Shoreline permafrost along the Mackenzie River

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Abstract: Shorelines mark one of the most abrupt changes in ground temperature in permafrost regions. The ground temperature in the vicinity of shorelines is controlled by the contrast in mean annual temperature between the particular water body and the adjacent land. Erosion or sedimentation along shorelines complicates ground temperatures by moving the boundary between relatively cold land and warmer water. A river channel migrating due to erosion on the outside of a bend introduces the relatively warm water condition to frozen ground, causing thaw to begin. At the same time, sediment is deposited on the opposite shore as the migration progresses. This results in ground temperatures again being determined directly by air temperature. Depending on water temperature and shoreline vegetation, temperature contrasts can range from about 4°C to over 10°C.

Résumé : C'est dans les berges des régions pergélisolées que l'on observe les changements de température les plus marqués dans les sols. La température du sol près des berges dépend de l'écart qui existe entre la température annuelle moyenne d'une étendue d'eau donnée et celle des terres adjacentes. L'érosion ou la sédimentation le long des berges modifie la répartition des températures dans le sol en déplaçant la limite entre les sols relativement froids et l'eau plus chaude. La migration d'un chenal fluvial causée par l'érosion de la berge extérieure d'un méandre met l'eau relativement chaude du cours d'eau en contact avec le gélisol, causant le dégel de celui-ci. Pendant que se déroule ce processus, des sédiments se déposent sur la berge opposée. Une fois de plus, les températures du gélisol dépendent directement de la température de l'air. Compte tenu de la température de l'eau et de la végétation de la berge, l'écart de température peut varier d'environ 4 °C à plus de 10 °C.

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INTRODUCTION

In permafrost regions, shorelines produce the most abrupt contrasts in ground temperature. Furthermore, shorelines change position because of erosion, sedimentation or sea-level change. This paper describes the probable effects of shoreline movement on permafrost distribution at sites in the Mackenzie valley. The locations of sites discussed are shown in Figure 1.

THERMAL REGIME ALONG THE SHORELINE

Where water depth steadily decreases toward shore, permafrost thickens landward from the point where winter ice comes in contact with sea, lake, or river bed sediments sufficiently long to freeze them perennially. As the water depth continues to decrease, the duration of ice contact increases, producing lower ground temperatures and thicker permafrost. Where the bottom profile is steep, these changes are abrupt. Figure 2 shows the distribution of average annual temperatures across this zone of ice contact with bottom sediments. This example represents the Mackenzie Delta coast, where the greatest range of ground surface temperature in the Mackenzie valley is likely to be encountered. Farther south the minimum temperature is warmer and the thickness of winter ice is less.

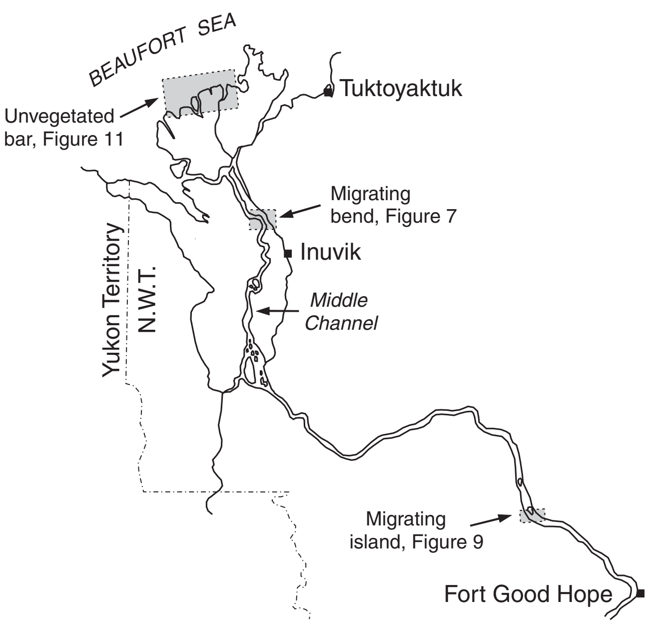

Figure 1. Lower Mackenzie River showing locations of sites discussed.

