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The Effects of the Holocene Sea Level Rise on the Evolution of the Southeastern Coast of the Canadian Beaufort Sea

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ABSTRACT

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In the Canadian Beaufort Sea, relative sea level (RSL) rose during the Holocene from approximately −70 m to its present position. The rate of RSL rise during the early Holocene was on the order of 4 to 5 mm a^{-1}, and then increased to 7 to 14 mm a^{-1} during the mid-Holocene. Over the last 3,000 years, the rate of RSL rise slowed markedly, approaching the present at an average rate of less than 3 mm a^{-1}. The Holocene rise of RSL induced coastal retreat and resulted in the formation of coastal embayments, formed by the breaching of thermokarst lakes. The transgression was also responsible for the development of spits and barrier islands. Modern barriers are retreating landward, in response to overwash processes, contributing to infill shallow breached lake/lagoons. High-resolution seismic profiles from the inner shelf suggest that this process of lagoon infilling by landward-migrating barriers began to occur during the middle Holocene, perhaps earlier. While the coastline was retreating, the shoreface experienced erosional retreat. The depth of shoreface erosion seems to have been less during the mid-Holocene due to high rates of RSL rise, a condition favorable to the preservation of coastal lithosomes on the continental shelf.

ADDITIONAL INDEX WORDS: *Beaufort Sea coast, Holocene, relative sea level rise, transgressive stratigraphy.*

INTRODUCTION

The coastline of the Canadian Beaufort Sea consists of bluffs developed in Quaternary sediments, and of spits, barrier beaches and barrier islands partially enclosing lagoons. This coast is undergoing rapid regional retreat (LEWIS and FORBES, 1975; FORBES and FROBEL, 1985; MACKAY, 1986). Bluffs are eroding at rates of 1 to 2 m a^{-1} (HARPER, 1990), and spits and barrier islands are generally retreating landward at rates in excess of 2 m a^{-1} (HÉQUETTE and RUZ, 1991). Present-day coastal evolution is partly controlled by relative sea level rise. Coastal retreat prevailed throughout the Holocene in response to rising sea level (HILL *et al.*, 1993).

In this paper, we present a review of the Holocene relative sea level history (FORBES, 1980; HILL *et al.*, 1985, 1993) and of the physical processes affecting the coast and nearshore zone (FORBES and FROBEL, 1985; MACKAY, 1986; HÉQUETTE and HILL, 1989, 1993; HARPER, 1990; HÉQUETTE and BARNES, 1990; HILL *et al.*, 1990; HÉQUETTE and RUZ, 1991; RUZ *et al.*, 1992). From this review and the interpretation of sidescan sonar records and high-resolution seismic reflection profiles, we assess the effects of Holocene sea level rise on the evolution of the coast and inner shelf of the southeastern Canadian Beaufort Sea. The preservation potential of coastal lithosomes during transgression is also discussed.

SETTING

The coastal plain of the southeastern Canadian Beaufort Sea essentially corresponds to the Tuktoyaktuk Peninsula which is located to the east of the Mackenzie Delta (Figure 1). The Tuktoyaktuk Peninsula is principally composed of Pleistocene sands covered in places by Holocene eolian and lacustrine sediments (RAMPTON, 1988; RUZ, 1993). This area lies within the zone of continuous

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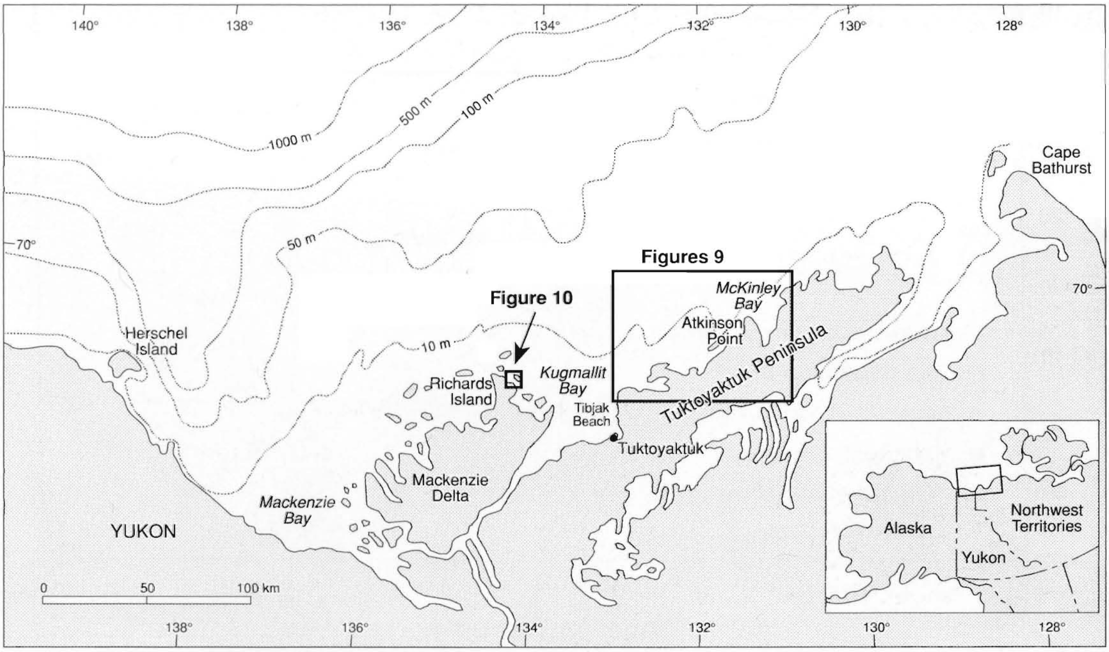


