

## Geological and geotechnical conditions of the Beaufort Sea coastal zone, Arctic Canada



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### Abstract

The coastal zone of the southern Beaufort Sea and Mackenzie Delta forms an extensive area of coastal lowlands in northern Canada. This region is underlain by unstable, perennially frozen soils subjected to high rates of marine erosion and deposition.

The nearshore sediments off northern Richards Island are comprised of a wedge of Holocene marine sand, silt and clay underlain by early Wisconsinan sand and clay. The geothermal regime is complex, reflecting deep permafrost conditions established during a period of terrestrial exposure and more recent marine submergence, which results in moderating ground temperatures and creation of a thick thawed layer at the sea bottom. Geotechnical problems encountered in the nearshore area include frost heave of Holocene sediments, thaw settlement related to degradation of ground ice in the early Wisconsinan sediments, and ice push and scour effects.

Onshore sediments consist of early Wisconsinan and older glacial, fluvial and marine sediments overlain by late Wisconsinan and Holocene, eolian and lacustrine sediments. Ground ice, which forms a significant volumetric component of the near-surface soils, occurs as pore ice, wedge ice, pingo ice and as massive bodies of segregated ice of various ages. Geotechnical problems in onshore areas include thaw settlement due to degradation of ground ice, creep of ice-rich soils and frost heave.

### Introduction

The Mackenzie Delta and coastal areas of the southern Beaufort Sea form a large region of coastal lowlands in northern Canada. Sedimentary basins underlying this area are rich in hydrocarbon resources and anticipated development has created an unprecedented need for detailed information regarding geological and geotechnical conditions. This need is particularly evident in coastal areas where construction of development-related structures is most likely.

The coastal zone as discussed in this paper includes onshore areas and nearshore areas to ap-

proximately one kilometre offshore. Diverse geological materials, complex thermal conditions and the occurrence of various forms of ground ice, present a variety of unique geotechnical problems. As part of ongoing geological and geotechnical studies of the southern Beaufort Sea area, the Geological Survey of Canada (GSC) has carried out a number of regional studies. These have included surficial geology mapping (Rampton, 1982, 1988), geothermal and geophysical studies (Taylor et al., 1982; Hunter et al., 1978), and geotechnical studies (Kurfurst et al., 1984; Kurfurst & Pullan, 1985). Site specific investigations of seabottom and terrestrial sediments have also been carried out along several

