GEOLOGICAL CONDITIONS IN THE COASTAL-NEARSHORE REGION OF THE MACKENZIE DELTA: IMPLICATIONS FOR DEVELOPMENT

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ABSTRACT
Environmentally sound development of hydrocarbon resources in the coastal and nearshore areas of the Mackenzie Delta region will require an understanding of the processes which govern coastal stability and associated nearshore morphology, sediment properties and thermal regime. This region is characterized by extensive shallow water and erosion rates exceeding 20 m per year. Water depths less than 2 m extend offshore from the low delta plain to nearly 20 km seaward of the delta front. Surficial sediment properties established by very limited sampling indicate that the area is dominated by silt and very fine sand, but pockets of coarser material may be associated with seaward extensions of low-relief distributary channels. Shallow onshore cores reveal high ice content in the form of lenses and layers down to at least 2 m below the delta surface. Ice lenses and veins are also found in nearshore cores in water depths out to 1 m. Depth of seasonal ice-bonding below the seabed (the subsea active layer) was found to be 1.9 m in one location. Coastal stability investigations have revealed high spatial variability in rates of retreat and progradation along the delta front. However long-term (decadal) retreat rates have been relatively consistent over time. A lack of detailed information about nearshore shallow bathymetry limits our understanding of processes in the region. New techniques for filling this data gap, including satellite imaging, ground penetrating radar and interferometric sidescan sonar, are being investigated.

RÉSUMÉ
Le développement bien pensé des ressources en hydrocarbures dans les aires côtières et littorales de la région du delta du Mackenzie exigera une compréhension des processus qui déterminent la stabilité des zones côtières et la morphologie des zones littorales associées, les propriétés des sédiments et le régime thermique. La région est caractérisée par la grande étendue des eaux peu profondes, et par un taux d'érosion dépassant 20 m par année. Des eaux de moins de 2 m de profondeur s'étendent à partir de la plaine du delta inférieur sur une distance allant jusqu'à 20 km au large du front du delta. Les propriétés des sédiments de surface, établies à partir d'un échantillonnage très limité, indiquent que le limon et les sables très fins dominent dans la région, mais que des petites zones de matériaux plus grossier sont parfois associées à l'extension vers le large des chenaux distributaires à faible relief. Des forages terrestres peu profonds révèlent un taux élevé de glace présente sous forme de lentilles et de couches jusqu'à une profondeur d'au moins 2 m sous la surface du delta. On trouve également des lentilles et des veines de glace dans les carottes de forage obtenues le long du littoral, dans des eaux d'une profondeur allant jusqu'à 1 m. À l'un des emplacements étudiés, la profondeur de la glace saisonnière sous le fond marin (la couche active sous-marine) fut observée à une profondeur d'1.9 m. Des recherches ayant trait à la stabilité des côtes indiquent une variabilité spatiale importante des taux de retrait et d'avancée le long du front du delta. Par contre, les taux de retrait à long terme (décennal) sont relativement constants. Le manque d'information détaillée concernant la bathymétrie peu profonde du littoral limite notre compréhension des processus actifs dans cette région. L'utilisation de techniques récentes permettant de combler cette lacune, telles la télédétection, le géoradar, et le sonar interférométrique, est à l'étude.

1. INTRODUCTION

Recent increases in the demand for natural gas have stimulated intensive exploration and incited interest in the development of a pipeline from the Mackenzie Delta to southern markets. If this proceeds, construction activities are likely to occur on the coast and in the nearshore. An understanding of the processes which govern coastal stability and associated nearshore morphology, sediment properties and thermal regime is therefore essential for sound and safe development of hydrocarbon resources in the region. The coast and nearshore region in the vicinity of the Mackenzie Delta is characterized by extensive shallow water, large portions of which have never been sounded or investigated for physical properties. In addition, much of the delta front is erosional with maximum erosion rates exceeding 20 m per year. Geoscientific studies have been undertaken by the oil industry and the Geological Survey of Canada intermittently during the past 3 decades. In order to improve our understanding of nearshore sediment conditions and coastal stability we have examined data from previous surveys and existing databases and combined them with information from more recent studies. This paper will provide a summary of the historical data in the nearshore areas and a preview of results from new investigations in the region.

