southard and Stanley, 1976).

Winnowing by Currents.- The shelf edge in the study area lies under the influence of the "Beaufort Current," in an energetic enviroment of low-frequency, reciprocating motion with a period of 3 to 10 days (Aagaard, in press) . The flow direction of current pulses is parallel to local isobaths, with easterly pulses strongest. At the 60 m isobath seaward of Prudhoe Bay, Aagaard maintained a double-current-meter mooring, with instruments 10 m and 20 m above the shelf surface, for a period of 380 days. During this period, current pulses of up to 70 cm sec^{-1} were recorded.

One can extrapolate from measured currents 10 m off the seafloor to the seabed itself thereby assessing their effects on sediment movement, following the theoretical guidelines summarized by Komar (1976). To do this, several assumptions must be made. Firstly, knowledge of seabed roughness is needed for calculating the boundary shear stress. Not knowing the actual bed roughness, we will assume a flat bed, where only the sediment grainsize causes roughness. For this case the roughness factor z_0 is given by

$$z_0 = \frac{D}{30}$$

where D is the grain diameter. An increase in roughness, such as from burrows, from ripples, and especially from ice gouges, enhances turbulence and

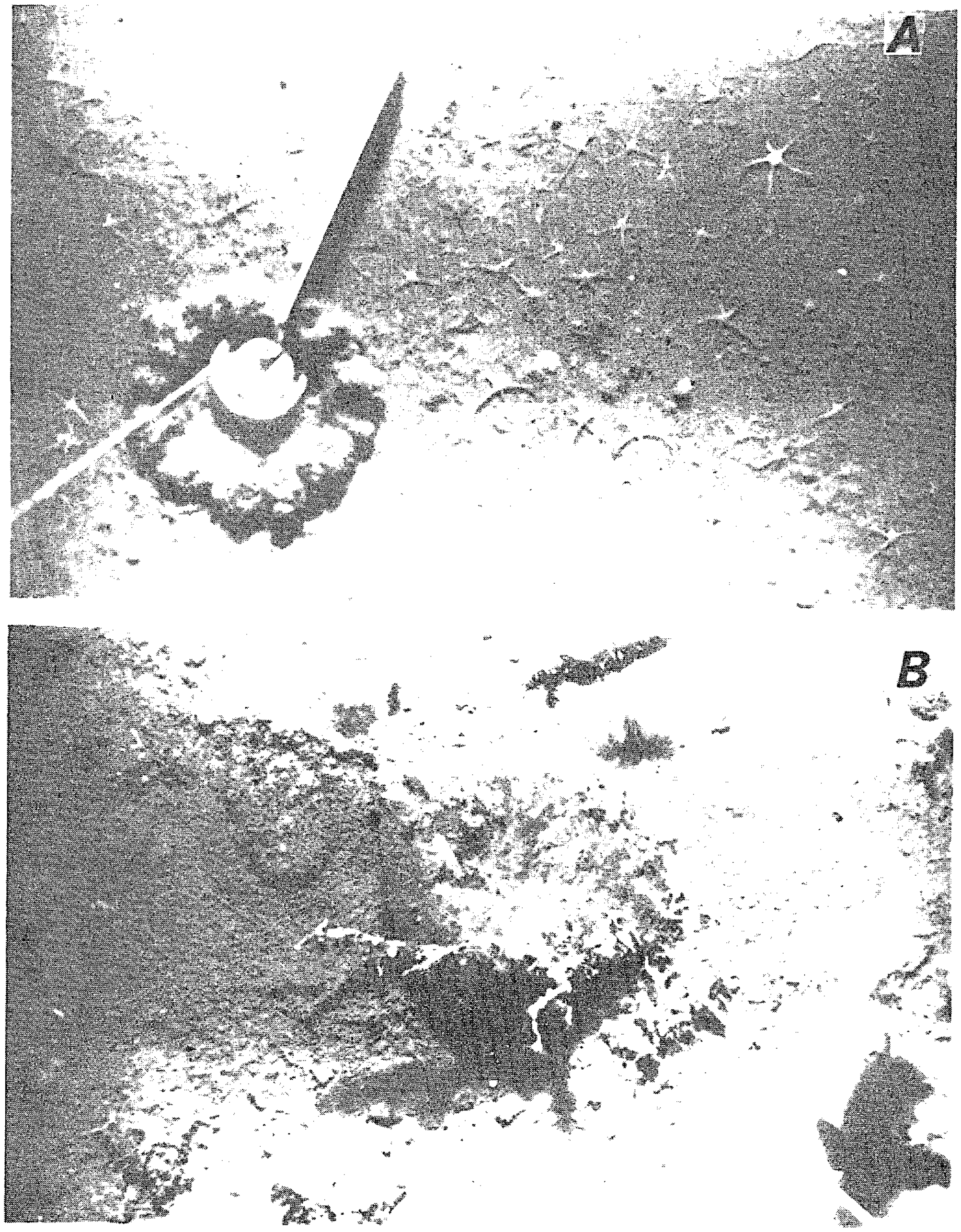

Figure 3. Two seafloor photographs taken a short distance apart near the shelf edge at a depth of 53 m (U.S.G.S. sta. 58, courtesy of A.G. Carey, Jr.). (A) Soft mud ponded within the trough of an ice gouge, with numerous brittle stars, (B) Pebbles and cobbles with attached organisms protruding through a thin film of mud on the crest of a ridge flanking an ice gouge.

