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COASTAL PERMAFROST INVESTIGATIONS ALONG A RAPIDLY ERODING SHORELINE, TUKTOYAKTUK, N.W.T

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Abstract

Rapid coastal erosion along a peninsula forming the seaward shoreline of Tuktoyaktuk has resulted in ongoing control measures since the mid-1970's. While wave-generated erosion is significant along this section of the Beaufort Sea coastline, subsidence resulting from thawing of massive ice beneath nearshore sediments is also suggested as a major contributory cause of recession.

This study presents the thermal and physical condition of subsurface sediments within the nearshore zone, where permafrost and massive ice was documented in 1974. Observations from six boreholes drilled in March 1994 indicate that alteration in subsurface thermal and ground ice regimes over the last 20 years has been significant. Thawing of ground ice likely resulted in nearshore subsidence in excess of 3 m. This subsidence may create a sediment demand, supplied by the shoreface, that results in ongoing erosion. This study illustrates the importance of linking thermal and mechanical aspects when assessing coastal instability in this environment.

Introduction

Numerous studies along arctic coastlines document the influence of permafrost on the rate and efficacy of coastal processes. Aré (1988), for example, demonstrated the need to consider both classical hydrodynamic factors and those related to permafrost stability. Recent numerical models have built on this theme by coupling thermal and hydrodynamic effects (Nairn et al., 1998 ; Kobayashi and Atkan, 1986).

Although such models can provide reasonable predictions of erosion rates, their reliability is hampered by significant data gaps, including a lack of information on permafrost changes in nearshore areas. With the exception of mapping changes in coastal positions, there are relatively few coastal studies that include time series observations.

This paper provides a case history of coastal evolution and changes in geotechnical, geothermal and ice-bonding conditions along a coastal shoreline at Tuktoyaktuk, Northwest Territories. Detailed subsurface conditions observed in 1994 are compared to those in 1974, emphasizing the impact of subsurface permafrost changes on shoreline stability. The study further provides an overview of impact of human activity on coastal conditions, documenting a variety of shoreline stabilization techniques undertaken during this period with recommendations for future strategies.

Study area

The Hamlet of Tuktoyaktuk was established as a harbour in 1934 by the Hudson's Bay Company and served as a trans-shipment point for goods brought down the Mackenzie River. Presently, Tuktoyaktuk is home to about 1000 people and has been the centre for Canadian Beaufort Sea oil exploration for about three decades. The townsite population and infrastructure are concentrated on a 1.2 km long peninsula, oriented north/south and exposed to the full fetch of Kugmallit Bay to the west and the Beaufort Sea to the northwest (Figure 1). Spits project both north and south from the peninsula, though the northern spit turns eastward to align with the dominant storm wind direction. Coastal erosion is endemic in the region with rates typically 1-2 $m\ a^{-1}$ (Harper et al., 1985; Mackay, 1986). The townsite is highly vulnerable to storm surges and high waves accompanying northwest storms (Rampton and Bouchard, 1975; Solomon et al., 1994). In the Hamlet's