2. STUDY AREA AND ENVIRONMENTAL CONDITIONS

The study area encompasses the coastal and nearshore regions of the modern Mackenzie Delta and adjacent uplands (Figure 1). It extends from water depths of approximately 4-5 m to the limits of marine inundation (ca. 2.5 m above mean sea level).

The coastal areas of the Beaufort Sea are ice-covered for 8 to 9 months of the year. Freeze-up begins typically in October and break-up in June (Environment Canada). The ice is often frozen to the seabed in water depths less than 1.5 m. Floating landfast ice extends offshore to a shear zone at the edge of the mobile polar pack. Pressure ridges, which develop in the shear zone, cause widespread scouring of the seabed in water depths greater than 8 m (Myers et al. 1996). The landfast ice zone is most extensive in the Mackenzie Delta region. The sea ice forms a protective cover preventing wave attack at the coast during this time period.

During the open water season, ice-free fetches of several hundred kilometres are common. Strong winds, which become increasingly frequent in late August and September, blow predominantly out of the west and northwest, with a secondary mode from the east. Winds blowing over open coastal waters generate significant wave heights of 4 m or more with peak periods up to 10 s (Pinchin et al., 1985). The range of astronomical spring tides is no more than 0.5 m, but winds can generate positive and negative storm surges (Henry, 1975). The maximum storm surge limit in the Tuktoyaktuk area is about 2.5 m above mean water level (Forbes and Frobel, 1985; Harper et al., 1988). Water level changes during surges occur over a few hours and can generate significant currents (>0.5 m/s) within restricted embayments (Solomon and Forbes, 1993). Higher water levels during storms also allow larger waves to reach the shore and increase the limit of wave run-up. These northwest storms with attendant waves are responsible for suspending and transporting sediments in water depths of less than 10 m. Sediment transport from west to east is responsible for the development of large sand and gravel spits and barriers associated with exposed headlands.

The Mackenzie River is one of the primary sources of sediments to the coastal, nearshore and marine environments. The mean annual suspended sediment load (> 90% silt and clay) delivered to the delta is estimated to be 128 Mt with about 4 Mt of sandy bed material (Carson et al., 1998). Approximately half of that material (65±15Mt) is estimated to be deposited in the delta itself (MacDonald et al., 1998) leaving about 63 Mt to be deposited in the marine environment. Since virtually all of that material is finer than sand sized, it is likely that it is only deposited in the nearshore where it is sufficiently sheltered so that it is not resuspended and advected offshore during storms. Coastal erosion also supplies sediment to the nearshore and marine areas. MacDonald et al. (1998) estimate that subaerial erosion of coastal bluffs supplies 7.1 Mt per year of material to the shelf.

2.1 Delta and Nearshore Morphology and Surficial Geology

The shoreline of the main delta is characterized by lobe-shaped vegetated islands separated by funnel-shaped bays (Hill et al. 2001). The islands are fronted by erosional coastal scarps composed of peat, silt and fine sand which are eroding at mean rates of 2.5 m a^{-1} (Harper, 1990) and up to 10 m during single storm events. Scarp heights range from 1-2 m above mean sea level and flooding at the outer coast is common, based on the presence of fresh rippled silt burying vegetation on the delta surface after a storm surge. Bar accretion occurs in the interior of large embayments where they may be emergent and at the mouths of distributary channels where they are lower. The erosional nature of the delta front, drowned morphology and other features indicate that the Mackenzie River delta is undergoing transgression resulting in limited water depths for sediment accumulation (Hill et al., 2001).

In many locations along the Mackenzie Delta front, beaches are not present or consist of several decimeters of detrital peat overlying silt to fine sand. Undercut, cohesive blankets of vegetation often armour the low scarps and peat balls and lumps litter the nearshore adjacent to the scarp. In place, inliers of Pleistocene sand and gravel form headlands and islands standing 10 to 20 m above the adjacent Delta and host wide fringing beaches and extensive spits and barrier islands (Rampton, 1988).