Figure 1. Location map of the Canadian Beaufort Sea coast.

permafrost (JUDGE, 1986). The topography of the coastal plain consists of thermokarst lakes surrounded by low hills of perennially frozen sediments (RAMPTON and MACKAY, 1971). Thermokarst processes have been active during the latter part of the late Wisconsinan and the Holocene. Thermokarst activity started as early as 12.9 ka BP (RAMPTON, 1988) and was widespread between 10 and 9 ka BP, probably in response to a climatic warming (RITCHIE *et al.*, 1983). Thermokarst appears to have remained active between 8.5 and 4 ka BP, but with limited development of new thermokarst depressions. Nearly 50% of the Tuktoyaktuk Peninsula consists of thaw lakes of various dimensions. Most of the lakes are shallow (< 5 m water depth), but water depth can vary significantly from one lake to another.

The Canadian Beaufort Sea is covered by sea ice for nearly 9 months of the year. During the open water season, wave energy is limited due to the presence of the fetch-restricting pack ice offshore. Nearly 80% of deep-water waves are less than 1 m in height (HARPER and PENLAND, 1982), indicating a moderate to low wave-energy environment. The Canadian Beaufort Sea is microtidal, the mean tide ranging from 0.3 m to 0.5 m. Positive storm surges may raise the water level up to 2.4 m above mean sea level at the coast (HARPER *et al.*, 1988).

The coast of the Tuktoyaktuk Peninsula is formed of low bluffs (< 10 m high), generally composed of sand, and of spits and barrier islands less than 2 m high. Most of these coastal depositional landforms consist of well-sorted, fine to medium sand. The continental shelf extends offshore to approximately 80 m water depth and is characterized by a very gentle gradient on the order of 1:2,000. Over most of the shelf, a thick sequence of several hundred metres of interbedded Pleistocene outwash sand and marine mud is overlain by a veneer of Holocene marine sediments, except in cross-shelf paleo-valleys where Holocene deposits may reach 30 m (BLASCO *et al.*, 1990). Sand is generally abundant inshore of the 10 m isobath while mud covers the central and outer shelf (VILKS *et al.*, 1979). The principal source of fine-grained sediment delivered to the Canadian Beaufort shelf is the Mackenzie River which supplies approximately 1.25×10^8 t a^{-1} of silt and clay (LEWIS, 1988).

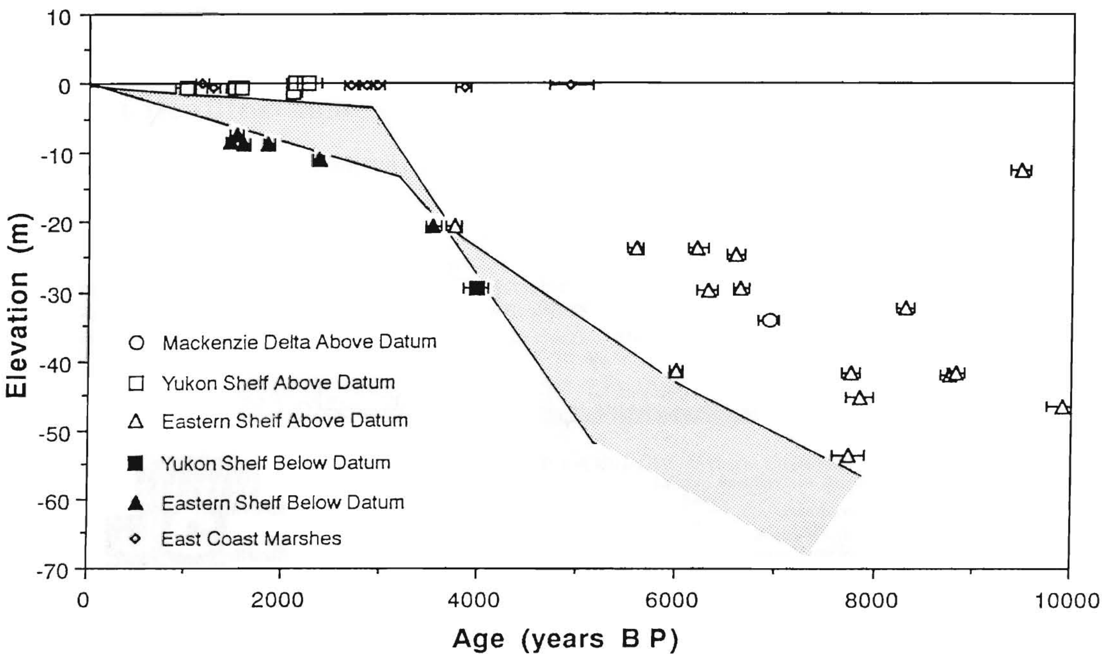


Figure 2. Envelope of Holocene relative sea level changes in the Canadian Beaufort Sea (after HILL *et al.*, 1993). The solid symbols represent samples deposited below mean sea level, while the open symbols represent samples deposited above mean sea level. The paleo-environmental interpretations of the samples are presented in HILL *et al.*, (1993). The data points constrain the line to a position approximately as shown, with a steep mid-Holocene section and a flatter late Holocene section.