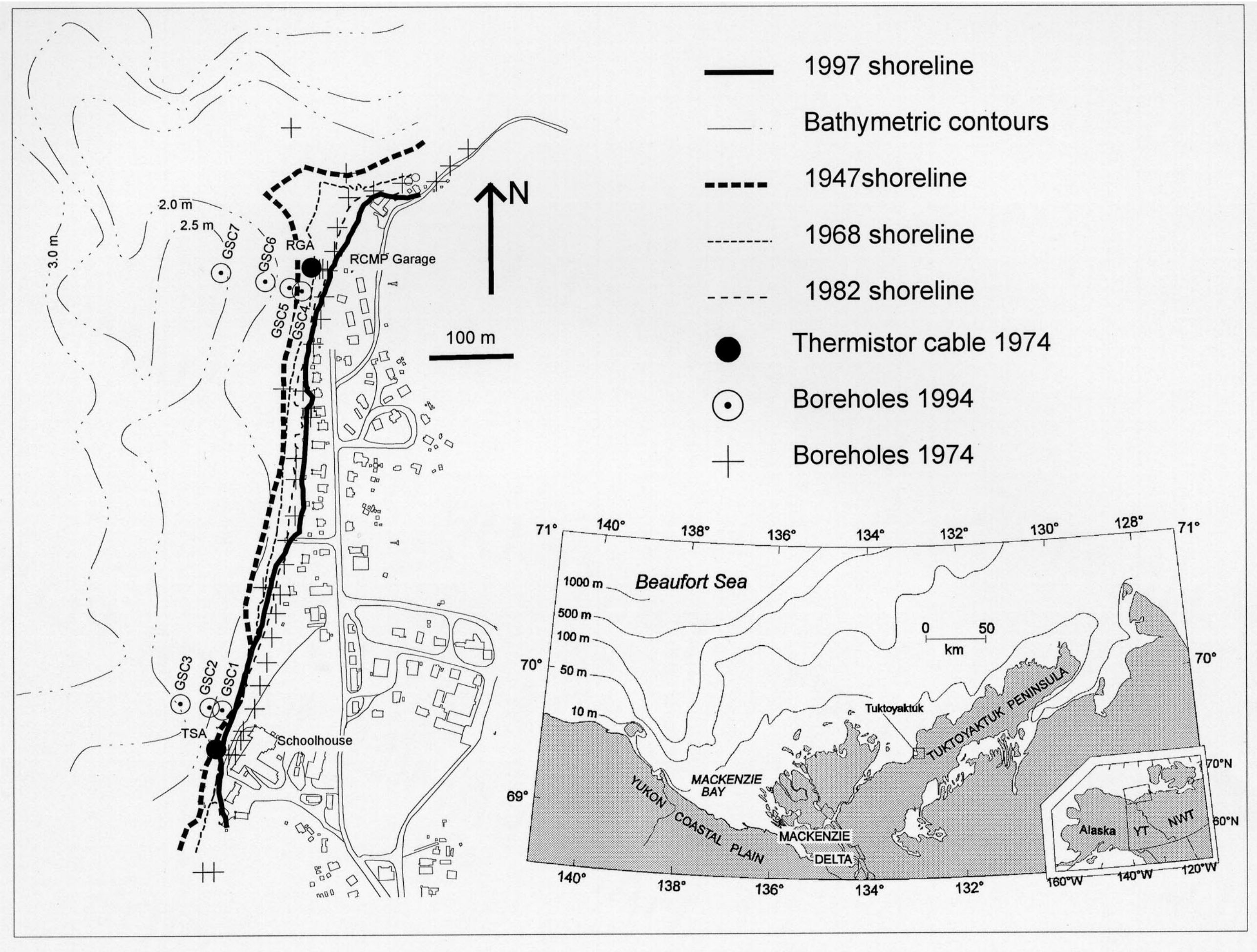

Figure 1. Location of study area (inset) and 1982 base map of Tuktoyaktuk showing cliff lines digitized from 1947, 1968 and 1992 and the location of boreholes and thermistor cables referred to in the text. Bathymetric contours (unpublished data) represent elevations in 1995 relative to mean sea level. Shoreline protection was installed in front of the schoolhouse in 1976 and along the rest of the shoreline in 1987.

short history, erosion has been responsible for the destruction of a curling rink, closure and demolition of an elementary school, and relocation of the RCMP detachment building.

Methods

Historical observations cited in this paper are primarily from engineering studies that evaluate various shoreline stabilization options for the community. The main field program that established permafrost and geologic conditions for these studies was conducted in the fall of 1974 (Kolberg and Shah, 1976). An extensive drilling program was carried out with 46 boreholes drilled at terrestrial and nearshore locations (Figure 1). Although sampling was limited, major sedimentary units, massive ground ice occurrences, and ice-bonding conditions were identified at that time. Three onshore-offshore ground temperature transects were also drilled to characterize nearshore ice-bonding and geothermal conditions. Each transect consisted of closely spaced air rotary boreholes in the beach area and a single borehole drilled in winter, 100 to 150 m offshore. Five supplementary offshore boreholes were drilled in 1986 along a line parallel to the peninsula, approximately 330 m offshore (Aveco, 1986).

