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Coastal Bluff and Shoreface Comparison over 34 Years Indicates Large Supply of Erosion Products to Arctic Seas

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THEME 12: Gashydrates and Permafrost - Onshore and Offshore

Summary: Thermal abrasion, driven by a relatively warm ocean in contact with frozen, ice-rich sediments, is thought by some to be responsible for Arctic, long-term coastal retreat rates typically ranging from 2 to 6 m/yr. Considering that erosion is active only during the relatively calm three summer months, the adjusted annual rates are the highest on the globe. Coastal retreat also rapidly modifies the topography of the affected terrain, especially the inner shelf, introducing huge amounts of sediment into the sea. We present data from one Alaska site studied in detail, with results that to some extent are applicable to Eurasia. The coast of the area selected had been re-mapped, showing an average retreat rate of 7.5 m/yr for a 23-km-long segment centered at the site. A vessel carrying the sea-level datum from a tidal bench mark to the site ran a shore- and isobath-normal sounding transect from the coastal bluff over 3 km seaward, 34 yrs after the original survey. A profile comparison shows that from the shore to the 6-m isobath, the depth difference between the two profiles decreases, and demonstrates an overall landward shift of the steepest portion of the shoreface. The profile includes landward migrating longshore bars locally cresting above sea level at distances of 250 to 1000 m from 3 m high coastal bluffs.

In order to calculate what part of the shore-face deepening can be attributed to thaw settlement we used published ice-volume percentages from 610 drill-hole samples covering the upper 9 m of the coastal plain. Subtracting "excess ice" from the 1951 profile we found that from the shoreline to 1 m water depth only 14 % of the missing section can be attributed to thaw settlement. This demonstrates that mechanical energy, requiring lateral displacement of clastic detritus, is far more important than thermal energy for the landward shift of the arctic shoreface. If erosion terminated at the 6 m isobath to which deepening is indicated, a 6-m deep platform roughly 10 km wide would have formed during the last 1000 yrs. The lack of such platforms around the Arctic Ocean suggests that coastal erosion and shelf-profile modification extends deeper than to 6 m. The sediment so released exceeds that supplied by Alaskan rivers manyfold. Likewise in Siberia, sediment released by coastal erosion introduces at least as much material to the Laptev Sea as the huge Lena River.

INTRODUCTION

Erosion rates for vast stretches of circum-Arctic coastlines are among the highest on the globe. Long-term average rates along northern Siberia typically are 2-6 m/yr (ARE 1980), while local short-term rates may reach 45 m/yr. Similarly high average erosion rates occur along the Yukon Territory in Canada (FORBES & FROBEL 1985), and a large stretch of northern Alaska (REIMNITZ et al. 1988). Considering that erosion is active not during stormy winter periods but only during three summer months, the adjusted annual rates are truly the highest on earth, despite the commonly short fetches due to the presence of drifting ice. The high coastal retreat rates in arctic regions are generally attributed to processes of thermal erosion and thaw settlement (TOMIRDIARO 1975, NATIONAL RESEARCH COUNCIL, MARINE BOARD 1982), driven by the temperature difference between frozen sediments of surrounding coastal plains and the relatively warm sea. Thus thermal rather than physical energy would be the driving force. The cutting of a notch into coastal bluffs followed by their slumping is an obvious and easily understood process associated with coastal retreat. The required removal of erosion products from the relatively low-energy littoral zone and the depth to which erosion occurs, however, remain as more basic and important questions.

Where the rapidly advancing sea slices off the coastal plains above sea level around the Arctic Ocean, it must also shape the shelf surface to some water depth, or else the advance would stop. In areas of vertical crustal stability, the processes would have acted at least since sea level approached its present position about 5,000 years ago. This fact leads to considerations of the submerged part of the profile, as discussed by REIMNITZ et al. (1988), and shown in Figure 1. At the seaward limit of modern erosion, a break in slope should form, with the eroding surface landward representing the dynamic equilibrium profile. Wide, well-developed erosional platforms do not surround the Arctic basin near sea level. Therefore, submarine processes reaching deeper must be maintaining the typically concave-upward continental shelf profile in some type of equilibrium to greater depth than generally thought possible. But the precise mechanisms of profile maintenance remain obscure (REIMNITZ et al. 1988).