Horizontal distance is not shown in Figure 2 because the width of the ice contact zone may vary from metres to kilometres, depending on the gradient of the bottom adjacent to the shore. Where the width of the ice contact zone is considerably greater than the ice thickness, heat flow from water to land is insignificant and ground temperatures are governed only by the average annual temperature beneath a given ice thickness; however, if the nearshore slope is steep (river scouring can produce channel sides steeper than 45°), then the width of the zone is reduced sufficiently so that a significant lateral thermal gradient exists. Contours of average annual temperature (isotherms) radiate from the shoreline (Fig. 3) and the pattern of these isotherms will be determined by the thermal equilibrium established between land and water temperatures. The extremes of shoreline temperature distribution that are likely to be found in the Mackenzie valley where permafrost distribution is in equilibrium with water and land temperatures is shown in Figure 3. A land-to-water contrast of -8°C to 2°C would be representative of the outer Mackenzie Delta and Beaufort Sea coast (Fig. 3a) and a contrast of -2°C to 4°C would be generally typical of any inland, or well vegetated river bank (Fig. 3b). With increasing depth, the lateral thermal gradient ceases to be greater than the geothermal gradient and the isotherms become horizontal.

MIGRATING CHANNELS

The most dynamic shoreline changes in the Mackenzie valley result from river-bank erosion and sedimentation along the Mackenzie River, its distributaries in the Mackenzie Delta, and tributaries. Scouring on the outside of river bends and sedimentation on the inside results in lateral migration of the channel. Along most of its length, the Mackenzie River is

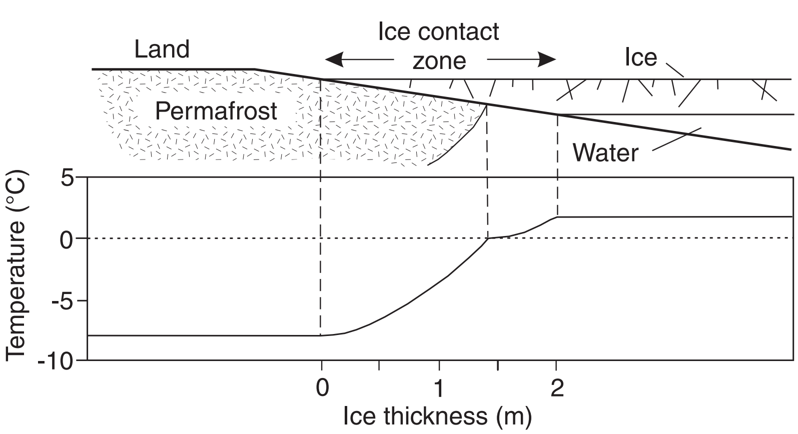

Figure 2.

Distribution of average annual temperatures across the nearshore zone in contact with winter ice, Mackenzie Delta front. Snowdrifts will locally increase temperature.

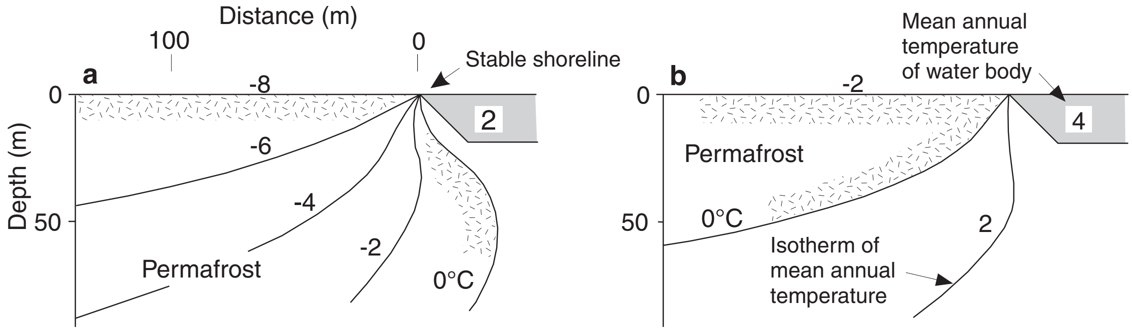

Figure 3. *Average annual ground temperatures adjacent to a laterally stable shore for:* ***a****) a temperature contrast between land and water of -8°C to 2°C typical of the Mackenzie Delta front, and* ***b****) a contrast of -2°C to 4°C typical of much of the Mackenzie River valley.*