In general, the nearshore in front to the modern Delta is very shallow. Water depths are less than 2 m at distances in excess of 15 km from the shore, except where channels are present. Where channels do exist, they do not cross the inner shelf, but terminate by shoaling. The termination has the appearance of broad distributary mouth bar (Hill et al., 2001). Hydrographic surveys in the study area are difficult because of the shallow water depths. Limited side scan surveys in the region in water depths of less than 4 m suggest that transient shallow scours form due to moving ice, possibly during break up of the landfast and bottom fast ice cover in the spring (Zevenhuisen and Solomon 1994). In water depths of less than about 1.5 m, sea ice freezes to the seabed, generally confining winter river discharge to the channels. However, adfreezing of sediments to the base of the ice suggests that it may be periodically lifted off the bed by tides and/or storm surges.

Beach and nearshore profiles on the seaward edge of the outer islands in front of the Delta (Ruz et al., 1992), at North Head and along the southern parts of the Kugmallit Bay coast are similar in that they flatten out at depths of several metres. Barred coasts tend to form where supplies of sand are large due to erosion of updrift sources (e.g. the west side of North Head – Figure 1), but they are less common than unbarred coasts. In sheltered locations where sand supply is large, shore-attached oblique or transverse bars form (Solomon, 2002).

2.2 Coastal stability

Coastal stability refers to the tendency for the coast to erode or accrete. Based on air photo analysis, most of the modern delta front is erosional (Harper et al., 1990; Solomon, in press). The erosional scarps on the exposed outer delta front exhibit some of the most rapid rates of retreat (mean of –1.8 m a^{-1}) in the region. Maximum retreat rates are approximately -17 m a^{-1} and there is no change in the rate between 1972-1985 and 1985-2000 (Solomon, in press). These rates are also similar to those measured by Harper et al. (1990) for the period 1950-1972. Variability is also high within the zone with localized retreat rates ranging from -17 m a^{-1} and progradation rates up to nearly 7 m a^{-1}. There are stable or accretional segments of coastline. These tend to be located in the lee of newly accreted shoals and islands at the mouth of an active distributary channel (cf. Jenner and Hill, 1998). Rapid retreat is centred on sections of coast which are exposed to the west and northwest as well as in locations which appear to be quite sheltered (along channels between the modern delta and coastal islands composed of older terrain). This spatial pattern of retreat and accretion has been constant on a decadal basis although infrequent storm events are responsible for retreat rates which are much higher than the average.

Relatively high mean rates of retreat (-1.3 to -1.7 m a^{-1}) are also associated with exposed fringing tundra islands and headlands. The highest individual measured retreat rates (up to -22.5 m a-1) in the region are associated with these features. The bluffs range from 5-30 m and are composed of sand and gravel with local high ice content. Lower elevation, drained lake bluffs that are characterized by finer sediments are also present; these are where the highest retreat rates are found. However, in general, there is little difference between retreat rates of ice-rich tundra and drained lake shores. Lower rates of retreat are found along south and east-facing shorelines. There are notable gradients in local retreat rates that are related to well-defined littoral cells. At one location retreat rates decline downdrift from the western end of the coastal reach (from -3.7 m a^{-1} to less than -1 m a^{-1}).

The fringing tundra islands are directly exposed to the high winds and associated storm surge and waves from the NW. Water depths in the nearshore increase fairly rapidly, allowing larger waves to impact directly on coastal bluffs during high-water events. Less intense events with lower associated water levels may have less impact than infrequent more intense storms (Wolfe et al., 1998). Gradients in erosion rate are related to variations in exposure and to updrift sediment supply. In the latter case, lower retreat rates in some downdrift locations are a result of buffering and protection by sediment deposition on the beaches and nearshore.