Coastal stability studies along the western shore of the peninsula were conducted by the Geological Survey of Canada in the 1990's. This work included precise measurements of coastal positions using multi-year low level aerial photographs and GPS surveys, nearshore bathymetric mapping, monitoring of storm activity and resultant changes in the coastline. A drilling program was conducted in March of 1994 in order to identify nearshore permafrost conditions and subsurface geology, and to assess changes that had occurred since 1974. For this work an ATV mounted CME 750 rotary drill rig equipped with solid stem and hollow stem flight augers and a CRREL coring system was used. Seven holes were drilled along two onshore-offshore transects sited as close as possible to the 1974 locations near the elementary school and RCMP garage. Drilling conditions were challenging, especially in the nearshore area where unfrozen loose sands were encountered at the seabed. However, a number of relatively high quality samples were collected, logged and sub-sampled for physical property measurements, salinity and moisture/ice content determinations. Multi-thermistor cables were installed with daily readings taken to establish equilibrium ground temperatures.

A location map of boreholes drilled in 1974 was registered into a GIS using recently completed surveys (UMA, 1994). The 1994 boreholes were located on the map based on direction and offset from existing buildings (Figure 1). The most appropriate boreholes for comparison with the 1994 boreholes were those drilled in 1974 for thermistor transects at the waterline close to the schoolhouse and the RCMP garage. These are identified as Tuktoyaktuk school A (TSA) and RCMP garage A (RGA). In both cases, the boreholes were drilled at about 0.7 m above chart datum (0.4 m above msl).

Subsurface geology and permafrost

The peninsula on which the Hamlet of Tuktoyaktuk is situated varies in elevation from about 2.5 to 6.5 m asl. Surficial sediments are composed primarily of glaciofluvial sands, typically on the order of 2.0 to 3.0 m thick, and underlain by massive ground ice (Rampton and Bouchard, 1975; Kolberg and Shah, 1976). Boreholes from 1974 revealed that massive ground ice is more or less continuous along the whole peninsula varying from 3 to 6 m thick. The upper and lower surfaces of the ice are undulating and the upper surface appears to roughly conform with the overlying topography. The ice extends below sea level, terminating at an average depth of about 3.0 m below sea level, but may extend more than 5.0 m. The sediment below the ice is typically silty sand most likely of fluvial origin. The ice and included sediments are foliated and folded, indicating that they have been glaciotectonically deformed. Indeed, ^{18}O values of -28.7 and -30.5‰ (SMOW) obtained from ice in an ice cellar in Tuktoyaktuk suggest that the ground ice has a glacial meltwater source (Mackay, 1983). Approximately 400 m of permafrost underlies the Tuktoyaktuk area with shallow ground temperatures recorded from instrumented boreholes on land indicating mean annual ground surface temperatures from -8 to -9°C (Dallimore, unpublished). Estimates of mean annual ground surface temperatures from 1974 boreholes drilled in the beach area are similar or slightly warmer (Kolberg and Shah, 1976).

Nearshore bathymetry and shoreline change

The nearshore bathymetry along the main portion of the peninsula is dominated by a relatively steep inner shoreface with coast-parallel isobaths (Figure 1). This 40-60 m wide zone extends to the 1.2 m isobath with a 1:25 slope. The morphology is more complex at the north end of the peninsula where nearshore slopes are more variable. Photographs and historical accounts from early in this century suggest that this area was sub-aerially exposed (R. Lemeur, pers. comm.). Seaward, between the 1.2 m and 3.3 m isobaths, the sea bed decreases to a 1:70 slope. In this area the seabed is characterized by a number of shallow (0.1-0.3 m) basin-like features and some shore-normal ridges. It is not clear as to whether these are related to permafrost degradation, nearshore currents or ice wallows. Offshore of the 3.3 m isobath, the sea-bed character is more similar to the rest of Kugmallit Bay with very shallow seaward slopes (1:400 or less).