confined within a generally narrow valley bottom. Only in the 100 km section immediately upstream from Tulita (formerly Fort Norman) and in the Mackenzie Delta, is the valley bottom sufficiently wide to permit development of high-amplitude meanders. Bends that are entirely within floodplain sediments migrate most quickly. Migration rates are highly variable but average a few metres per year in the Mackenzie Delta (Lapointe, 1986) and can reach 10 m/year where scouring is strongest. Tributary channel migrations can be faster (*see* Brooks, 2000).

The effect of channel migration is to transport the river heat source across already frozen sediments and thus upset the thermal equilibrium between land and water. Smith and Hwang (1973) modelled this process for a channel in the Mackenzie Delta and show good agreement between measured and predicted ground temperatures. Scouring on the outside of bends continually removes thawed sediment, thereby keeping permafrost at or close to the bed of the channel. With continued channel migration, downcutting will extend to the depth of the channel (thalweg) causing permafrost to extend beneath the river. Eventually the rate of melting of permafrost beneath the river bottom will exceed the removal of sediment, resulting in a thawed zone beneath the channel bottom. Along the opposite side of the thalweg, sedimentation begins along the river bottom and the channel shallows; however, thawing slows because of the increasing distance between the river bottom and the thaw front. Although this process is likely ubiquitous along migrating channels in permafrost regions, few specific cases are documented (e.g. Hollingshead et al., 1978). Migration ultimately results in emergence of the river bottom to form a subaerial bar and re-establishment of permafrost. The size of the resulting thawed zone (talik) beneath the river will depend primarily on migration rate of the channel, the temperature regime on the accreting side of the channel, and the size of the channel.

THE ROLE OF VEGETATION

After climate, vegetation plays the next most important role in controlling the re-establishment of permafrost on the accreting side of channels. The insulating effect of snow trapped by vegetation cover greatly ameliorates winter cold at the ground surface. The expected average annual ground surface temperatures corresponding to different types of vegetation across aggrading shores for three Mackenzie valley settings are shown in Figure 4. Shown in Figure 4a are the temperatures as cold as -8°C at the front of the Mackenzie Delta which reflect the influence of the Beaufort Sea and unvegetated bars. On land only sedge meadows develop. This limits snow entrapment and produces an average annual ground surface temperature of about -5°C. Inland, wide channels are still associated with unvegetated bars but sedges are succeeded by willows (Fig. 4b). Willows trap more snow, raising the ground temperature to about -2°C (Fig. 4b). Banks on the lee side of channels and narrower secondary channels, also offer protection for snow accumulation. Unvegetated bars in these locations may become the warmest subaerial environment in any area because of their burial by the resulting snow drifts (Fig. 4c). Smith (1976), in a detailed study of subsurface temperatures beneath an aggrading point bar in the central Mackenzie Delta, found the temperature of the bar surface to average about -1°C. His study site shows a succession of sedge to willow, ending in spruce forest with a lowering of temperature to -4°C because of summer shading and the interception of some snowfall by the forest canopy in winter. The data for preparing Figure 4 is derived mainly from the Mackenzie Delta and therefore temperatures will be expected to increase gradually with increasing distance south; however, temperatures for vegetated alluvial sites in the Norman Wells area (A. Judge, pers. com., 1995) are only about 1°C warmer than equivalent sites in the Mackenzie Delta, suggesting that Figure 4c is broadly applicable to a considerable part of the Mackenzie valley.