2.3 Permafrost

The modern delta is underlain by permafrost to depths of more than 60 m (Dallimore and Matthews, 1997). The permafrost formed as deposition raised the subaqueous delta above sea level during its aggradation over the past 10,000 years. At a geotechnical borehole drilled 25 km landward from the delta front, permafrost conditions were established within the past 4500 years (Unipkat borehole - Taylor et al., 1996). In the adjacent older upland areas, permafrost has formed over a much longer time period and can reach over 700 m in thickness on Richards Island (Judge, 1986). Taliks, in some cases extending entirely through the permafrost layer exist under lakes and river channels which are deeper than 1.5 m (Mackay, 1979 as cited in Hill et al., 1990). Permafrost also exists beneath the Beaufort Sea as sea level has risen and transgressed over surfaces which were previously subaerial (Mackay, 1972). Active layer thickness on the delta varies between 0.6 and 1.3 m depending on sediment type and surface characteristics such as snow cover and vegetation (Circum-Arctic Active Layer Monitoring - www.geography.uc.edu/~kenhinke/CALM/).

Permafrost distribution in the coastal regions is complex because the thermal environment changes so rapidly from the subaerial to the submarine conditions. The region includes the inter- and supratidal environments of the beaches and flats. Tides, waves and storm surges periodically inundate these environments, winnowing or depositing sediments, adding salts and affecting the thermal regime (Are, 1988). Thaw rates and active layer thickness in intertidal zones are controlled by sediment texture (i.e. permeability), sea water salinity and temperature, snow cover, erosion and deposition of sediments, and air temperatures. The mean annual ground temperature regime in the coastal zone is largely unaffected by vegetation, however snow cover and sediment dynamics do play a role (e.g. Dyke and Wolfe, 1993; Dyke, 1991). Sediment deposition raises the intertidal surface insulating and protecting permafrost beneath whereas erosion exposes permafrost to degradational influences (positive water and air temperatures, elevated salinity).

High ice content in the form of pore, wedge and massive ice is typical of some coastal localities. Where deposits with high excess ice content straddle the water line, rapid subsidence will take place when thaw fronts intersect them (e.g. Wolfe et al. 1998). Thermokarst depressions resulting from thaw consolidation in nearshore and coastal environments are likely to be quite transient as sediments from adjacent areas are scavenged by normal coastal processes. However, the accommodation space created by intertidal thermokarst processes may play a role in forcing local erosion rates and nearshore thermokarst could have substantial impacts on coastal infrastructure (e.g. pipelines).

Where the maximum winter ice thickness exceeds water depth the ice freezes to the seabed (becomes “bottom-fast”). The thermal state of the seabed within the bottomfast ice zone depends on mean annual bottom temperatures which depend in turn on water depth (effectively determines the date at which the ice becomes bottom-fast) and sea water temperature during the open water season. In this situation, permafrost, if it exists, can be aggrading (in shallower water) or degrading (where water depths are greater). Subtle changes in water depth (on the order centimeters) or ice thickness can make a significant difference in the thermal state of the nearshore sediments since that will determine to what extent (if any) the seabed is coupled to very cold winter air temperatures.

Once the sea ice is bottom-fast, a seaward-thinning seasonal active layer develops (e.g. Osterkamp et al. 1989; Dyke, 1991; Wolfe et al. 1998). This zone is also characterised by very high horizontal temperature gradients and seasonally reversing vertical subbottom temperature gradients affecting seabed sediments to depths in excess of 10 m (Hunter, 1988). Beyond the bottom-fast ice zone out to 10 m water depth range, mean annual seabed temperatures are above 0°C because of the influence of the warm Mackenzie River plume (Hunter et al, 1976). Therefore permafrost degrades from the top. The depth to the top permafrost in this zone increases to 10s of metres in many locations (O'Connor and Associates, 1982; Hunter et al, 1976).

2.4 Sea ice processes

As mentioned above, sea ice covers the surface of the Beaufort Sea for 9 months of the year. Sea ice formation is thought to play a significant role in the transport of sediments in the nearshore regions of the Alaskan North Slope (Reimnitz et al. 1993). Here frazil ice formation in the early freeze-up season entrains sediments in the rapidly forming ice canopy. The ice and entrained sediments are advected off the shelf during breakup. Sediment concentrations in the sea ice near the Mackenzie River region of the Beaufort Sea range from 4-862 mg L^{-1} (Forbes and Taylor, 1994).