Some Russian scientists believe that thermal energy and related processes play the most important role in shaping the arctic shelf profile. TOMIRDIARO (1975) stated "The eastern Arctic seas are largely young Holocene bodies of water formed by thermo-abrasional processes." Thus the seafloor simply settles as ice-rich underlying sediments thaw, and therefore little lateral transport of clastic detritus is required. In fact, thaw settlement of the inner shelf should produce depositional basins for concurrent sediment supply, as speculated by HARPER (1978). In contrast, ARE (1980) and REIMNITZ et al. (1988) argue that mechanical energy is more important than thermal energy for the maintenance of the dynamic equilibrium profile. REIMNITZ et al. (1988)

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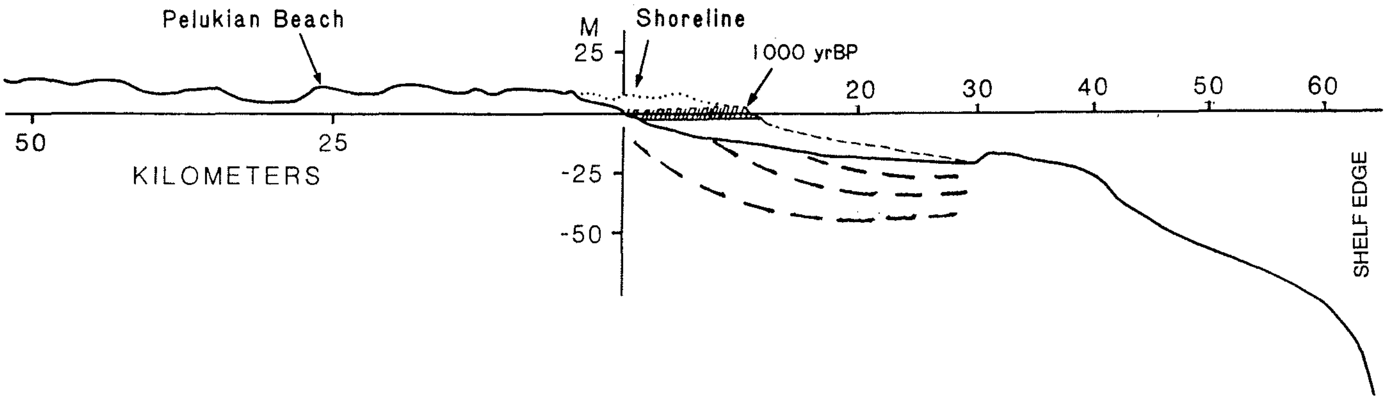

Fig. 1: Coastal-plain/shelf profile through the study area (approximate location indicated in Figure 2), showing the shoreline location 1,000 years ago, and where the corresponding shelf surface might have been at that time. Typical configuration of truncated sub-bottom seismic reflectors on Alaska shelf show erosion. The mid shelf hump in this section is atypical for Alaska. The consistent 7 m elevation of the linear belt of Pelukian barrier island and beach deposits over a distance of >200 km indicates vertical tectonic stability during 120,000 years.