HOLOCENE RELATIVE SEA LEVEL HISTORY

FORBES (1980) compiled and interpreted a number of radiocarbon dates from the southern Canadian Beaufort Sea which suggested that relative sea level (RSL) has been rising over the last 15,000 years. This author concluded that these RSL changes were not compatible with solely eustatic sea level rise, but suggested that isostatic effects, as a result of late Wisconsinan glaciation, recent sediment loading, or both, were important. HILL *et al.* (1985) provided additional dates on freshwater peats from boreholes on the Canadian Beaufort Shelf and proposed a sea level curve for the late Wisconsinan and Holocene. They inferred that, during the Holocene, RSL rose from a late Wisconsinan lowstand of approximately −70 m to its present position, but the Holocene part of the sea level curve was not well constrained.

HILL *et al.* (1993) obtained twenty additional radiocarbon dates pertaining to the Holocene sea level history in the Beaufort Sea region. These dates were obtained on samples deposited above mean sea level (freshwater and tidal marsh peats) or below mean sea level (mainly marine shells). Although none of the samples directly record the position of RSL, this suite of dates and previously published radiocarbon dates (JOHNSTON and BROWN, 1965; FORBES, 1980; HILL *et al.*, 1985) have been used to better constrain the regional Holocene RSL changes (Figure 2). At present, there are still insufficient data to establish separate curves for the western, central and eastern Beaufort Sea. Because the samples used to construct the RSL curve are distributed over a broad geographic region, this RSL curve reflects effects such as consolidation, basin subsidence, postglacial isostatic rebound and forebulge collapse which were likely variable across the region.

The RSL curve is constrained to a relatively narrow envelope for the last 4,000 years, but is less constrained between 4,000 and 10,000 years BP. The constraints on the curve, however, are sufficient to suggest that RSL rose rapidly during

Figure 3. Eroding bluff affected by retrogressive thaw failure, eastern shore of Kugmallit Bay (Figure 1).

the middle Holocene, probably ranging from 7 to 14 mm a^{-1}, which is relatively rapid compared to the rates of 4 to 6 mm a^{-1} which were previously documented for the same time interval (FORBES, 1980; HILL *et al.*, 1985). Over the last 3,000 years, the rate decreased to an average of less than 3 mm a^{-1}. The flattening of the curve over the last 3,000 years seems to indicate a slowing of RSL rise towards the average eustatic rate of 1.0 to 1.2 mm a^{-1} (GORNITZ *et al.*, 1982). Although the true rate could be between 1.0 and 4.4 mm a^{-1}, it more probably lies between 2.5 mm a^{-1} and the eustatic rate (HILL *et al.*, 1993). Analysis of tide-gauge data from Tuktoyaktuk from 1952 to 1980 suggests that relative sea level is still rising at a rate of 2 mm a^{-1} (D.L. Forbes, personal communication, 1991).

PRESENT-DAY COASTAL EVOLUTION

Transgressive coastal morphology and high rates of coastal retreat (FORBES and FROBEL, 1985; HARPER, 1990; HÉQUETTE and RUZ, 1991; RUZ *et al.*, 1992) also suggest that RSL is rising. Bluff retreat in excess of 10 m a^{-1} has been documented along the Tuktoyaktuk Peninsula (HILL *et al.*, 1990). Bluff erosion is generally episodic, being mainly due to the action of storm waves (FORBES and FROBEL, 1985). In addition to wave-induced erosion, thermal erosion promotes rapid bluff retreat when ground ice is present in the bluff sediments (MACKAY, 1986; DALLIMORE *et al.*, 1988). Thermal erosion results in unique arctic erosional processes at the coast including retrogressive thaw failure (Figure 3), and thermally-triggered block slumping and block failure. These bluffs, however, remain stabilized until waves and wave-induced currents have removed the eroded material deposited at the toe of the bluff.

During coastal retreat, thermokarst lakes are drained or breached, depending on the initial depth of the lake (RUZ *et al.*, 1992). A shallow lake, perched above sea level, is commonly drained when the retreating coastline intercepts the lake edge. In the case of a deeper lacustrine basin, the lake when breached results in the formation of a coastal embayment. In newly formed embay-

Figure 4. Oblique aerial photograph showing a small spit developing across a breached thermokarst lake, northern coast of Tuktoyaktuk Peninsula.

ments, a spit usually develops rapidly from an updrift headland (Figure 4). Aerial photograph comparison revealed that a spit can develop within a few years across a newly breached lake (MACKAY, 1986). Geomorphic evidence indicates that, in the study area, spits may evolve as barrier islands. The most common mechanism of barrier island formation seems to be the breaching of spits connected to the mainland or to small islands. Aerial photograph analysis and field observations revealed that inlet formation in the headland-attached end of a spit may lead to spit segmentation and to the formation of a barrier island (RUZ *et al.*, 1992).

The morphology of most spits and barrier islands along the Tuktoyaktuk Peninsula is typical of transgressive coastal landforms. They have a low crestal elevation, rarely exceeding 1.5 m above mean sea level, and are retreating landward in response to storm-induced overwash processes (Figure 5). Beach sediments are transferred to the backbarrier region during overwashing, contributing to progressive lagoon infilling. At Atkinson Point (Figure 1), a core collected in a large barrier-spit near the edge of the lagoon (Core A2-87, Figure 6) shows that high-angle landward-dipping sand beds overlay lagoon sediments and freshwater peat. These prograding sand beds represent washover delta forests deposited at the edge of a washover fan when sea level was close to or slightly lower than present. With continuing barrier retreat, freshwater peat is eventually exposed on the foreshore. Peat outcrops on the foreshore of numerous beaches and barriers in the region are evidence of landward migration of coastal landforms (Figure 7).