Sea ice is also present during the breakup of the Mackenzie River so that a portion of the sediment-laden spring freshet waters flood out over the surface of the ice. This process is known to lead to the formation of strudel scours on the seabed beneath drainage holes along the Alaskan North Slope (Reimnitz et al. 1974). Strudel scours may excavate to depths of several metres below the seabed surface. While there are no documented occurrences of strudel scour in the Mackenzie region (Pilkington and Associates, 1988), the conditions for their formation exist. According to Hill et al. (2001), most of the spring discharge flows out of the delta via sub-ice channels, bypassing the zone of bottomfast ice.

Since virtually all of the Mackenzie Delta is well within the zone of landfast ice (Dickens, 1987), the processes of ice push and ice ride-up have not been recognized and are not likely to occur. Small ice pile ups 1-2 m in height were observed in Kugmallit Bay in March 2004. These are thought to have formed during late fall or early winter storms which cause the newly formed ice canopy to break up temporarily.

3. RECENT RESULTS

3.1 Sediment properties and bathymetry

The Beaufort Sea Geotechnical Database (supplied by Indian and Northern Affairs Canada) and the Expedition Database of the Geological Survey of Canada (Atlantic) were examined as part of an ongoing effort to compile existing information about sediment texture and thermal state of the nearshore in this region. Recent data compilations in support of Marine Protected Area proposals in the area were also examined (Solomon, 2004). The databases were imported first into spreadsheets for sorting and filtering, then into a GIS for spatial analysis. Nearshore bathymetry was explored using hydrographic charts and field sheets (both analogue and digital). These were acquired from the Canadian Hydrographic Survey and their agents, digitized if necessary, and imported into a GIS for analysis and generation of a digital elevation model (DEM).

A digitized field sheet (FS1300962) based on data collected in 1974 and 1976 with 500 m line spacing illustrates some details of the Delta front morphology (Figure 2). A DEM was generated for this area and 1-metre contours were extracted using GIS software. The 1-metre contours are convex offshore suggesting sediment deposition at the mouths of several channels at the north edge of the delta. This region is characterized by inliers of older Pleistocene uplands which are being over-run by modern deltaic sediments. Channels cross part of the inner shelf and then shoal in water depths of about 1.5 m. In one instance a channel shoals in an embayment defined by islands composed of Pleistocene inliers. The islands have large well-developed shoals on their southeast sides, whereas to the west and north, water depth increases more rapidly. Beyond 2 m water depth, the isobaths become more or less shore-parallel.

Core and grab samples from both government and industry span the period from the late 1960s to the present. Sample distribution is sparse in the shallow waters (less than 2 m) which front the delta. On average there is about 1 sample location (core, borehole or grab) every 15 km^2, although the distribution is quite spotty. Many of the locations were sampled by industry in support of site surveys for artificial island construction and aggregate exploration in the 1970s and 1980s. Analysis results vary considerably in detail and quality. In many cases only grain size statistics are available, such as mean and percentage of textural classes. In other cases grain-size curves are available in analogue or digital form.

In general, sediments are composed of silt with variable amounts of clay and sand. Surface samples from several cores collected less than 300 m from the shoreline are characterized by unimodal grain size distributions with D_{50} of 0.05-0.06 mm (coarse silt), less than 2% clay-size materials and more than 25% sand. In the vicinity of Kendall and Garry Islands, the surface samples average 68% silt and 23% sand with the remainder composed of clay. In contrast to the shallowest areas, descriptions of several cores in water depths of 2-3 m indicate that this depth zone is characterised by thick beds of fine to very fine sand with interbedded silt (Hill et al., 2001).

Out of 132 industry boreholes in water depths of less than 5 m, only 9 surface samples were identified as sand- or gravel- dominated, the remaining samples were classified as silt. The coarse samples are almost invariably associated with spits or barriers. In most cases, the silt-sized sediment is classified as either non-plastic or of low plasticity.