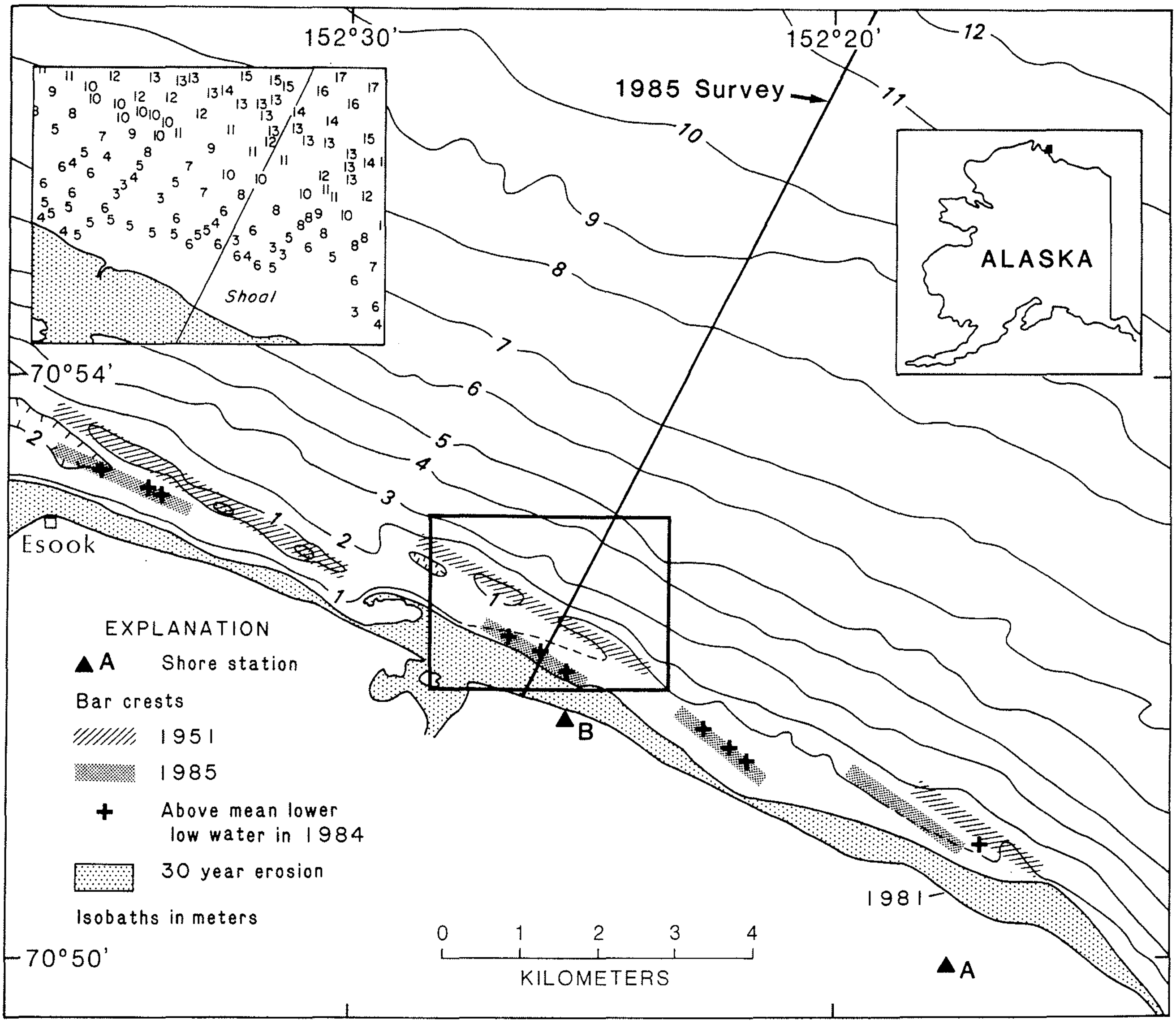

Fig. 2: Isobaths of study area from 1951 hydrographic surveys and coastlines as mapped in 1951 and remapped in 1981. Inset shows typical density of data points defining former longshore bars. Bars in 1985 are sketched from our own surveys, and from measurements of emergent points made by the State of Alaska in 1984.

and in various other publications give ample evidence from studies using such techniques as seismic profiling, side-scan sonar surveys, vibrocoring, diving observations, and bottom photography, showing that the inner shelf in the Beaufort Sea is an erosional surface with only a spotty, thin cover of Holocene marine sediments. This layer is generally only as thick as the depth of reworking by such cryogenic processes as strudel scour and ice gouging, and therefore represents a non-homogenous "rototill" layer blanketing the inner shelf. All previous work in the Beaufort Sea, however, lacked proof for shoreface erosion in form of long-term comparisons of profiles or water depths. In the Laptev Sea with equally high coastal erosion rates, several poorly documented profile comparisons show that the shoreface is adjusting out to water depths of 5 or 6 m, as summarized by ARE (1999).