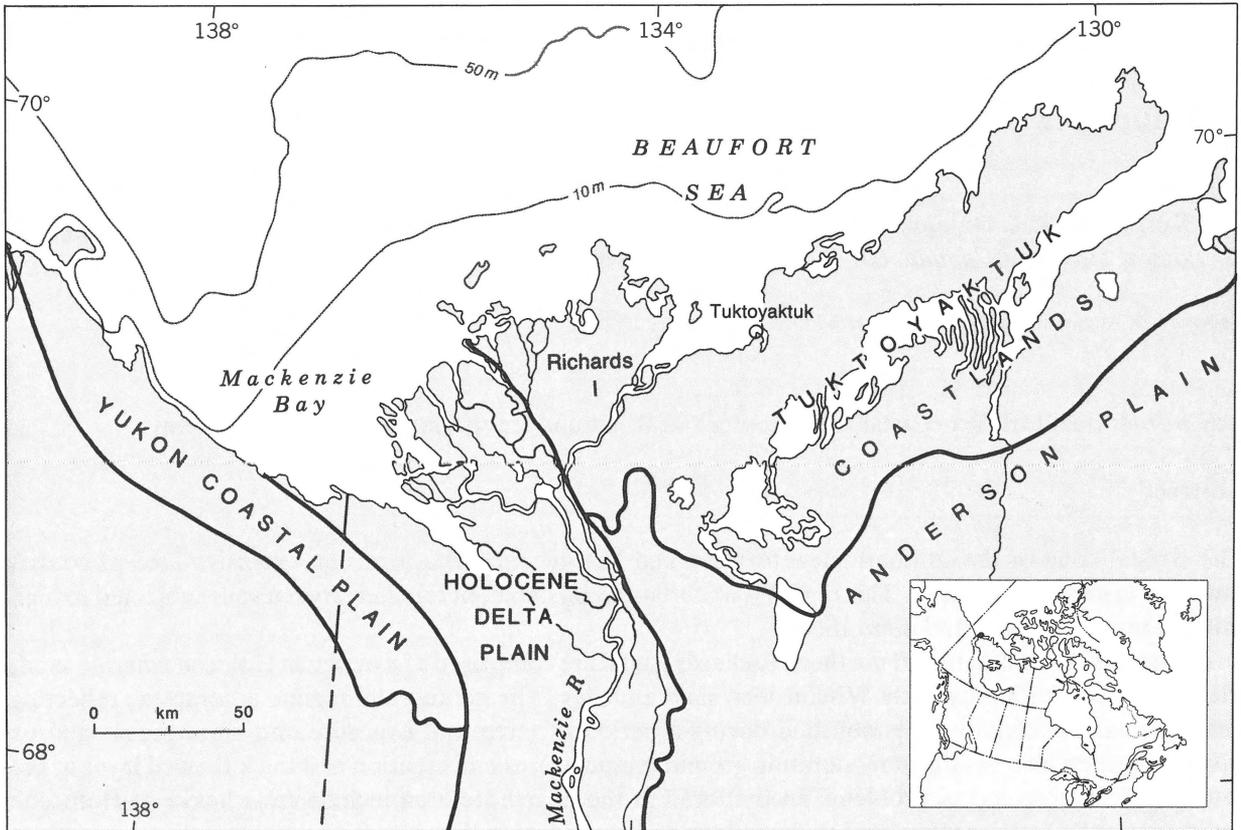


Fig. 1. Physiographic units of the Beaufort Sea coastal zone (after Rampton, 1988).

onshore-offshore transects near areas of particular development interest (Kurfurst, 1984 and 1986; Hill et al., 1986).

This paper discusses the geological conditions of the coastal zone and some of the unique geotechnical problems which are encountered in this arctic environment. Results of recently completed geotechnical investigations along onshore-offshore transects in the vicinity of Richards Island, N.W.T. are discussed in detail.

## Geological setting

### General

The coastal lowland area of the Canadian Beaufort Sea can be subdivided into three general physiographic units (Rampton, 1988), bounded by upland areas to the south. The Yukon Coastal Plain, the

Holocene Mackenzie Delta and the Tuktoyaktuk Coastlands, shown in Fig. 1, form an area over 20 000 km<sup>2</sup> in size. Most of this region is made up of low-lying areas with elevations below 30 m ASL; large areas have elevations below 10 m ASL.

The submarine morphology of offshore areas is complex with a relatively narrow shelf area off the northern Yukon, a deep U-shaped trough in the Mackenzie Bay area and a large shelf area to the east with numerous drowned river channels and other remnant terrestrial features.

### Geology of onshore areas

Thick deposits of unconsolidated Quaternary and Holocene sediments with virtually no bedrock exposures characterize nearly all of the onshore coastal zone. The Mackenzie Delta is located in the centre of this zone, forming an extensive low-lying plain with a maze of lakes and channels (Hill, 1987;

Mackay, 1963a). The Tuktoyaktuk Coastlands and the Yukon Coastal Plain have experienced a complicated Quaternary history during which a variety of sediments of various ages have been deposited. Correlation of Quaternary deposits and events is often difficult (Heginbottom & Vincent, 1986). The oldest deposits exposed on the Yukon Coast are thought to be early Wisconsinan or older glacial, marine and alluvial sediments (Rampton, 1982). In the Tuktoyaktuk Coastlands area pre-early Wisconsinan sediments are extensive and occur as a marine clay and as thick marine and alluvial sand units (Rampton, 1988).

Glacial deposits thought to be related to early Wisconsinan ice advances are widespread in the Yukon Coastal Plain and the Tuktoyaktuk Coastlands area. Late Wisconsinan ice is thought to have been confined primarily to the Mackenzie Valley area. Processes affecting the landscape after the retreat of Wisconsinan ice sheets have continued at varying rates to the present. Postglacial and Holocene sediments include widespread alluvial, lacustrine, and colluvial deposits and local eolian and marine deposits.