The comparison of nearshore echosounding records from 1987 with bathymetry from 1971 showed that, while the coast is retreating, the shoreface is characterized by erosional retreat (HÉQUETTE and BARNES, 1990). Wave and current measurements obtained on a sandy shoreface at Tibjak Beach (Figure 1), near the mouth of Kugmallit Bay, suggest that intense current scouring occurs

Figure 5. Oblique aerial photograph showing extensively overwashed barrier island, southwest of Atkinson Point (Figure 1), Tuktoyaktuk Peninsula.

during storm surges, resulting in seabed erosion in water depths of less than 5 m (HÉQUETTE and HILL, 1993). During these events, some sand is likely transported seaward to the lower shoreface by high velocity seaward-directed near-bottom currents.

HOLOCENE COASTAL EVOLUTION

Shoreface Erosion and Development of a Transgressive Sand Sheet

Shoreface erosion was probably a continuous process throughout the Holocene. Over most of the eastern Canadian Beaufort shelf, the Holocene marine sediments are underlain by a 40 m thick sequence of fine- to medium-grained sands of late Wisconsinan age (HILL *et al.*, 1985). Several lines of evidence, including seismic reflection patterns, the 3-dimensional geometry of the sequence, and quartz-grain surface textures of sand samples collected within this unit, strongly suggest that the sands were deposited in a prograding glacial outwash system in advance of the late Wisconsinan ice sheet (HILL and NADEAU, 1984; BLASCO *et al.*, 1990). The upper limit of this sequence is frequently identified on high-resolution seismic reflection profiles by a well-defined regional unconformity (HÉQUETTE and HILL, 1989) which is clearly erosional in some places. Radiocarbon dating of peat samples collected below this reflector revealed that this unconformity is of Holocene age (HILL *et al.*, 1985). It is therefore interpreted as the ravinement surface produced by shoreface retreat during the Holocene sea level rise.

The ravinement surface is overlain by Holocene marine sediments. The thickness of these sediments is variable over the shelf, but they are usually thicker closer to the Mackenzie Delta. Over the eastern shelf, they form a landward-thinning wedge of interbedded sand and silt with some silty clay intervals (HÉQUETTE and HILL, 1989; BLASCO *et al.*, 1990). Seaward of the 10 m isobath, the sand and silt sequence is overlain by a veneer of silty clays derived from the Mackenzie River and

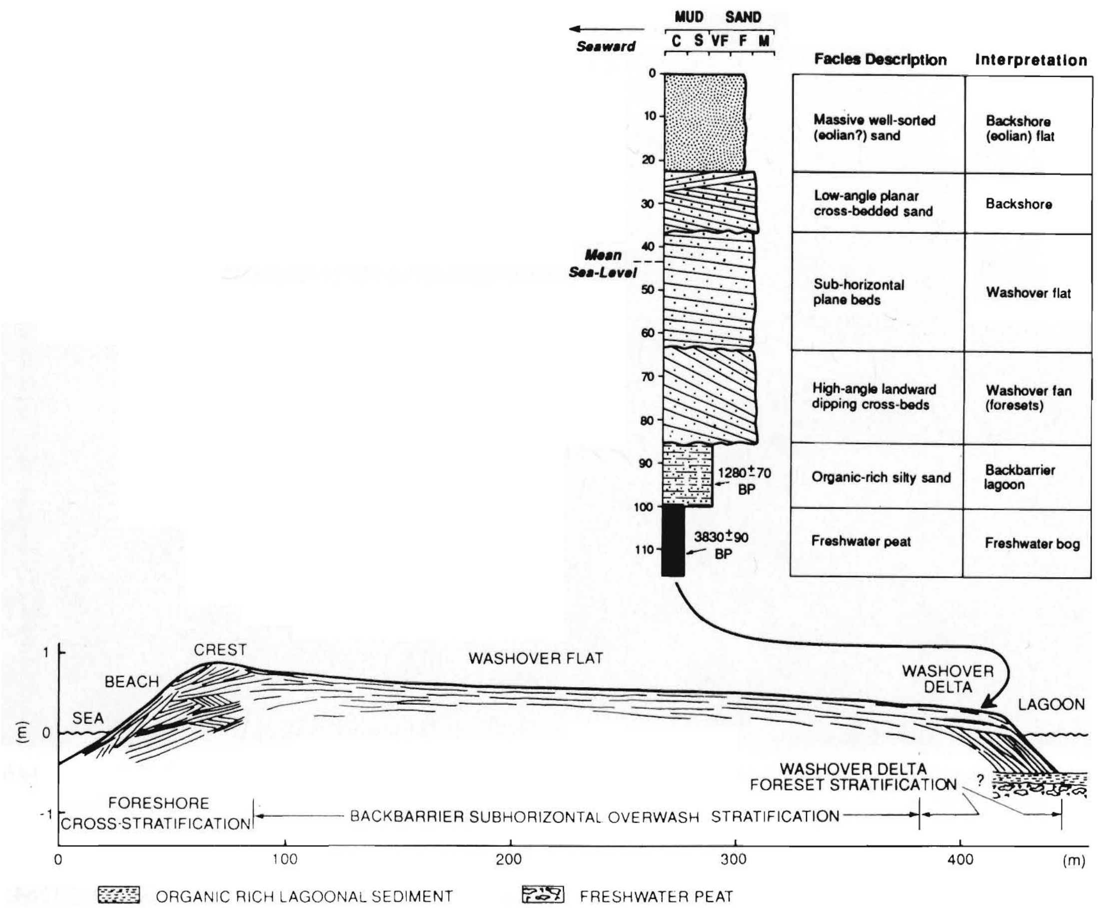


Figure 6. Schematic illustration of the internal structure of a spit at Atkinson Point (Figure 1) based on shallow vibracores. The lithological and facies description of core A2-87 is also shown (after HÉQUETTE and RUZ, 1991 and RUZ *et al.*, 1992).