Knowledge of how the shoreface responds to extensive shoreline displacement is important not only for evaluating whether the seafloor provides a sediment sink or sediment source, but also for evaluating such problems as the fate of inundated archaeological sites and the design of oil pipeline crossings for arctic coasts.

RESULTS

This report presents the results of a shoreface study at a site in Alaska where coastal retreat is well documented, locally measuring 400 m over a 30-year period. Important for the selection of this site was that vertical crustal movement, or relative sea level change can be ruled out as contributors to depth changes measured. Vertical stability of this area was shown by REIMNITZ et al. (1988), based partly on the occurrence of the linear belt of Pelukian barrier island deposits (Fig. 1). The results of this Alaskan study are also applicable to many areas in Siberia, and will help to estimate sediment yield from coastal retreat.

The earliest bathymetry in the study area and the shoreline configuration (Fig. 2) stem from work by the U.S. Coast and Geodetic Survey in 1951 at a scale of 1 : 40 000, as described in more detail by REIMNITZ & KEMPEMA (1987). Most of the dense trackline pattern of that survey, shown as an example in the inset of Figure 2, was controlled by the use of Shoran, and the soundings were referenced to mean lower low water (MLLW). The coastline was remapped by the State of Alaska together with the National Ocean Survey in 1981, and again referenced to the same tidal bench marks. This most recent coastal configuration is also shown in Figure 2. The 30-yr average retreat rate for a 23-km-long coastal segment centered on Figure 2 is 7.5 m/yr (REIMNITZ et al. 1988). The original reference tidal bench marks located about 25 km west of the study site still existed during our survey in 1985, and were used again by us. The details of how navigation transponders were established at three coastal sites (Fig. 2), how the vertical datum was carried from the old tide station to the site, and how the survey was accomplished are described in REIMNITZ & KEMPEMA (1987). The possible error in the transfer of the vertical datum to our study site is estimated at less than 10 cm.

Figure 3 shows the changes that occurred in the shoreface profile from the beach 3.2 km seaward to the 6 m isobath over the 34 yr interval. At the very shoreline is a possible uncertainty of 25 m horizontally in the location of data points, as the retreating coast had been mapped four years prior, and the otherwise very accurate acoustic ranging system used near the beach failed shortly before the beach was reached. The comparison in Figure 3 shows that the shoreface of 1951 over the first several hundred metres had deepened by a meter or more during the 34 yr period. In parallel with the shoreface deepening there was a landward shift of the system of gravelly longshore bars by as much as 500 m, comparable to the rate of bluff retreat. At 6 m water depth the two profiles merge, but as explained by REIMNITZ & KEMPEMA (1987) the location of the "depth of closure" may actually lie seaward of that point.