Prior to installation of shore protection, the coast of the peninsula consisted of ice-rich cliffs up to 6 m high, fronted by a narrow gravel beach. Historical shoreline erosion is well-documented by airphotos extending back to 1935. Parts of the townsite experienced more than 100 m of erosion between 1935 and 1971 (Rampton and Bouchard, 1975), suggesting a coastal retreat rate similar to other ice-rich areas along the Beaufort Sea coast in this area (Forbes and Frobel, 1985; Mackay, 1986; Dallimore et al., 1996). However, it is clear that this rate varies considerably depending on location and interannual variations in storm frequency and intensity (Solomon et al., 1994; Solomon and Covill, 1995).

The first documented shore protection measure was an experiment using Longard tubes in front of the now-demolished elementary school in 1976 (Shah, 1978; Shah, 1982). These shore protection measures were all but destroyed by 1981 as a result of vandalism and storms. The character of the shoreline was altered substantially in 1986-87, when fill was brought in to rebuild and regrade the coastal bluffs and sandbags were placed at the back of the beach to protect the bluffs.

Historical bluff retreat based on photogrammetry reveals that erosion has been highest at the north end of the townsite, in the vicinity of the RCMP detachment (Figure 1). In any given airphoto interval, at least 60% of the land lost along the peninsula has occurred in this area (Solomon et al., 1994). Between 1974 and 1987, the cliff edge near the north end of the peninsula retreated approximately 13 m, at which time shoreline protection measures resulted in reconstruction of the shoreline, seaward, by about 7 m. Thus, the present shoreline in the vicinity of the RCMP garage is partially built on the reclaimed beach and nearshore. To the south, near the former elementary school, only about 5 m of cliff edge retreat has occurred in the same time period, partially as a result of the installation of trial shore protection in the late 1970's.

Nearshore borehole transects

GEOLOGY AND GEOTECHNICAL CONDITIONS

Figure 2 summarizes the geology observed in the 1994 nearshore drilling transects along the peninsula. In borehole 94GSC1, drilled at the shoreward edge of the landfast sea ice (rough estimate of shoreline) along the Schoolhouse transect, the geology is similar to borehole TSA drilled close to that site in 1974. Approximately 1 m of beach gravel (perhaps containing re-worked fill) is underlain by about 3 m of pebbly glaciofluvial sand, 2 m of massive ground ice and 3 m of fine-grained, ice-rich sand with deformed ice lenses 5-10 mm thick. Unlike in 1974, when sediments were observed to be well ice-bonded, several thin layers at 3.5, 5.7 and 6.7 m were unfrozen or weakly ice-bonded in borehole 94GSC1. Extracted pore waters from these horizons had 4 to 5‰ salinities, while the remainder of the borehole had essentially fresh pore waters. Approximately 15 m further offshore, at 94GSC2, the strength, ice-bonding and stratigraphy of the sediments changed dramatically. At this location, approximately 1.25 m of sea ice was observed with only 0.15 m of beach gravel at the seabed. Underlying sediments were composed of pebbly sands which were ice-bonded to 3.5 m depth and then thawed to 6.4 m. A hard drilling layer encountered at 6.4 m was interpreted as a contact with well ice-bonded sediments. Pore water salinities were elevated compared to 94GSC1, averaging 8‰. This sequence is interpreted as a thawed equivalent of the stratigraphy in 94GSC1, with complete melt-out of massive ice and icy sand. Higher salinities are likely the result of emplacement of brackish sea water coincident with thawing. If this interpretation is correct it implies that approximately 3.5 m of sediments annually freeze and thaw below the sea bed. Similar depths of annual freezing have been predicted in the sea ice contact zone by others working in the area (Dyke and Wolfe, 1993). The most likely reason seems to be a lack of snow cover in the immediate nearshore area in the winter (<0.3 m) allowing for deep winter freezing. At 94GSC3, approximately 45 m from the shoreline, 0.9 m of water was observed beneath 1.5 m of sea ice attesting to the rather steep nearshore bathymetric gradient. Sediments were unfrozen to 11.2 m, where a hard drilling interface was interpreted as marking the contact with well ice-bonded sediments. The seabed stratigraphy consisted of a 0.7 m thick sandy gravel layer underlain by 1.0 m of soft sandy silt and 0.9 m of pebbly sand. Loose, water saturated sands, susceptible to sloughing below this depth, prevented sampling.