#### *Geology of nearshore areas*

Relatively little is known about the surficial geology of the nearshore zone primarily because of difficulties in collecting geological and geotechnical information in this area of shallow water. A simplified model for the surficial geology of the Beaufort Sea has been presented by O'Connor (1983). Three units are recognized, based on the last marine transgression in the area. The oldest unit consists of sediments which were exposed terrestrially prior to submergence. The second unit was deposited during the marine transgression and the third unit consists of fine-grained marine sediments deposited subsequent to this transgression. In the nearshore area, sediments of the first two units are generally present.

#### *Permafrost and Ground Ice*

Permafrost, or perennially frozen ground, is continuous onshore and widespread in offshore areas. The present ground thermal conditions and permafrost thickness reflect a sequence of geologic and

climatic conditions which have occurred since early or even pre-Wisconsinan times. These events include fluctuations in sea level, general climatic warming and cooling, and the presence or absence of insulating masses of glacial ice.

At present, permafrost thickness on land varies from less than 100 metres beneath the flood plain of the Mackenzie Delta (Smith 1975) to over 700 metres thickness beneath Richards Island (Taylor et al., 1982). Offshore permafrost is also widespread in certain areas of the Beaufort Sea. In particular, a substantial thickness of permafrost has been detected offshore in the area to the east of the Mackenzie Delta (Hunter et al., 1978).

Nearly all perennially frozen soils in the coastal zone contain some pore water in the form of ice, with the proportions of ice and water being determined by physical and chemical conditions unique to each soil. In addition to pore ice, ground ice also occurs in the form of thin lenses or veins, and as large bodies of nearly pure massive ice. The type and amount of ground ice is highly variable, being determined by the physical characteristics of the enclosing soil material, the hydraulic and thermal conditions experienced during freezing, cover and preservation of glacial ice, and post-ice formation processes such as creep and glacial tectonics.

#### *Coastal stability*

Much of the coastline of the Canadian Beaufort Sea is undergoing high rates of coastal retreat with only a few areas of local accretion (Mackay, 1963a, b; McDonald & Lewis, 1973; Lewis & Forbes, 1974; and Harper et al., 1985). Maximum retreat rates of over 20 m/a have been measured in the distal areas of the Mackenzie Delta; however, most coastal sections exhibit retreat rates between 1 m/a and 3 m/a (Harper et al., 1985).

#### **Richards Island**

##### *General*

Richards Island is situated east of the modern Mackenzie Delta within the Tuktoyaktuk Coastlands physiographic region (Fig. 1). The island is strategically situated for hydrocarbon-related de-