The database also includes information about the presence or absence of ice bonding. The geotechnical boreholes were drilled between the end of February and the beginning of May from the surface of the ice, therefore the presence of ice-bonding in the surface samples is an indication of a seasonal active layer (where it overlies permafrost) or seasonal frost, and an indicator of bottomfast ice. Frozen surface sediments were found in 31 out of 132 boreholes drilled in water depths of less than 5 m. The average water depth associated with ice-bonded sediments was 1.1 m with a range of 0 to 2.13 m (only 1 location exceeded 1.5 m water depth).

Several shallow cores were obtained by the GSC in 1993 (Solomon, 1993) in a transect extending 500 m seaward from an eroding delta shoreline. The frozen surface layer was observed to be 1.9 m thick at one location where ice was 1.6 m thick Stratified and randomly-oriented visible ice was found in the upper 1-2 m of cores where ice was bottomfast. In one core, the uppermost 30 cm of ice-rich silt was underlain by 20 cm of clear ice, suggesting that sediment had frozen to the ice and subsequently been lifted off by water-level changes (tides and/or storm surge) prior to freezing to the bed again. This phenomenon was observed in a field survey in 2004 as well.

3.2 Bottomfast ice mapping and radar satellite Imagery

Backscatter variations identified in radar satellite imagery (e.g. Radarsat, ERS1 and ERS2) have been used to delineate the distribution of bottomfast ice (BFI) in lakes in Alaska (Jefferies et al. 1994). The backscatter signature of BFI is lower than that of the adjacent floating ice because the radar signal can penetrate through the freshwater ice and is attenuated in the frozen sediment beneath. Where ice is floating, the backscatter signature is higher because the radar signal is reflected back from the ice-water interface. The key to the application of this technique in the estuarine/delta environment characterized by the Mackenzie River delta is the salinity of the nearshore waters and the sediments beneath. The technique has been applied in the Laptev Sea at the mouth of the Lena River Delta (Eicken et al. in press). Nearshore ice and sediment cores from the delta front acquired in 1993 indicate that both sediment and the overlying ice canopy are essentially fresh. Salinities based on refractometer measurements are less than 2 parts per thousand in both ice and sediments. This information suggests that techniques used in lacustrine settings may be applied in the shallow, fresh portion of the delta.

Radar imagery data from the Canadian Radarsat satellite and the European Space Agency's ERS1 were acquired and imported into an image processing package. The images were georeferenced to a Landsat 7 image (already georeferenced) and adjusted for optimal contrast. Qualitative analysis of the imagery was undertaken to map areas of low backscatter in shallow water in order to examine their relation to the distribution of bottomfast ice.

ERS1 imagery of a portion of the delta front at the mouths of several distributary channels shows a distribution of low backscatter (seen as relatively darker areas in Figure 2) which is similar in shape to the 1 m contours shown from the field sheet described above. However, water depths at the outer edges of the high backscatter region vary considerably from about 0.5 m to 1.4 m water depth. Ice thickness on the approximate date of the image was 1.6 m. These data suggest that water depths shallower than the nominal ice thickness may be misclassified as floating ice. In that sense, the radar interpretation appears to under-predict the extent of BFI. Ground penetrating radar surveys undertaken in support of ice thickness mapping for the oil industry generally corroborate the satellite-based interpretation. The lack of consistent correspondence between the area of BFI and water depth may also reflect the 20 year hiatus between the imagery and the bathymetry or natural variations in ice thickness due to currents. Work is currently underway to better understand the relation between radar backscatter and BFI distribution along the delta front using ground penetrating radar (GPR), coring, and up-to-date bathymetry.

4. DISCUSSION

Hill et al. (2001) propose a model to account for the distribution of sedimentary facies found in cores in the nearshore region along the delta front. The model suggests that the region shoreward of the 2 m isobath is largely bypassed by sediments because of, channelization in the winter, overflooding and channelization in the spring, and frequent resuspension during storms in the summer. The authors assume that ice in much of the area shallower than 2 m is bottomfast and that sub-ice channels extend beneath the ice and across this portion of the inner shelf. The model would suggest that there is potential for extensive shallow seasonal frost in this depth zone outside of the channels and that high velocity flows during breakup are mostly confined to channels.