deposited under low-energy conditions on the shelf. It has been suggested that the sandy Holocene sediments "may partially represent reworked older sediments" of the underlying unit "and reflect depositional conditions associated with shallow-water, higher energy environments" (BLASCO *et al.*, 1990, p. 497). Based on the lithostratigraphy, the seismic facies and 3-dimensional geometry of this depositional sequence and on the interpretation of the lower bounding unconformity of the sequence as the Holocene shoreface erosion surface, we believe that this unit represents a transgressive sand sheet composed of reworked littoral sediments deposited during transgression.

HÉQUETTE and HILL (1993) showed that downwelling, storm-generated currents are capable of transporting coastal sand offshore below fairweather wave base. Such processes should result in a net aggradation on the lower shoreface and on the inner shelf, especially during a period of rising sea level (SWIFT, 1976). We, therefore, suggest that the transgressive sand sheet that developed on the shelf during the transgression was formed by offshore-flowing, near-bottom flows generated during episodic storm surges. The silty clay intervals are thought to represent fairweather deposits preserved beneath storm-generated sand beds. This interpretation implies that offshore sediment dispersal by downwelling currents was an active process throughout the Holocene.

During winter, ice scouring of the seabed by the

Figure 7. Freshwater peat outcropping on the foreshore of a retreating beach on the northern coast of the Tuktoyaktuk Peninsula.

keels of pressure ridges is a significant process contributing to sediment remobilization and seafloor erosion on the inner shelf (HÉQUETTE and BARNES, 1990). However, high resolution seismic profiles show that the inner shelf undergoes net deposition. Ice keels virtually never penetrate beneath the Holocene unconformity, the average scour depth on the inner eastern shelf being on the order of 60 cm (DESROSIERS and HÉQUETTE, 1993).

Submergence and Preservation of Thermokarst Lakes

Although shoreface erosion occurred during the Holocene transgression, it appears that some thermokarst lakes were submerged and partially preserved during the RSL rise. Seaward of the Tuktoyaktuk Peninsula, numerous shallow depressions lie just below the shoreface erosion surface (Figures 8 and 9). The majority of these depressions are small (100–300 m wide) and show little negative relief. Based on their horizontal and vertical dimensions, which are similar to those of the thermokarst lakes presently seen on the adjacent Tuktoyaktuk Peninsula and on the geometry of the basin-fill seismic facies, most of these features have been interpreted as breached thermokarst basins which survived the erosion induced by the Holocene transgression. Most of the Holocene peats, recovered from boreholes on the Canadian Beaufort shelf, were deposited in thermoskarst lakes that were subsequently submerged by the transgressing sea and buried beneath Holocene marine sediments (HILL *et al.*, 1985; BLASCO *et al.*, 1990).

Submergence of thermokarst lakes has taken place since at least the middle Holocene, as indicated by freshwater peats and sub-bottom depressions found at depths of more than 40 m below present sea level. According to the sea level curve presented in this paper (Figure 2), these lakes were transgressed prior to 5,000 BP. The preservation potential of the submerged thermokarst lakes is controlled by several factors in-