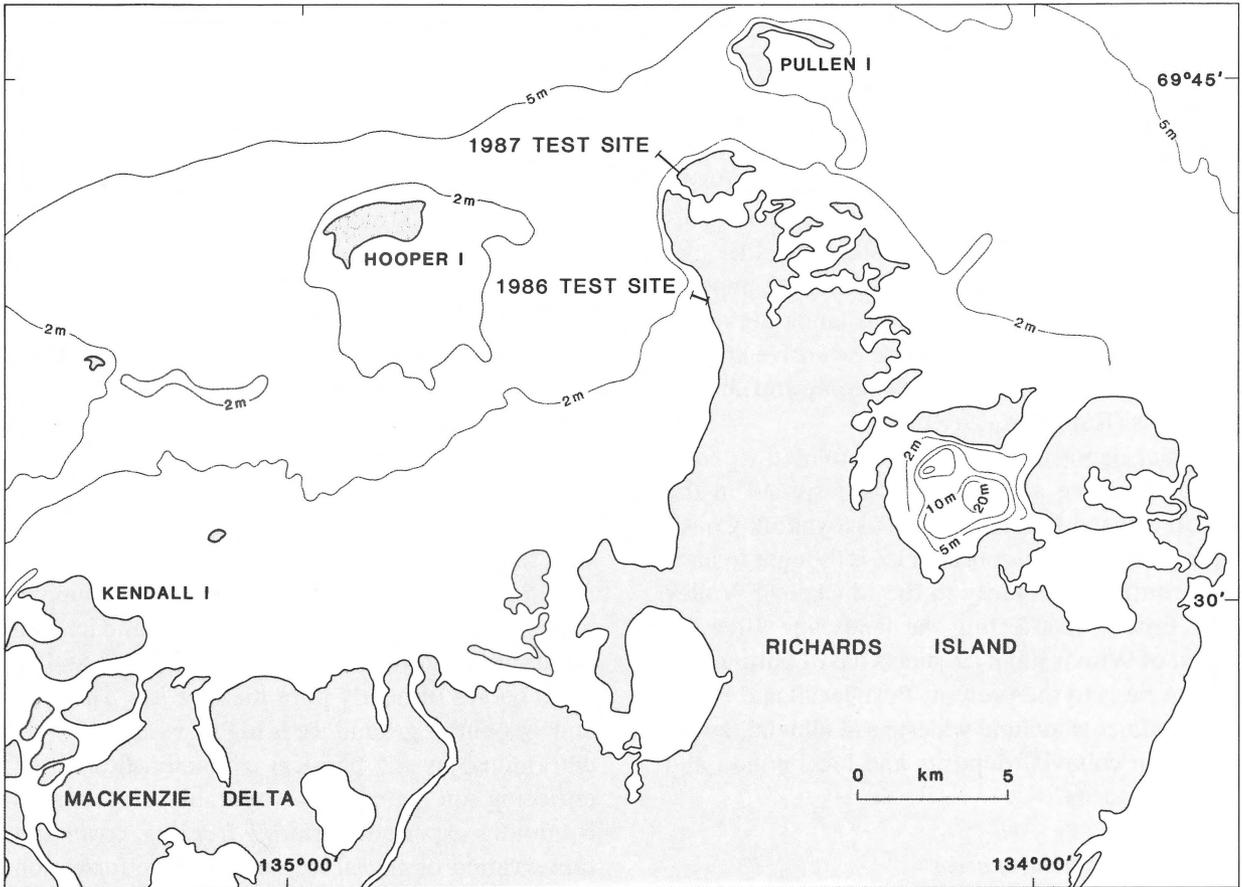


Fig. 2. Richards Island – location of onshore-offshore transects.

velopment with potential production fields located at the western end of the island and in areas immediately offshore. At least two proposed pipeline routes cross the island. One of the proposed pipelines would bring offshore oil from the north with an anticipated landfall near the northern tip of the island.

The topography of Richards Island is flat to gently rolling with numerous small lakes, some of which have been inundated by the sea. Land areas in the northern part of the island are covered by a discontinuous veneer of glacial till which overlies older preglacial sands. The coastal areas exhibit a variety of erosional and accretional landforms. As in other areas of the Beaufort Sea coastline, many localities are undergoing rapid coastal retreat while some appear to be relatively stable. Although conditions

in onshore and offshore areas of Richards Island cannot be considered as a model for the whole Beaufort Sea region, many of the geotechnical problems encountered in this area are similar to those which might be encountered elsewhere.

For structures such as port facilities or offshore/onshore pipelines, the transition between the offshore and onshore areas is critical. The sites for detailed investigations were therefore chosen to study and document geological and geotechnical conditions in this transitional zone. In order to assess the importance of coastal stability, geotechnical investigations were undertaken in 1986 and 1987 at two sites on northern Richards Island (Fig. 2). The 1986 test site is located in an area of stable coastline, whereas the 1987 test site is characterized by active marine erosion.