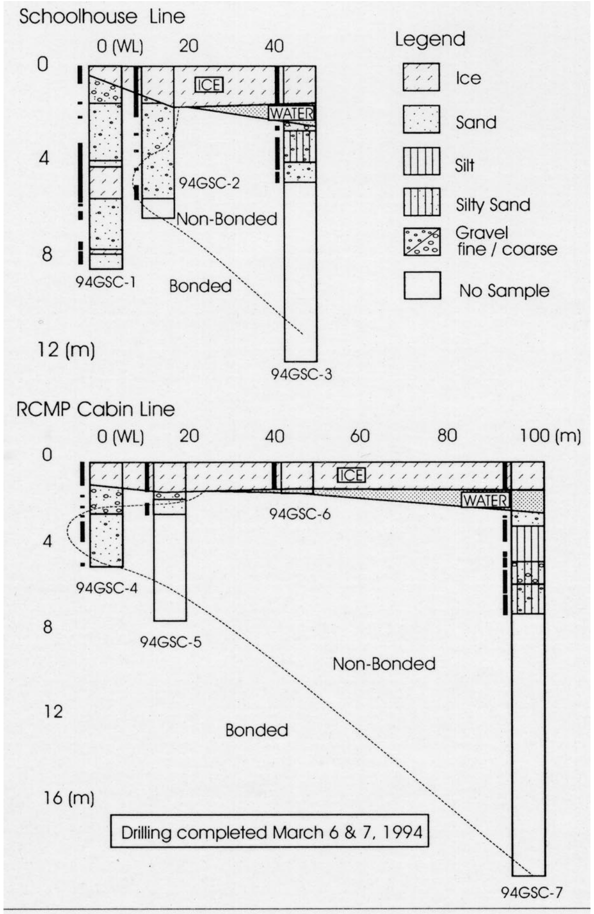

Figure 2. GSC borehole logs from 1994 drilling along the schoolhouse and RCMP garage transects.

At the RCMP transect, 94GSC4 was drilled a few metres offshore of the edge of landfast sea ice with approximately 1.0 m of sea ice in contact with the seabed. This borehole was positioned as near as possible to the RGA borehole drilled in 1974 (Figure 1). The stratigraphy and ice-bonding conditions at this site were similar to 94GSC2. Approximately 1.7 m of ice-bonded sand at the sea bed was underlain by 2.7 m of very loose unfrozen sand with brackish pore water salinities. A distinct well ice-bonded interface was observed at 6.4 m depth. Approximately 15 m from the shoreline at 94GSC5, 1.4 m of sea ice was in contact with 0.55 m of ice-bonded sand at the sea bed. Loose unfrozen sands encountered beneath the ice-bonded sediments presented drilling and sampling problems. A hard layer at 5.8 m was interpreted as the contact with a lower ice-bonded layer. Borehole 94GSC6 was attempted 45 m from the shoreline. However this borehole had to be abandoned as the 0.2 m thick water layer beneath 1.25 m of sea ice was pressurized, with artesian flow occurring onto the ice surface for several hours. Borehole 94GSC7 drilled 100 m offshore on the RCMP transect line had 1.35 m of sea ice and 1.05 m of water. Similar to the offshore borehole at the Schoolhouse line, sediments were non ice-bonded at the sea bed with a hard drilling interface at 18.5 m depth interpreted as the top of a lower ice-bonded interval. The geology was characterized by 0.2 m of sand at the sea bed underlain by 2.2 m of soft, laminated organic silt with peaty organic layers. Pebbly sands were encountered at depth. Given the finely laminated nature of the silts and