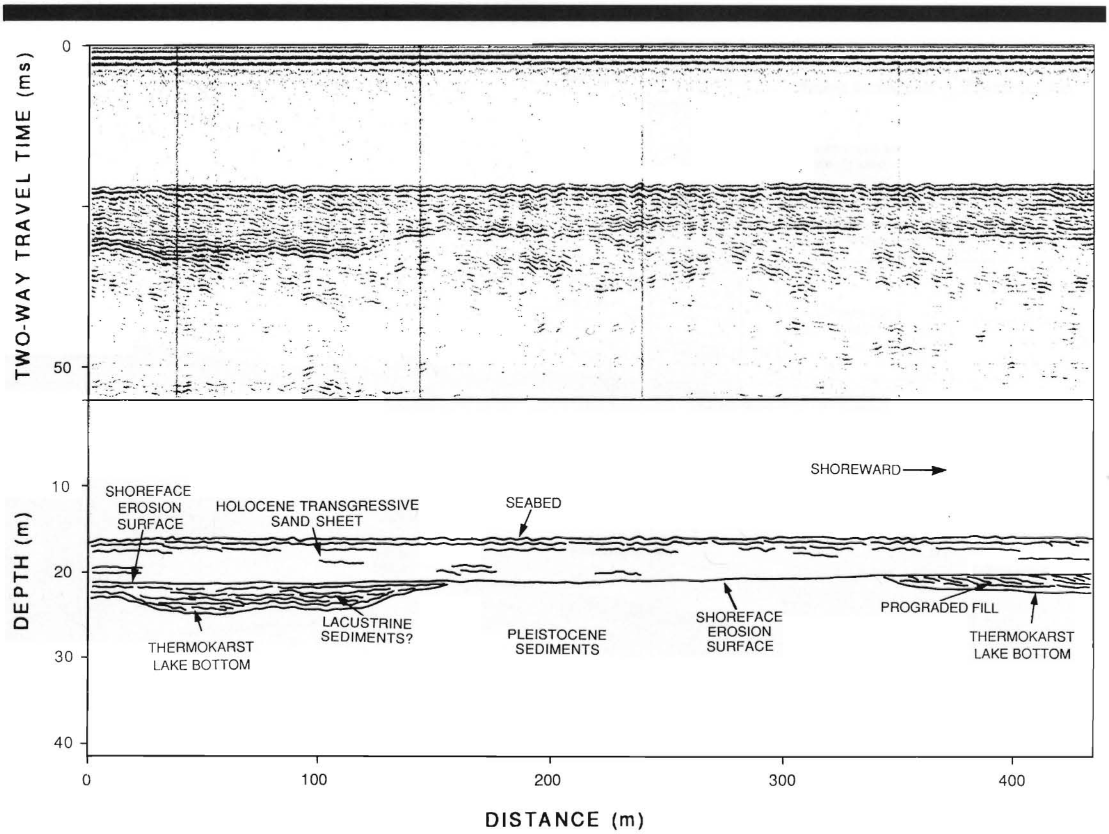


Figure 8. Shore-normal high-resolution seismic profile and interpretation showing preserved thaw lake basins and unconformity representing shoreface erosional surface on the inner shelf seaward of the Tuktoyaktuk Peninsula. Note the prograded landward dipping reflectors in the small depression at right suggesting that the submerged thaw lake was infilled by a retreating barrier. Water depth is 16.5 m (after RUZ *et al.*, 1992).

cluding the rate of RSL rise, the nearshore wave-energy regime and the initial depth of the lake basin. As the breached lakes were affected by shoreface erosion when they were transgressed, the deeper basins had a higher preservation potential, presuming all other conditions equal (*i.e.*, wave energy at the coast, sediment supply, and rate of RSL rise).

Partially preserved thermokarst lakes underlying the Holocene ravinement unconformity are common at depths greater than 15 m below present sea level. Assuming that shoreface erosion occurred within the first few metres of water (based on present depth of shoreface erosion), these lakes were affected by shoreface erosion when RSL was at 15 m below present sea level or more. In comparison, preserved thermokarst lakes below the unconformity are rare at depths of less than 12 to 15 m below present sea level (Figure 9). This suggests that the depth of erosion on the shoreface was less when paleo-sea levels were lower than 15 m below present sea level, and that the depth of erosion increased when RSL reached −15 m at about 3,500 years BP according to the sea level curve (Figure 2). These results strongly suggest that deeper shoreface erosion occurred during the late Holocene, during a period of slowly rising RSL which was not favorable to the preservation of the lake basins. Conversely, the preservation potential of these lacustrine basins was higher during the period of rapid RSL rise which characterized the middle Holocene. During that period, the high rate of RSL rise likely resulted in shallow shoreface erosion due to rapid landward and upward translation of the shoreface, thus favoring the preservation of breached-lake bottoms