### ONSHORE-OFFSHORE SECTION - STABLE COASTLINE

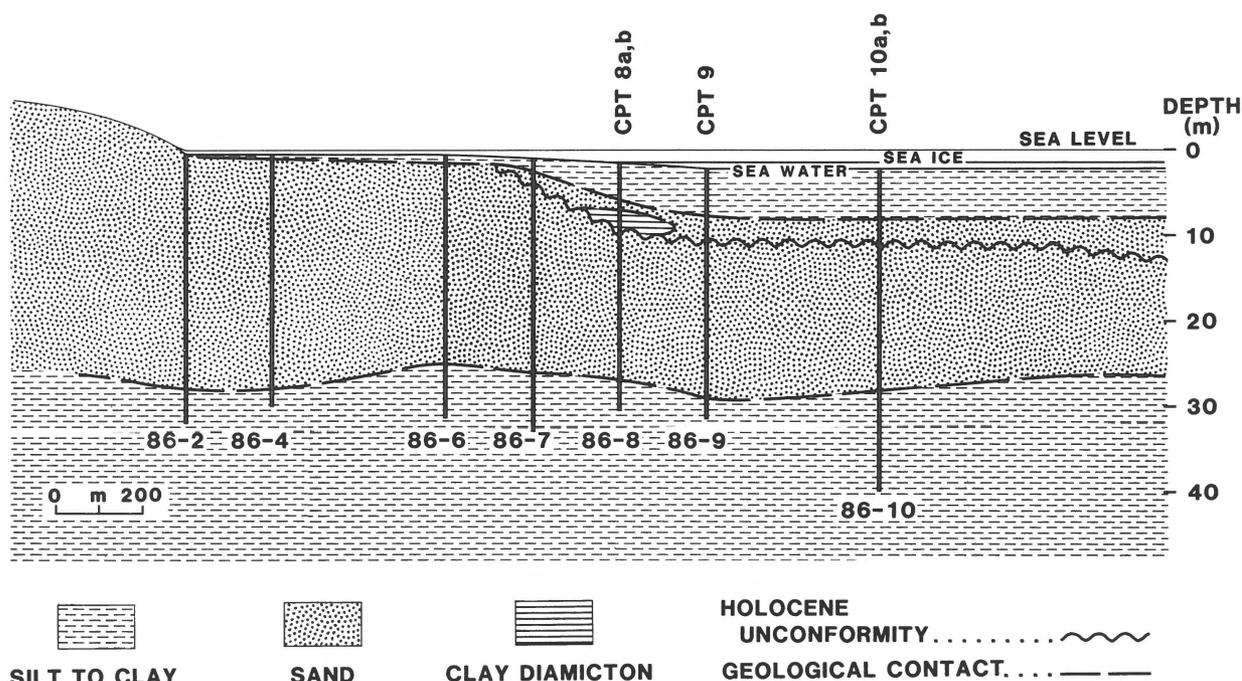


Fig. 3. Stable coastal site – geological conditions.

#### *Stable coastal site*

The 1986 geotechnical investigation was undertaken on the west side of Richards Island in an area which has shown no coastal retreat since 1947. This area has a very gentle offshore profile with gradients of approximately 1.0 m/km. The coast has been stabilized by the development of extensive longitudinal sand bars which have been built up by longshore drift from the southwest.

A summary of the geology of the onshore-offshore transect is given in Fig. 3. A seaward thickening wedge of Holocene sediments occurs in the nearshore zone. These sediments represent a transgressive sequence of reworked sands overlain by fine-grained marine silts. The sediments beneath the Holocene unconformity consist of alluvial sands and marine silts of early Wisconsinan or older age. The early Wisconsinan sand is exposed close to the surface near the coast and is present inland where it is overlain by a discontinuous cover of glacial till and colluvial material.

The ground ice and permafrost conditions at the

stable coastal site are shown on Fig. 4. The 0°C isotherm, which defines the permafrost table, occurs within 50 cm of the surface at the coast at the end of the thaw season in September. It dips very gently offshore to a depth of less than 2 m, approximately 800 m from shore. Beyond this point between boreholes 86-7 and 87-10, the permafrost table dips down more steeply to approximately 10 m depth beneath the sea floor. The zone of frozen sediments near the shore between boreholes 86-2 and 86-7 is caused primarily by the effect of sea ice freezing to the sea bed during the winter. This exposes the underlying sediments to very cold temperatures (Kurfurst, 1986) throughout much of the year. At 800 m offshore the water column is sufficiently thick that a layer of warm sea water is present year round, causing rapid thaw.