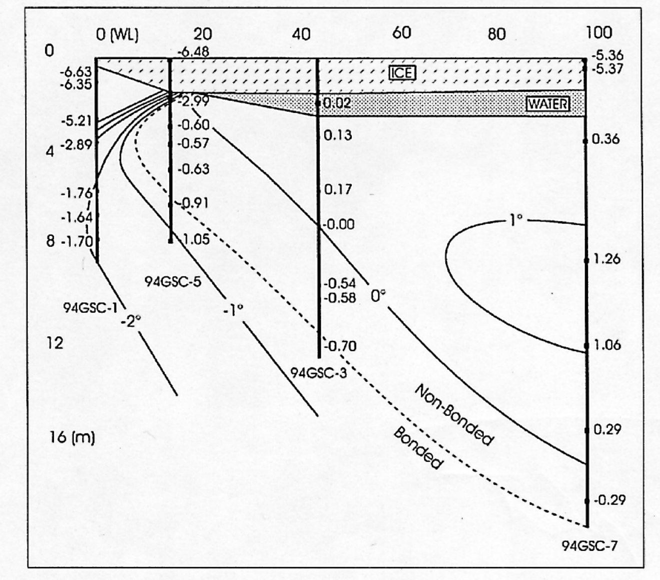

Figure 3. Ground temperature logs and composite profile from temperature data collected April 24, 1994.

the occurrence of terrestrial peat layers, this sequence in interpreted as either submerged lacustrine or lagoonal sediments.

GROUND TEMPERATURES AND ICE-BONDING

Temperature loggers were installed in 94GSC1, 94GSC3, 94GSC5, and 94GSC7 (2 boreholes on each line) with data collected over a 46 day period to ensure dissipation of thermal disturbance due to drilling. The two transects are depicted as a composite section of seabed temperatures from the shoreline to 100 m offshore (Figure 3). Given recent shoreline changes near the RCMP garage, it is unlikely that all temperatures are in equilibrium with annual seabed temperatures near the shore at this location. Nevertheless, this composite profile provides a useful generalization of the subsurface thermal regime along the Tuktoyaktuk shoreline from which several conclusions are drawn.

Mean annual ground temperatures are near 0°C at the ice grounding line and warm offshore to about 1°C at 100 m offshore. In the shoreline area and immediate nearshore, where the sea ice freezes to the bed in the winter, mean annual ground temperatures are below freezing but are still relatively warm. Of particular note, the temperatures recorded in 94GSC1 were some 3 to 5°C warmer than those measured in borehole TSA drilled in a similar coastal position in 1974.

The temperature section also permits examination of the relationship between ice bonding and ground temperature. This clearly illustrates that significant portions of the borehole sediments that are below 0°C are non ice-bonded. In boreholes 94GSC5 and 94GSC3 the interface between non ice-bonded and ice-bonded sediments occurs between -0.7 and -0.9°C. For the most part, this freezing point depression is likely due to the presence of saline pore water. Measured salinities and freezing point depression studies in the laboratory suggest values of 8 to 12‰ are common. For most boreholes, ice-bonded sediments typically showed variable strengths related, in part, to variations in the amount of ice within the soil pores. This is well illustrated in borehole 94GSC1 which had thin soft unfrozen zones at temperatures between -1.6 and -2°C.

Discussion

PERMAFROST AND SHORELINE STABILITY

In their development of a thermal-mechanical model for predicting arctic shore erosion processes, Nairn et al. (1998) emphasized the need to address changes below the waterline including erosion of frozen sediments by warmer seawater and volumetric loss to the sediment balance by ground-ice melting.