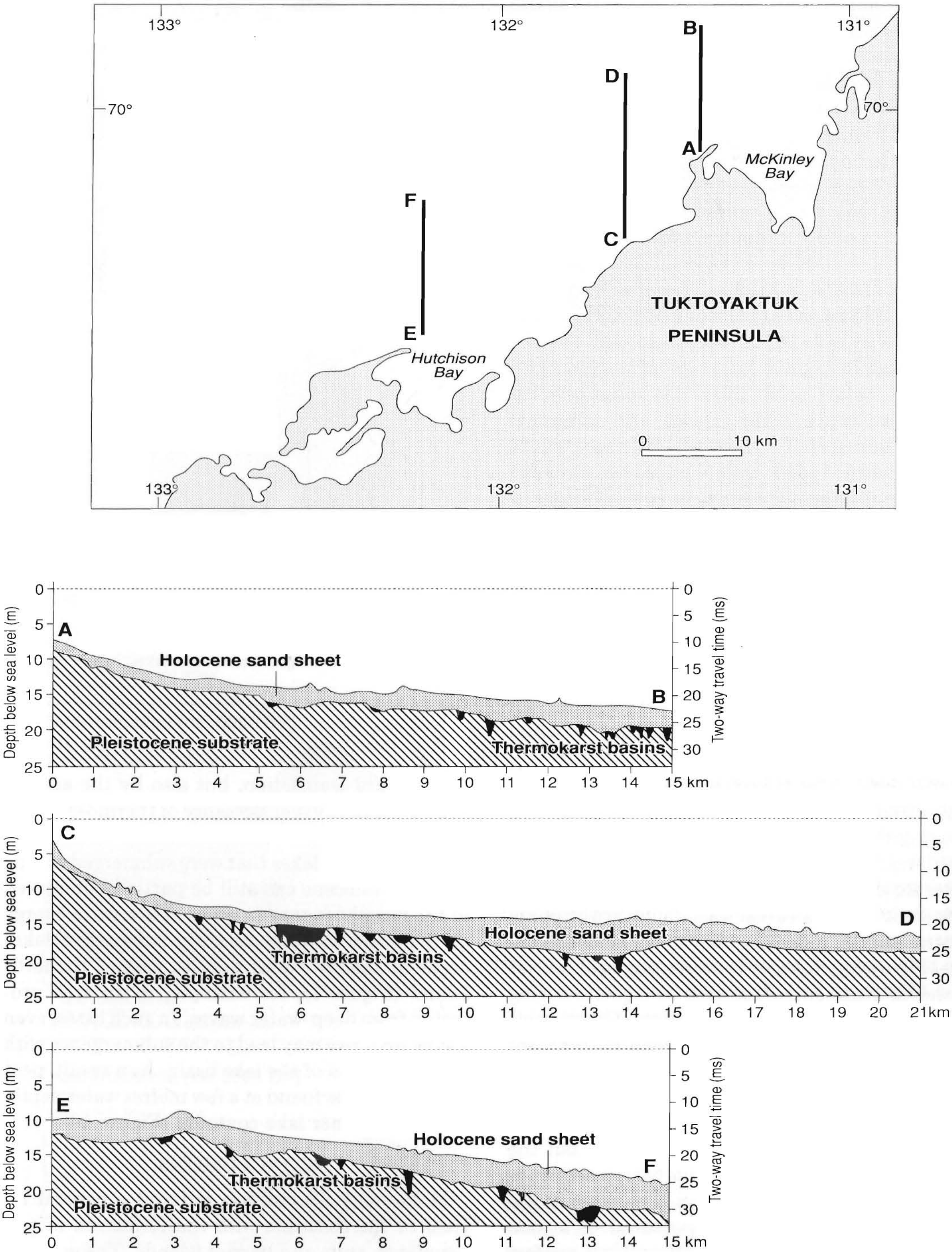


Figure 9. Interpretation of high-resolution seismic profiles across the inner shelf and shoreface, seaward of the Tuktoyaktuk Peninsula, showing the ravinement surface and partially preserved thermokarst lake basins overlain by Holocene transgressive sediments.

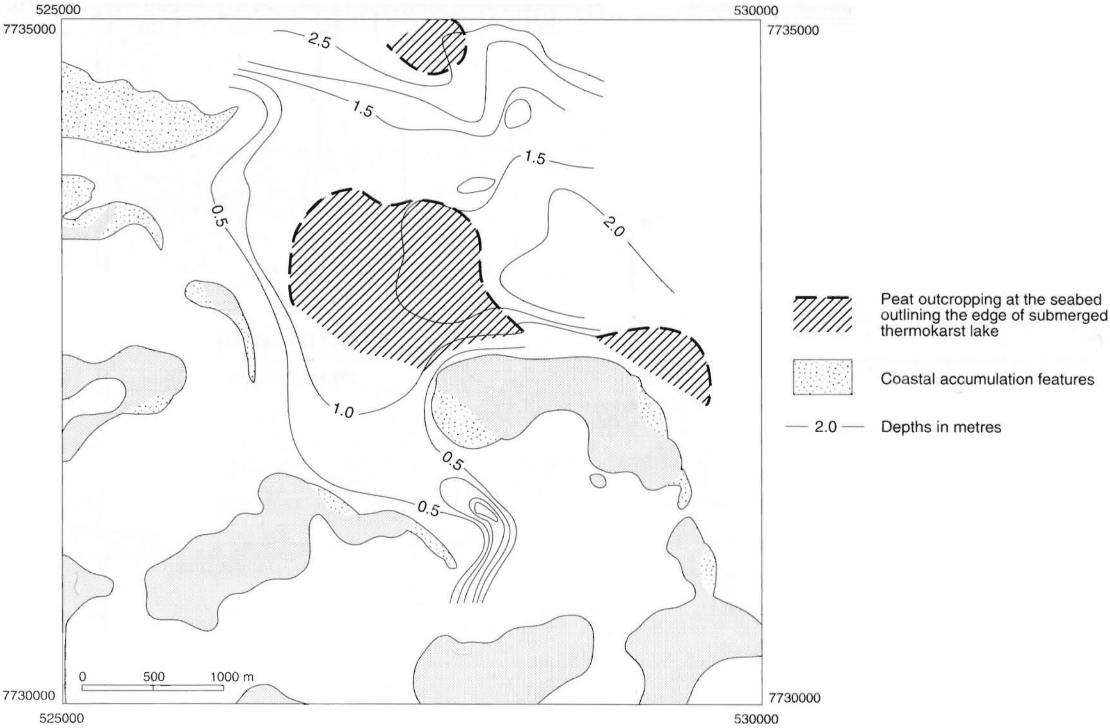


Figure 10. Distribution of linear peat outcrops at the seabed, outlining the edge of submerged thermokarst lakes, east of Richards Island (see Figure 1 for location); based on sidescan sonar records.

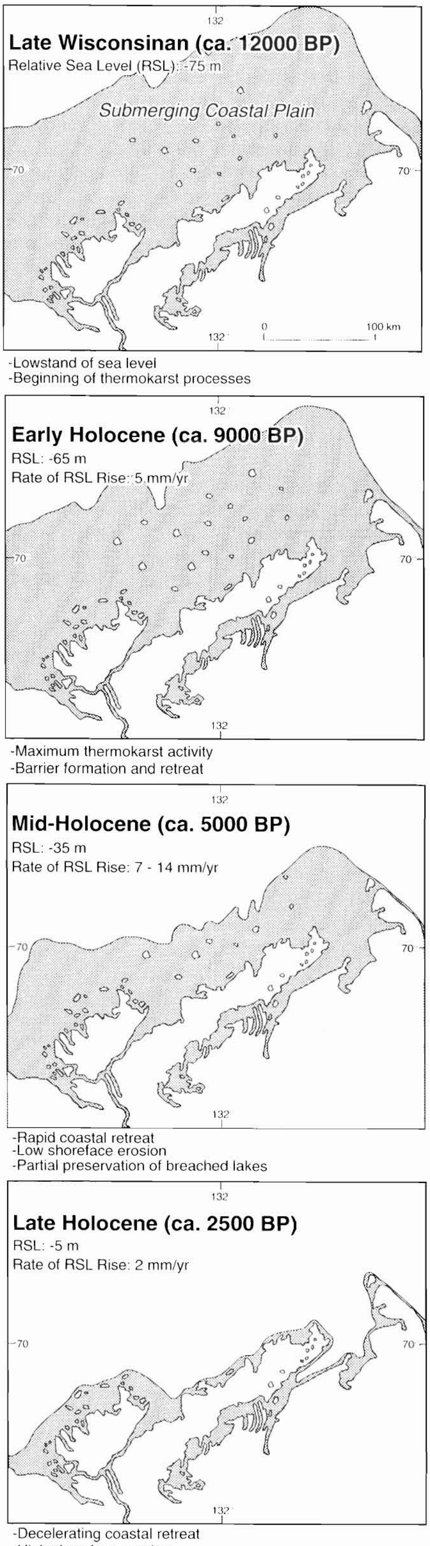
on the shelf. A high rate of RSL rise has been recognized in several other studies as a condition favoring the preservation of coastal facies in the shelf stratigraphic record (BELKNAP and KRAFT, 1981; BOYD and PENLAND, 1984).