#### *Actively eroding coastal site*

The site of the 1987 geotechnical investigation is located at the northern tip of Richards Island. This area is exposed to direct wave action from the

### ONSHORE-OFFSHORE SECTION - STABLE COASTLINE

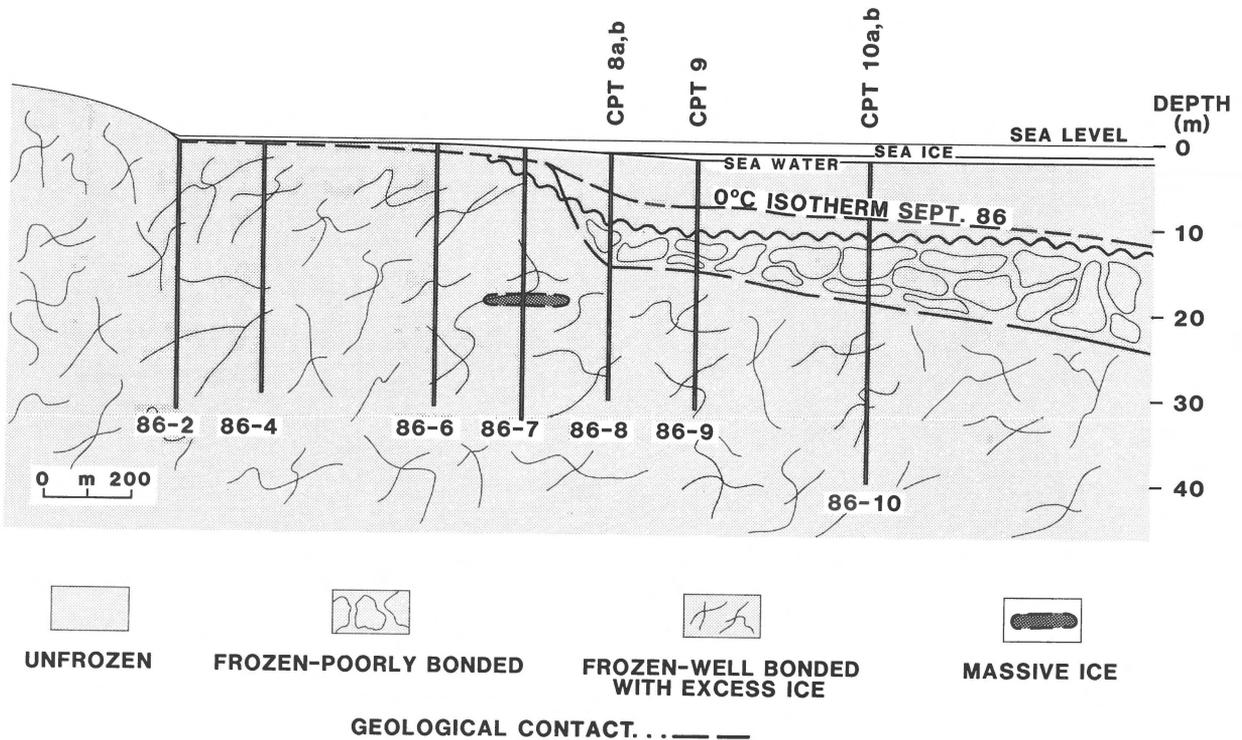


Fig. 4. Stable coastal site – ground ice and permafrost conditions.

Beaufort Sea. Coastal retreat rates measured from sequential air photography since 1947 range from 0.8 m/a to 3.5 m/a. At the site of the onshore-offshore transect, approximately 80 metres of retreat occurred between 1947 and 1985. A nearly vertical coastal bluff approximately 16 m high has developed because of the high rates of erosion.

A summary of the geology at the active coastal retreat site is shown on Fig. 5. Similar to the 1986 site, this site shows a transgressive sequence of re-worked sand overlain by fine-grained marine sediments. The early Wisconsinan sediments, which occur below the Holocene unconformity and are exposed onshore, are more variable than at the stable coastal site. These sediments contain substantial amounts of excess ice in the form of thin lenses and as a pod-shaped body of massive ice exposed just below sea level. It is probable that the higher ice content has contributed to the rapid rate of coastal retreat, accelerating erosion as a result of

ablation and reduced sediment deposition offshore.