Data presented in this paper demonstrate that coastal stability at Tuktoyaktuk is dependent on both thermal and mechanical processes. Subsidence resulting from thermal degradation of massive ground ice beneath the Hamlet peninsula was undoubtedly a primary driving mechanism causing rapid erosion prior to shore stabilization in 1976. Since then, installation of shoreline protection measures and their continued maintenance have slowed the progress of coastal retreat, but have had additional effects on thermal and mechanical coastal processes. These include a reduction in the amount of sediment available for transport (both onshore and alongshore) due to the armouring of the cliff face with sand bags and steepening of the inner nearshore. This steepening, which has likely been further enhanced by thaw subsidence, permits only a narrow zone of bottom-fast sea ice to form, thereby limiting the potential for permafrost preservation. The bottom-fast zone is characterized by a relatively thick frozen layer. For instance, 3.5 m of ice-bonding was observed in 94GSC2, and may be indicative of shallow offshore permafrost. Thaw profiles completed along shore-normal lines in front of the eroding peninsula in July 1994 during the subsequent thaw season confirmed more than 2 m of unfrozen sediments in this zone. In addition, saline porewaters add to seasonal thawing, which is marked approximately by the -0.7°C isotherm. This thaw zone is significant in that, during late-season storm events, much of the sediment lost may be derived from this area which can create significant undercutting of the cliff face and armoured shoreline.

Degradation of massive ice has continued to cause thaw settlement beneath the beach area that has been replaced by sands and gravels on both the Schoolhouse and RCMP transects. At the RCMP garage, the present shoreline is partially built on top of the reclaimed beach and nearshore, which previously experienced higher mean annual temperatures near the waterline. These changes in the shoreline position have resulted in complete melting of massive ice beneath the present shoreline. In contrast, massive ice is still present at the shoreline near the former schoolhouse, although less than observed in 1974. In addition, a comparison of ground temperatures between 1974 and 1994 reveals a strong warming trend at this location, indicating that the coastline has continued to thaw. This volumetric loss due to melting of ground ice creates a sediment imbalance that is further amplified by the reduction in sediment availability due to armouring of the cliff face by shoreline protection measures. Scour of thawed sediments at the base of the steep shore protection may also play a role in enhanced erosion at the RCMP garage.

Strategies for Continued Shoreline Protection

Shoreline protection to date has stabilized the shoreline position since 1974 but has required considerable maintenance. Severe damage by a storm in 1993 demonstrated the tenuous condition of the efforts to date. As a result, the government of the Northwest Territories and the Hamlet have explored a range of alternatives for the future, including possible abandonment (UMA, 1994). Relatively high regional coastal retreat rates in excess of 1 m a^{-1} indicate that, even if erosion at the peninsula were stopped completely, it is likely that the peninsula would be breached at its southern end within 50-100 years. Therefore, the most appropriate long-term response is a phased withdrawal. There is still, however, an immediate need to manage the erosion problem.

A variety of shoreline protection strategies are presently being examined. A plan to sink barges at the northern tip of the peninsula to act as a breakwater was dismissed recently during an environmental review because they were found to be relatively ineffective in reducing wave energy during storm surges (C. Klengenberg, pers. comm.). In addition, the Hamlet has begun mining gravel from the southern spit to place on the beach at the northern end of the peninsula. Limestone boulders have also been purchased from a quarry in Inuvik and were installed at the waterline during the winter of 1996-97.

The observations on thermal evolution of the nearshore combined with analyses of coastal changes (e.g., Solomon and Covill, 1995) provide some guidance for future attempts at slowing the progress of coastal retreat at Tuktoyaktuk. The decrease in the amount of massive ice in the nearshore suggests that the thaw subsidence that assists in driving rapid coastal erosion has been largely completed. Thus, although insulation of the beach to prevent thermal erosion has been previously recommended (Kolberg and Shah, 1976; Aveco, 1986), it may be unnecessary now that most of the massive ice has thawed. However, the lack of sediment available to replace the volume lost due to thaw subsidence has produced an over-steepened foreshore which permits larger waves to attack the shoreline, especially during storms. Placing gravel or boulders on the beach above the shoreline will be relatively ineffective unless it is accompanied by adequate protection at the toe of the beach. Presently, sand bags are continually undermined at the toe of the beach, resulting in breakage and progressive collapse of the upper layers of bags. In 1993, a storm accompanied by high water levels overtopped the shoreline protection at several places, mining out the unprotected fill and causing collapse of the sand bags (Solomon and Covill, 1995). In essence, the sand supplied by broken bags and the underlying fill is scavenged during storms, and contributes to a form of time-release beach nourishment. Future installations will require improved protection against significant storm events and must address the need for nearshore nourishment.

Acknowledgments

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