boundary shear stress, thereby aiding sediment movement. The seabed on the outer Beaufort Sea shelf certainly is rougher than a "flat bed" and the stated assumption therefore makes our assessment very conservative.

Secondly, we assume that the instrument moored 10 m above the bottom is within the logarithmic layer, where currents "feel" and are influenced by bottom drag. In reality, this layer probably is only 2 to 3 m thick, and thus we are again underestimating the stress available at the seabed.

Finally, we assume that silt and sand size particles lack cohesion, and are not held to the seafloor by any force other than gravity. These particle sizes predomimte in the water depths of interest here, and make this is a reasonable assumption.

Now the following equation canbe used to solve for the frictional velocity U^*,

$$U = \frac{u^*}{K} \ln \frac{}{0}$$

which is measure of the stress available for moving sediment at the seabed where K = 0.4 (von Karman's constant) and z = 1000 cm (current meter height) and U is the current velocity observed at the current meter.

The critical entrainment velocities, at which grain movement is initiated (U* critical), taken from a recent compilation of laboratory tests (Miller, et al., 1977) are shown on Table I. This table compares these critial velocites with frictional velocities computed for several sediment grain sizes and current velocities likely to be encountered at 60 m water depth. The table suggests that grain movement in silt occurs when currents at 10 m from the seaflor are above 30 cm sec^{-1}, and medium sand will start moving when currents are between 50 and 60 cm sec^{-1} still below the measured current velocities. Thus, even with our generally conservative assumptions, sand and silts must be routinely in motion along the outer shelf. The higher speed pulses of 70 cm sec^{-1} could move even coarser material than considered in Table 1.

Activities of Bottom Dwellers: The effects of a benthic community on the elimination of bedforms can not be quantified, but probably is substantial along the shelf edge in the Beaufort Sea. Newell, et al., (1981) discuss recent investigations pertinent to sediment entrainment by currents. They conclude that "Benthic organisms play a significant role in modifying the conditions for sediment entrainment by: 1) altering the individual particle characteristics for entrainment; 2) changing the bulk characteristics of the sediments, such as its permeability; and 3) varying the boundary properties of the flow by altering the surface roughness of the bed." According to experiments, surface tracks made by benthic organisms double the boundary roughness and decrease the critical entrainment velocity by 20%. A sampling transect crossing from seafloor areas dominated by suspension feeders to areas extensively burrowed by surface deposit feeders, showed that the porewater content of the upper 5 cm of sediment increased from 30% to 70% (Newell, et al., 1981). This type of benthic-community related variability in sediment

TABLE I

Movement of grains is likely for values within the box

D (cm)	U* critical (cm see-’)	U at 10 m (cm sec^{-1})				
		30	40	50	60	70
		U* calculated (cm sec^{-1})				
5×10^{-2}	f1.6	0.9	1.2	1.5	1.8	2.1
1×10^{-2}	f1.0	0.8	1.1	1.5	1.6	1.9
1×10^{-3}	f0.8	0.7	0.9	1.2	1.4	1.6

characteristics probably is similar to that shown in the two bottom photographs near the shelf edge in the Beaufort Sea (Figs. 3A, B) .

Radiographs of box cores raised from the shelf edge in the Beaufort Sea indicate that the upper 5 to 20 cm of sediments are extremely bioturbated (Barnes and Reimnitz, 1974). These findings are supported by studies of the fauna in the Beaufort Sea (Carey, et al., 1974) , which found the biomass maximum at the shelf break off Prudhoe Bay. Therefore there must be significant effects of the intensive benthic activity in the upper 20 cm of surficial sediments on transport by currents. In the presence of gravel, the combined effects of animals and currents over long time periods should result in a winnowing of fines and gravel enrichment, forming the lag deposit commonly observed on the outer shelf.