The thermal and ground ice conditions of the 1987 transect are summarized on Fig. 6. The permafrost table occurs close to the sea bottom only in the nearshore area within 100 m of the cliff. In areas of deeper water further offshore, the permafrost table dips rapidly away from the coast, as it is influenced by relatively warm year-round sea bottom temperatures.

It appears that offshore areas in this region are experiencing thermokarst-like conditions that are common in the adjacent terrestrial environment. During marine transgression, ice-rich early Wisconsinan sediments are eroded to wave base by melting and wave action. Initially, thaw beneath the sea bottom is limited because of the shallow water depths and sea ice freezing to the bottom. As the coast continues to retreat, the water becomes deeper and thaw is accelerated. Where the early

ONSHORE - OFFSHORE SECTION - ACTIVELY ERODING COASTLINE

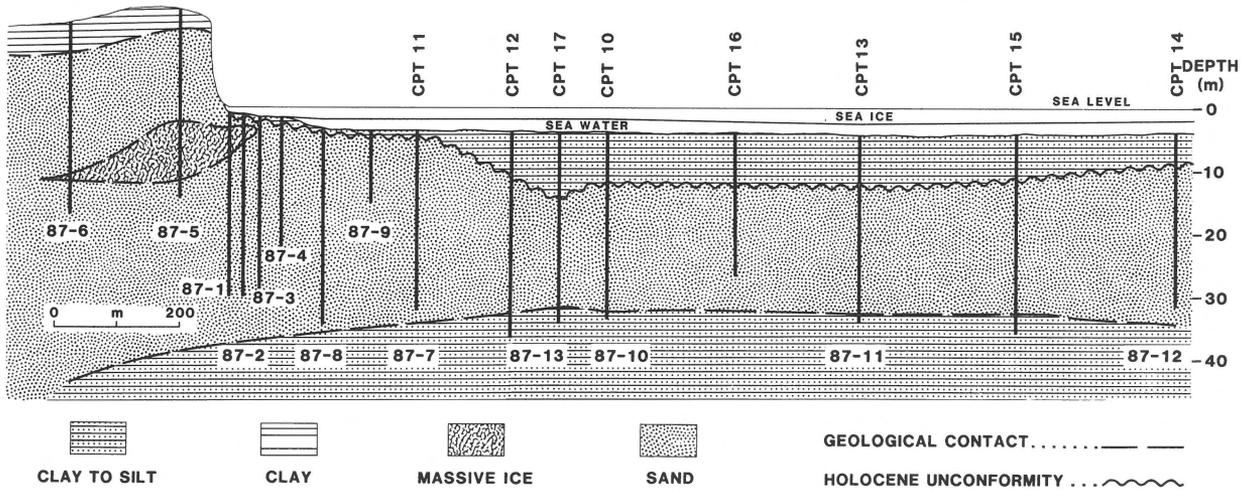


Fig. 5. Actively eroding coastal site – geological conditions.

Wisconsinan sediments are ice-rich, a substantial volume reduction occurs during the thaw process, creating a pitted topography on the sea floor. It appears offshore sedimentation is so rapid that in the vicinity of the 1987 transect the thermokarst depressions are quickly infilled.

Geotechnical considerations

Cone penetrometer tests of Holocene sediments at both sites show that the silts and clays present at the sea bottom are relatively soft materials with low bearing capacities. A further reduction in bearing capacity can be expected in offshore areas where