This hypothesis has implications for pipeline development in the region. If most of the river outflow is channelized, then the depth of scour and sediment properties will likely be very different in the channel and inter-channel areas. The latter regions may be relatively stable, except during storms in the open water season when sediment is suspended and re-deposited, whereas channels may be scoured primary in the spring. Bottom-fast ice also implies the potential for near-surface ice-bonding in the winter, which would influence dredging and trenching activities. As illustrated above, there is very little recent detailed bathymetric information in this region to support or contradict this model. Initial interpretation of bottomfast ice distribution from satellite imagery suggests that the extent of the BFI may be quite limited and that much of the area less than 2 m may not be bottomfast. Near-surface freezing and permafrost aggradation is therefore likely to be more restricted and under-ice flows may be much less confined by sub-ice channels then predicted.

The technique for mapping BFI from radar satellite imagery may also be flawed and be under-predicting the extent of BFI. However, if we can develop a better understanding of the relations between BFI and radar backscatter, this technique may be our best hope for extensive mapping in a zone where it is mostly too shallow to use conventional echosounding and too turbid for bathymetric LIDAR.

Rapid deposition from suspension during waning phases of storms is thought to characterize water depths of 3-4 m. Sandier, thicker beds in the shallowest water thin and fine offshore (Hill et al., 2001). Sandy beds with scoured bases suggest that there is potential for exhumation of pipelines once they are laid, and for infill of trenches during the open-water season. These interpretations are based on a few cores located at the southern end of the delta (in Mackenzie Bay – see Figure 1). There is a lack of data on which to define the distribution of potential storm-related scour and scour depth. There is also virtually no data on the magnitude of under-ice flows during the spring freshet, during which scour could also occur. Shallow-water multibeam bathymetry using interferometric sidescan techniques along with sub-bottom profiling could help to map scours or scour infill following spring break-up and after storms. This information will also be essential to develop an efficient sampling and coring program to investigate physical and geotechnical properties of sediments and to define geohazards related to pipeline planning and design. Measurements of currents under-ice and during the open- water season and combined wave and current velocities are also critical to an evaluation of geohazards in the shallow waters of the delta front. This is an extremely hostile environment for instrument deployment. Installation and recovery are also challenging in shallow waters that are also quite far from shore.

Finally, rapid coastal change represents a design consideration for pipeline landings and onshore infrastructure. Recent measurements and mapping of shoreline change rates provide guidance for the development of set-back standards in the region. The impacts of potential climate change (especially accelerated sea level rise, reduced ice cover and longer open-water seasons) on shoreline stability remains an outstanding question. A better understanding of the erosion processes in the high latitude delta setting would help reduce uncertainties which may result in higher safety factors (e.g. greater set-back, deeper trenching at approaches) and associated costs.

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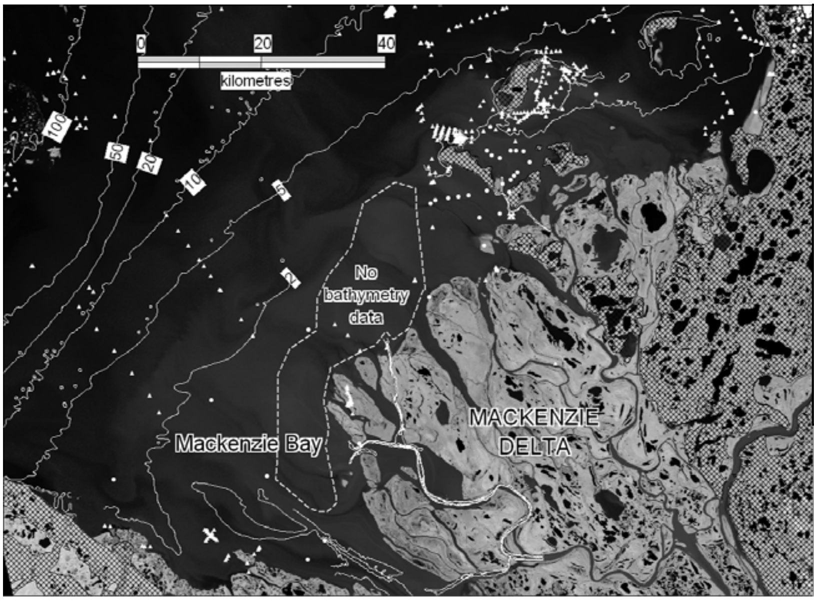