Besides the effects of bottom-dwelling organisms on sediments entrainment by currents, their burrowing and ploughing activity must be significant in redistributing sediments, especially in areas of steep ice gouge relief. Diving observations have shown that the effects of benthic activity on the aging of gouges is noticeable over short time periods (Reimnitz and Barnes, 1974). Time lapse photograph of biologic activity on the California shelf by F. H. Nichols (personal communication, 1983) demonstrate the rapid rate at which this activity reshapes the seafloor. The site, at depth of 93 m off the Russian River (38°30′ N) , has little relief compared to an ice gouged shelf. At this site the activity of organisms (starfish, brittle stars, and heart urchins) , roughened the surface over a period of several days. The resulting microrelief is subsequently smoothed over again by waves or current. Organisms then again reshaped the surface entirely within two days. Nichols (Personal communication, 1983) estimates that the upper 5 cm of the sediment blanket is totally reworked by organisms every one or two months.

Discussion

Microrelief produced by ice gouging can be traced clearly to depths between 51 and 64 m on the Alaskan Beaufort Sea shelf , and to 49-52 m depth in the Chukchi Sea near Barrow. This interpretation is different from that by Reimnitz et al. (1972) , who thought they could trace ice gouge relief on fathograms to water depths of more than 100 m. This is also in part a reinterpretation of the work by Reimnitz and Barnes (1974): linear, parallel, and rythmic features along the shelf edge between longitudes W 150 and 153, were originally classified as probable gouges. These patterns, seen on all of our monographs seaward of unquestionable ice gouge patterns, now are considered current-produced bedforms.

Let us assume that ice gouges between 47 m (the deepest observed ice keel), and 64 m (the depth at which available **data puts the deep-water limit** of ice gouges) , are relict forms that have been preserved for 10,000 years or 10 nger. This raises the question, why gouges do not exist beyond the shelf edge to greater depths? We have no reason to believe that the sea ice regime in the Arctic Ocean was very different at the close of Wisconsin time than that of today. Only sea level was about 80 m lower (Forbes, 1980). Given these conditions, the deep-water limit of ice gouges should lie at over 120 m depth, rather than at 64 m (Fig. 4). Most workers would agree, however, that glacial ice with much deeper draft than that of normal sea ice, was calving into the Beaufort Sea Gyre at that time. In northern Baffin Bay, a grounded iceberg was recently sighted at a water depth of 450 m (John Lewis, oral communication, 1982). Thus, given the presence of glacial ice together with lower sea level at the end of Wisconsin time, one would expect to find ice gouges on the continental slope to water depths of at least 500 m. Because no ice gouges exist, where according to the above arguments ice plowing must have occurred, such relief forms are not preserved for ten thousand years.

If ice gouges along the shelf edge were preserved for some 5,000 years, the configuration of the seaward ice gouge limit should reflect Holocene vertical crustal movement. Tectonic uplift seems to be occurring off Barter Island (Dinter, 1982). Uplift following the retreat of large glaciers seems to be occurring in the MacKenzie Bay east of our study area (Forbes, 1980) . Thus, the seaward limit of ice gouges should lie shallower in the eastern than in the western Beaufort Seas. Such trend is not observed. This limit in the Mackenzie regions lies between 80 m (Lewis, et al., 1982) and 82 m (Hantiuk and Brown, 1977). This is about 20 m deeper than in Alaskan waters and the reverse of the trend expected for relict gouges.

Gouges **near Point Barrow in the Chukchi Sea are up to 15 m shallower than in the J3eaufort Sea but do not follow a pattern that can be explained by vertical crustal movement. More data points are needed for a meaningful interpretation.** We believe that the current regime is probably more dynamic and the ice conditions less severe in the Barrow Canyon area than in the Beaufort Sea. Therefore the gouges at the deep water limit in that area are younger than those seen in the Beaufort Sea due to faster currents reworking.

Additional evidence for a relatively young age of deep-water gouges is seen in the central, topographically flat Chukchi Sea, where currents are stronger than in the Beaufort Sea. Here gouges have been traced to a depth of 58 m (Toimil, 1978), and individual furrows commonly are associated with