ONSHORE - OFFSHORE SECTION - ACTIVELY ERODING COASTLINE

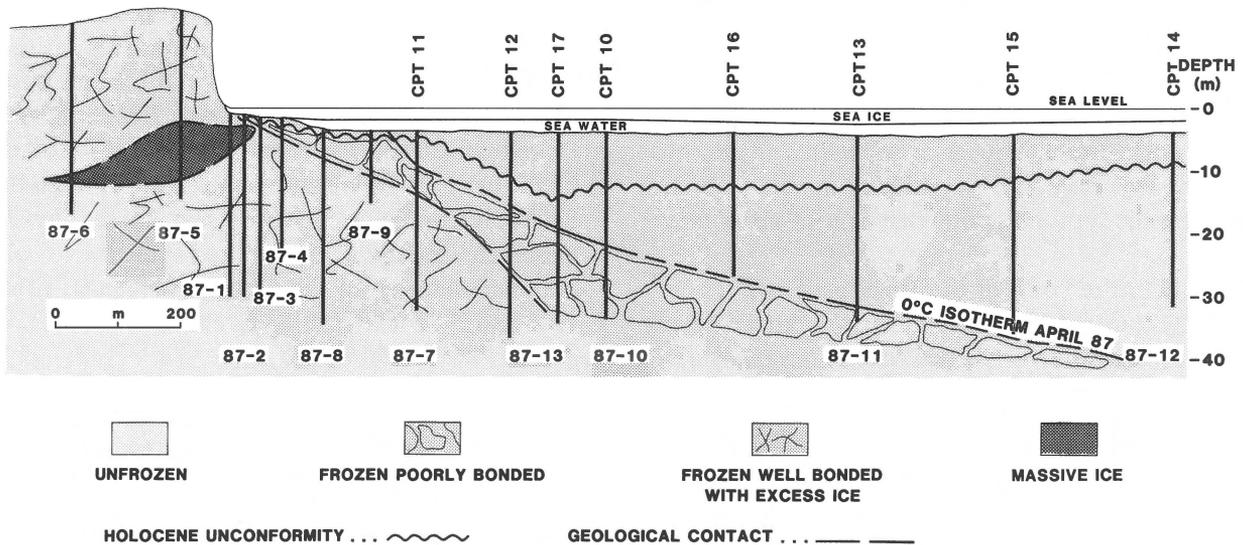


Fig. 6. Actively eroding coastal site – ground ice and permafrost conditions.

ice-rich sediments are thawing at depth. The liberation of water after thawing may also cause high pore water pressures in overlying sediments. Most onshore sediments provide relatively stable foundation conditions provided sediments are preserved in the frozen state. Creep of ice-rich soils and the effect of pore water salinity may negatively effect deep foundations.

Nearshore areas with shallow coastal gradients and water depths less than 1.5 m are likely susceptible to frost heave caused by ice aggradation in the near-surface layer which seasonally freezes and thaws. Further work is being undertaken in the vicinity of the transects to determine the importance of this process. Frost heave is also a major concern in onshore areas, in the active layer, or in areas where drained lakes are experiencing permafrost aggradation.

Thaw settlement caused by melting of excess ice is a major geotechnical concern where engineering structures may alter the existing ground thermal regime. Thaw settlement is also an ongoing natural process in the nearshore area where previously exposed terrestrial sediments are submerged. The amount of settlement expected as a result of man-made or natural thaw is a function of the type and volume of ground ice present, and the physical and hydraulic properties of enclosing sediments.

There are a number of geological hazards which may influence geotechnical design. Although relief in the coastal zone is relatively low, small retrogressive thaw flow slides occur naturally and can be initiated as a result of construction-related disturbance. The weak Holocene sediments in the offshore area may be susceptible to liquefaction due to seismic induced loading or as a result of wave action.

The entire coast of the Beaufort Sea is undergoing constant changes which may affect development facilities well within the lifetime of a particular project. For example, rapid coastal retreat may occur during major storm events. High rates of coastal erosion may be compounded by raised water levels related to storm surges. Conversely, locally high rates of sedimentation in the nearshore zone can affect the construction, operation and maintenance of engineering structures.

## Conclusions

Much of the Canadian Beaufort Sea coastline has been undergoing coastal retreat which has averaged 1–3 m/a during the period 1947–87; however, a few areas of local accretion have also been documented. The nearshore areas to approximately 1 km offshore exhibit diverse geotechnical conditions which may influence the design of hydrocarbon development-related structures such as pipelines, harbours and artificial drilling islands and have negative effects on their construction and performance.

The submerged terrestrial sediments are in a state of thermal disequilibrium which can result in melting of ice-rich sediments and massive ice, resulting in volume reduction and pitting of the sea floor, reduction of bearing capacity, and thaw settlement. Onshore sediments may be susceptible to frost heave, thaw settlement, and the initiation of small retrogressive thaw flow slides by construction-related disturbance. However, the majority of onshore sediments are considered relatively stable foundation materials provided they are maintained in the frozen state.

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