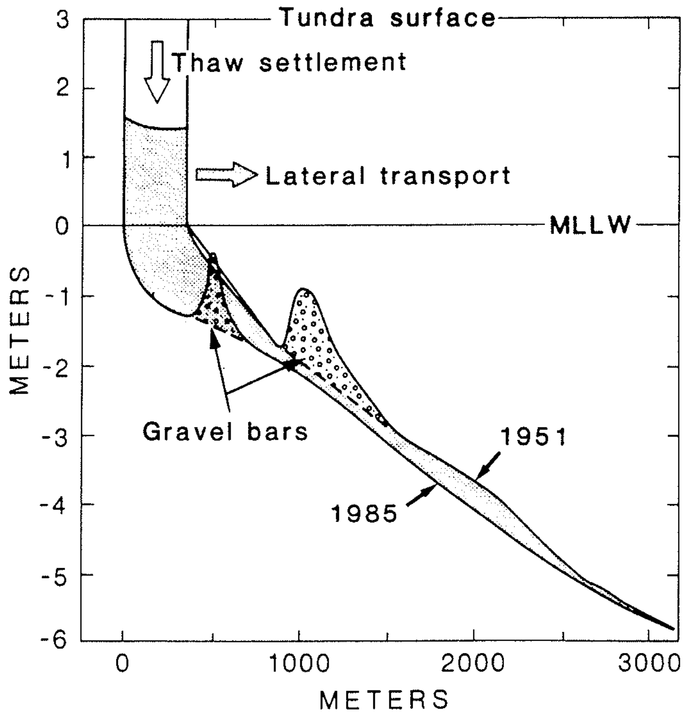

Fig. 3: Shore-face evolution from 1951 to 1985 along transect shown in Figure 2. Portion of profile change from thaw settlement is shown by blank areas. In submerged portion of profile virtually no thaw settlement occurs, most change representing removal by mechanical energy and sediment transport.

To calculate what portion of the profile lowering in Figure 3 may have resulted from thaw settlement, we removed the excess ice content (interstitial ice exceeding 37.5 % of the frozen sediment volume) from the 1951 profile. For these calculations, the ice content in the coastal plain west of the study area (SELLMANN et al. 1975) was used, an area geologically very similar to the study area. In that part of the coastal plain, 610 measurements are available for the upper 9 m section below the tundra surface, the section involved in the profile deepening. Subtracting the excess ice one finds that from the 1951 shoreline to the 1 m isobath (3-4 m below the tundra surface), only 14 % of the indicated deepening can be attributed to thaw settlement. At more than 1.5 m water depth, none of the profile deepening can be due to thaw settlement. From the upper 3 m of the section eroded since

1951 we subtracted an additional 20 % to account for the maximum volume of ice that may occur in form of ice wedges (SELLMANN et al. 1975). Figure 3 shows that the maximum amount of thaw settlement possible according to the wealth of published data can account for only a small portion of the section that is missing below sea level. We therefore conclude that the shoreface is an important sediment source rather than a sediment sink, a finding that is supported by the broad range of research approaches referred to earlier.

During the course of our fieldwork we also observed a series of elongated gravelly longshore bars that reach sea level and higher (Fig. 4) in numerous locations at distances of 250 to 1000 m from coastal bluffs. At four locations, off A, B, and Esook (Fig. 2) and at the site of the tidal bench marks 25 km to the west, we scraped bottom across a gravel bar and found relatively deep water landward in a trough that provides safe anchorage protected against storms and drifting ice at night. The islands along the crests of longshore bars, important for defining coastal boundaries, were landed on by helicopter and located by the State of Alaska in 1984 and 1985, and served as aids to locate the bars shown in Figure 2. A study of the 1951 hydrographic survey (inset in Fig. 2) reveals the existence of a similar system of troughs and bars, locally emergent, oriented at an angle of about 10° to the coast. The longshore bars consist of sand and gravel, materials absent in local bluffs, and probably migrate obliquely shoreward. The island north of A consisting of "sticky clay, apparently bulldozed by pack ice" (N. Johnson, oral commun. 1986), was very different from the elongated, wave-washed gravel bars (Fig. 4), and had disappeared by the time of our own survey. This observation suggests that ice gouging of strata exposed on the shoreface, and subsequent winnowing by waves and currents, may provide coarse material for bar construction where such materials are absent in coastal bluffs. This cryogenic phenomenon is the process responsible for the generation of the roto till layer blanketing Arctic shelves. In any case, the migrating mini-lagoon system described, which here spans a distance of at least 40 km of shoreline, has not been described anywhere previously, and apparently is in some regions an important component of the shoreface.