Seismic records reveal that landward dipping progradational reflectors may occur in some basins (Figure 8), probably representing backbarrier washover sediments deposited in lagoons during the landward migration of barriers. Given their depth below present sea level, such basins were transgressed during the mid-Holocene based on the RSL curve (Figure 2). In these cases, the barrier superstructure was truncated when the active shoreface erosion surface passed over it, but the basal portion of the transgressive barrier sequence was preserved in the depression. Therefore, it appears that the preservation potential of lagoon and backbarrier facies in the Canadian Beaufort Sea was favored by the rapid rate of RSL rise during the middle Holocene, when the shoreface erosion surface was undergoing rapid landward and upward translation, but also by the antecedent topography (*i.e.*, presence of thermokarst basins).

Thermokarst lakes that were submerged during the late Holocene can still be partially preserved in the nearshore zone in areas of low wave energy at the coast. Several recently submerged lakes occur in shallow water depths, east of Richards Island (Figure 1), for example, in an area protected from deep-water waves, In such cases, even a slow RSL rise may lead to the submergence with limited erosion of the lake basin. As a result, peat outcrops can be found at a few metres water depth, outlining former lake contours (Figure 10).

CONCLUSIONS

Holocene RSL rise has induced a general retreat of the coastline with the formation of embayments, spits and barrier islands. The geomorphic response of the coast and shoreface to sea level rise varied, mainly as a function of the rate of RSL rise. As the coastline has retreated, the



shoreface has undergone erosional retreat, partly eroding and reworking the Pleistocene substrate. Seismic data from the inner shelf and shoreface suggest that the depth of shoreface erosion was greater during periods of slow sea level rise. Erosional shoreface retreat was accompanied by sedimentation on the adjacent inner shelf floor forming an advancing transgressive sand sheet. The pre-existing topography, namely the thermokarst topography, was another significant parameter controlling coastal evolution during the transgression.

During the late Wisconsinan, a broad glaciofluvial outwash plain formed to the east of the present-day Mackenzie Delta (BLASCO *et al.*, 1990). From a sea level lowstand of approximately 70 m below present sea level, rising waters began to transgress the coastal plain sometime around 12,000 years BP (Figure 11). This period also corresponds to the beginning of the thermokarst activity in the region and to the initiation of thermokarst lake basins. Thermokarst processes were especially intense between 10,000 and 9,000 years BP, leading to the formation of numerous new thermokarst basins. During the early Holocene, the rate of RSL rise was moderate, on the order of 4 to 5 mm a^{-1}, and shoreface erosion was probably relatively high. Such conditions were likely favorable to the development of coastal accumulation landforms.

During the middle Holocene, the rate of RSL rise increased significantly (7 to 14 mm a^{-1}) resulting in high rates of coastal retreat, including landward barrier migration, but shallower shoreface erosion. During that period, sea level was transgressing over a topography of thermokarst lakes leading to the formation of embayments and lagoons partially enclosed by retreating barriers (Figure 11). Seismic evidence suggests that retreating barriers partially infilled breached lakes/lagoons in response to storm-induced overwash processes and that some of these backbarrier facies may have been preserved on the continental

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Figure 11. Schematic illustration of the evolution of the coastal plain of the southeastern Canadian Beaufort Sea since *ca.* 12 ka BP. Paleo-sea levels were reconstructed based on the Holocene sea-level curve (Figure 2) and on the depth of the shoreface erosion surface on seismic profiles assuming constant shoreface erosion at −3 m water depth. RSL: depth of relative sea level below present sea level.

shelf below the ravinement unconformity. Shoreface erosional retreat resulted in the partial erosion of the pre-existing topography, leaving a well-defined regional unconformity. The rapid rate of RSL rise during the middle Holocene, however, was favorable to the preservation of breached-lake basins and possibly backbarrier lithosomes, depending on the initial depth of the basin, as the shoreface was rapidly retreating landward and upward.

In the last 3,000 years, the rise of RSL slowed markedly towards an average rate of about 2 mm a^{-1}. As a consequence, the coastline retreated at a slower rate (Figure 11) and the depth of shoreface erosion increased. These two factors resulted in the complete erosion of virtually all the breached lakes transgressed after that time. According to our observations on the stratigraphy of the inner shelf and because of erosional shoreface retreat, only an erosional surface overlain by a transgressive sediment sheet should be expected to remain after the passage of the shoreface.

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