Figure 1. Locations of cores and boreholes (triangles) and grab samples (circles) in the nearshore of the Mackenzie Delta are unevenly distributed. Many areas are poorly sampled and bathymetric information is unavailable for significant portions of the inshore. The delta is incised into older upland terrain (cross-hatching) consisting of sand and gravel. The data are overlain on a Landsat 7 image.

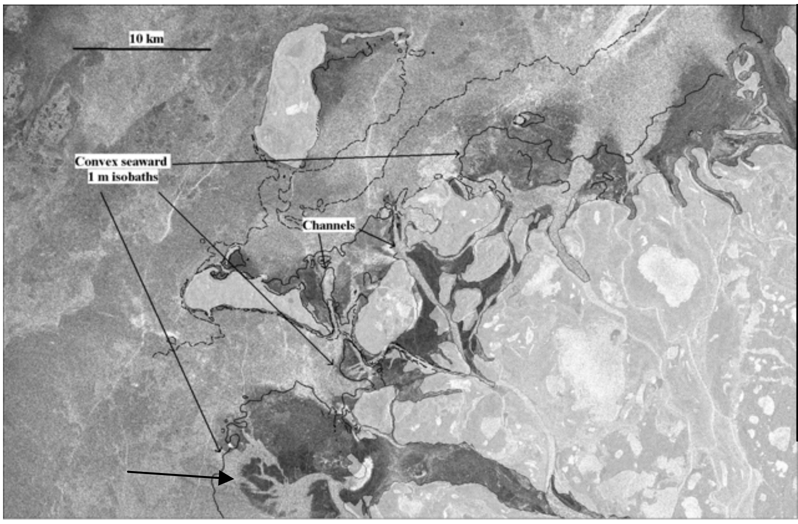

Figure 2. Digitized field sheet data (1974 and 1976) was used to create a DEM and extract a 1 m contour. Note the seaward convex shape of the contours suggesting deposition at the mouths of channels. The contours are overlain on an ERS1 synthetic aperture radar image acquired in 1993. The land areas are overlaid with a light grey stipple. Dark areas are interpreted as bottom-fast ice. Note the dendritic pattern at the mouth of the distributary pattern (arrow) at the bottom of the image.

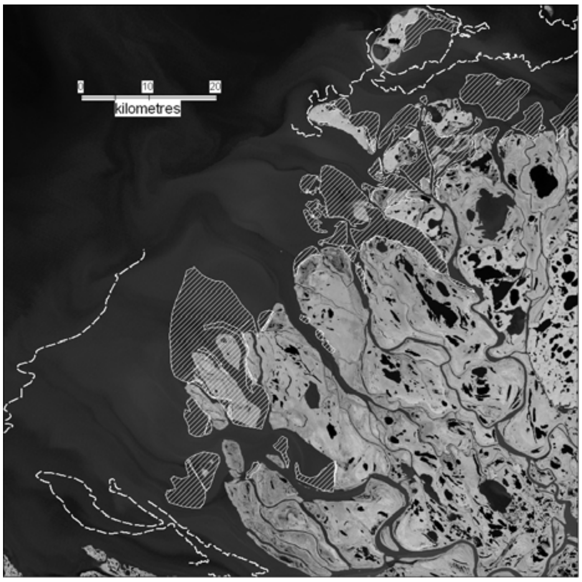

Figure 3. Interpreted distribution of bottom-fast ice from a Radarsat image acquired in April 2002 is shown as a cross-hatched pattern overlaid in a Landsat 7 image. The dashed white line shows the location of the 2 m contour. Much of the area inside of the 2 m contour appears to be too deep for the ice to become bottom-fast suggesting that near-surface frozen sediments are similarly limited (see text for more details).