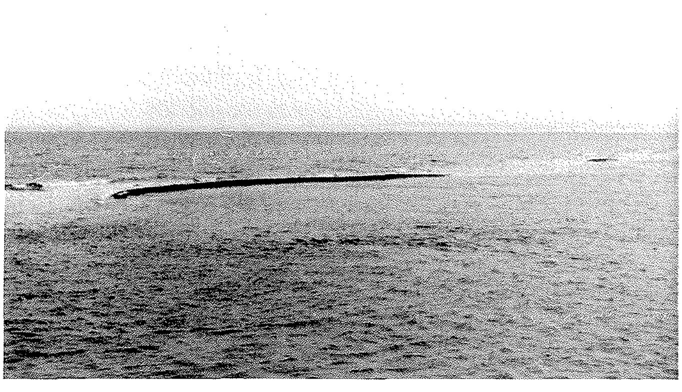

Fig. 4: View seaward across a 12 m long gravel island located due north of shore station B (Fig. 2) in 1985.

Only a small portion of the >1 m shoreface deepening in 34 yr can be attributed to melting of excess ice. Most of the deepening is caused by erosion and seaward displacement of sediment. This, together with the landward migration of the longshore bar system, demonstrate that mechanical energy is far more important than thermal energy for arctic coastal retreat. The deepening extends seaward as far as the 6 m isobath. If erosion terminated at this 6 m depth, a horizontal platform roughly 10 km wide would have formed there during the last 1000 yr. A study of coastal zone bathymetry around the Arctic Ocean nowhere reveals such a flat surface which could be interpreted as the seaward limit of modern erosion. In a detailed study of erosion covering 344 km of shoreline in areas adjacent to the present study, REIMNITZ et al. (1988) calculated the sediment yield, assuming that the 2 m isobath, or the seaward edge of the characteristic 2 m bench, is the outer limit of erosion. In their calculations, the sediment yield from the submerged part of the profile was slightly higher than that from the subaerial part. Moving the depth limit of seafloor erosion from 2 to 6 m, would triple the sediment yield. Not knowing reliably the depth limit for shoreface erosion in this unique Arctic shelf-environment makes sediment budget calculations for the Arctic Ocean questionable. Even with 2 m as the maximum water depth for coastal erosion of a particular segment, the sediment yield exceeds river supply to the same region seven fold (REIMNITZ et al. 1988). ARE (1998), analyzing sediment yield from erosion in the Laptev Sea, found it comparable to or possibly larger than sediment supply by rivers.

Sediment supply from coastal erosion probably was highest just after the end of the last transgression and before the coasts began to stabilize, about 5000 years ago (ARE 1999). At this stage, coastal erosion also began to actively shape the morphology of the continental margin, as shown by the Alaskan example in Figure 1. Here the eroding shelf surface truncates deposits of several previous transgressions. The differences between depositional shelf environments after the end of the previous transgressions and the abrasional setting of today is a question that should be answered by future investigations. With sea ice being the principal cross-shelf transport agent, there truly is no limit on the distance to depocenters. We do not know where these are, but the Arctic shelves of today can be ruled out as sediment sinks.

SUMMARY AND CONCLUSIONS

Our study demonstrates that the Arctic shoreface is eroding to a water depth of at least 6 m at a site where the coast is retreating at a rate of >7 m/yr. This is three times deeper than assumed in previous calculations of sediment yield from shoreface erosion, and therefore triples the yield. As a result, coastal erosion products exeed sediment supply from local rivers manyfold. Our study also shows that mechanical rather than thermal energy is driving the Arctic coastal retreat. What we learned from this study in the Beaufort Sea probably also applies to other circum-Arctic regions marked by high rates of coastal retreat. Associated with the retreating coast and shoreface at our study site is a set of migrating mini-lagoons. Coastal erosion is an active agent shaping the Arctic continental margin today.

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