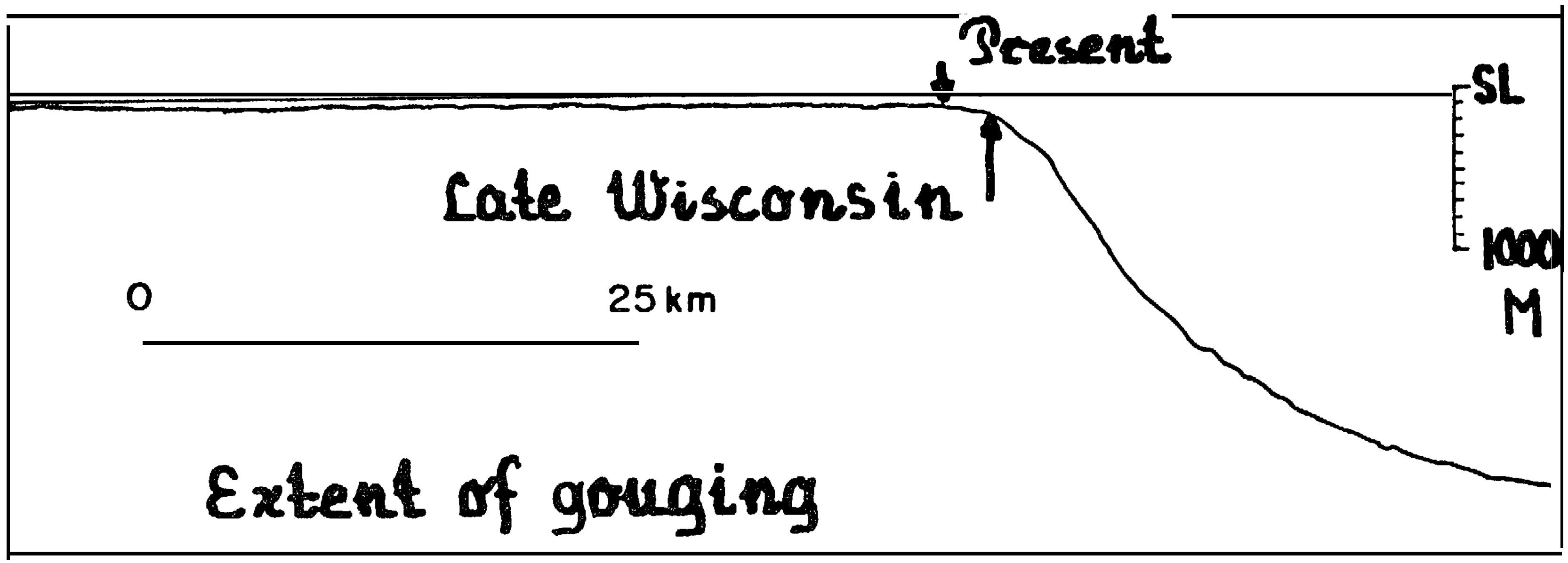

Figure 4. Profile of the middle shelf to lower continental slope north of Prudhoe Bay. Between the two arrows relict gouges could be expected, but none are present.

hydraulic b edf orms. Migration of apparently active ripples and sand waves would obliterate ice gouge relief. Also, ice gouge density is patchy in these deep waters, varying from featureless bottom to heavily gouged, in identical settings. This is inconsistent with a relict gouge surface undergoing gradual burial. Ice gouging during thousands of years of high sea level without active furrowing, should result in a more even distribution (Reimnitz, et al, *1977)* .

We believe that ice gouges seen in water deeper than 47 m, the deepest ice keel seen from submarines, result from recent still deeper keels with a return period of a few hundred years or less. This is not incompatible with ice keel data obtained from submarines in the deep sea and ridge distribution studies on Arctic shelves. Wadhams (1975) suggested that the coastal areas of the Arctic, such as the Beaufort Sea shelf region, probably have the deepest keels in the Arctic Ocean, since they have a combination of high ridge frequency and a preponderance of first year ridges. Higher density ice in first year ridges results in deeper keels for the same ridge height. Reimnitz and Barnes (1974) suggested that ridge and keel data are more representative of the quiet state of the ice than the catastrophic events during which the large ridges form. During ridge formation larger, but unstable ice masses may exist long enough for gouging to occur. Ice keels erode with the aging of ridges, thereby further biasing keel distribution date (Wadhams, 1977) . Following similar reasoning, Gaver and Jacobs (1982) pointed out that the submarine data from the Beaufort Sea were obtained during a relatively short period of time in only one year, allowing no assesment of month-to-month or season-to-season variability. They suggested that the extreme features may therefore not be well known.

Notwithstanding the above problems the latest attempts at predicting extreme keel depths from sea ice profiles were made by Wadhams (1982). Using reasonable values for calculating the required depth of pipeline burial in the Beaufort Sea, and extending from ice impacts along a line to impacts on an area, return periods of several hundred years can be shown for ice keeps deep enough to form the deepest gouges we mapped.

Summa ry

We have shown that relief-levelling processes along the Alaskan Beaufort Sea shelf break are dynamic, with current pulses capable of transporting coarse sand, and the additional action of a rich benthic fauna. Ice gouge relief on the outer shelf thus is obliterated by lateral sediment movement, and pending of sediments in local depressions. Filling of gouges by lateral grain motion is also indicated by the presence of rythmic hydraulic bedforms the presence of suspension feeders, and the lack of net sediment accretion along the shelf edge. This mode of ice gouge obliteration is very different from that postulated by Pelletier and Shearer (1972), in which ridges and troughs are blanketed by an even rain of particles settling out vertically from suspension and under which relief forms would preserve for thousands of years.

We believe that the record of ice gouges extending to as deep as 64 m in the Alaskan Beaufort Sea is also a record of ice keels to be encountered within a period of less than two hundred years.

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