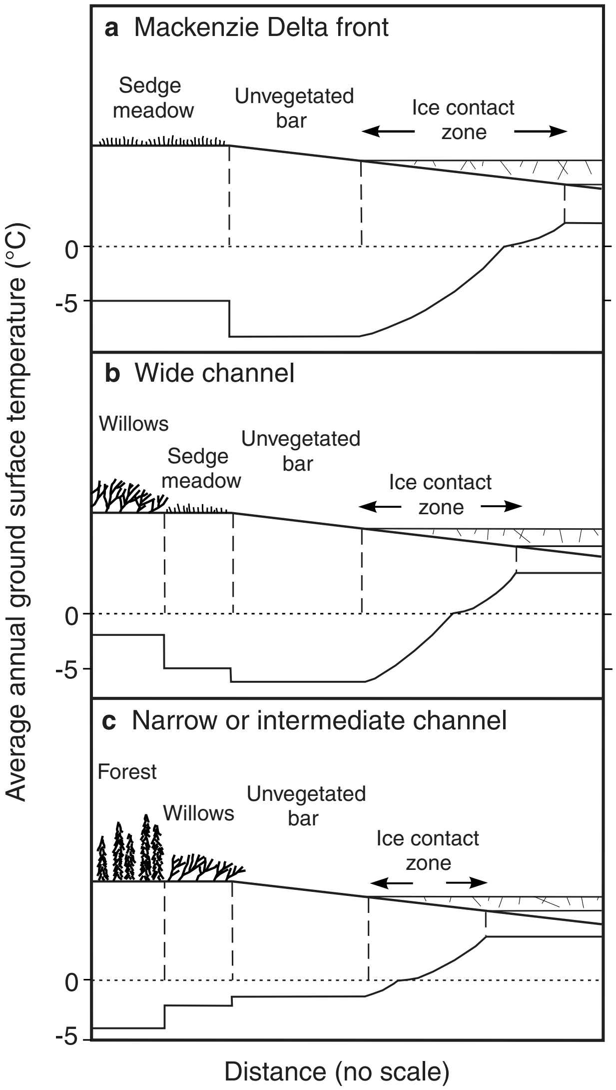

Figure 4. *Schematic drawing of the average annual ground surface temperatures characterizing three river-bank environments within the Mackenzie Delta:* ***a****) Beaufort Sea coast at the Mackenzie Delta front,* ***b****) wide channels and major distributaries,* ***c****) narrow and intermediate channels.*

PREDICTION OF THAWING BENEATH MIGRATING CHANNELS

All permafrost distributions presented in this chapter are predicted by using the one-dimensional heat-flow equation modified to account for complete melting of ground ice at 0°C (Neuman solution; Jumikis (1977)). These predictions agree with limited observations recorded in the course of pipeline crossing explorations where permafrost boundaries are observed to be close to channel sides that are undergoing scouring (petroleum company observations included in Traynor and Dallimore (1992)); however, the observations are too widely spaced to locate boundaries precisely so that theoretical predictions have been used to determine sensitivity to the conditions noted above. A single set of sediment conditions and thermal properties is used in all examples: unfrozen thermal conductivity = 1.8 Wm/°C, frozen thermal conductivity = 3.0 Wm/°C, unfrozen volumetric heat capacity= 2.0 J/cm^3°C, frozen heat capacity = 1.2 J/cm^3°C, and water content by weight= 20%, giving a latent heat content of 117 J/cm^3.

A generalized channel profile with a width typical of major Mackenzie Delta distributaries (e.g. *see* Fig. 7) but similar in shape to cross-sections elsewhere along the river is shown in Figure 5. Thawing estimates are based on an average annual water temperature for the Mackenzie River of 4°C. Water temperatures rise slightly with distance downstream from the source at Great Slave Lake but do not vary more than 1°C from this value (MacKay and Mackay, 1974). The depth of thaw is directly dependent on this temperature and the length of time over which it prevails. After sediment accretion raises the river bottom into the ice contact zone, thawing stops and refreezing from the surface occurs in response to a progression of thermal conditions as represented in Figure 4. The predicted talik for migration rates of 1 m/year and 3 m/year with a vegetation succession on the aggrading shore from sedges to willow is shown in Figure 5. These rates are rarely exceeded except in the lower part of the Mackenzie Delta. In both cases the talik extends through permafrost. In all examples, the vegetation succession is assumed to follow the migration of the river concomitantly, thereby controlling the average annual ground temperature.

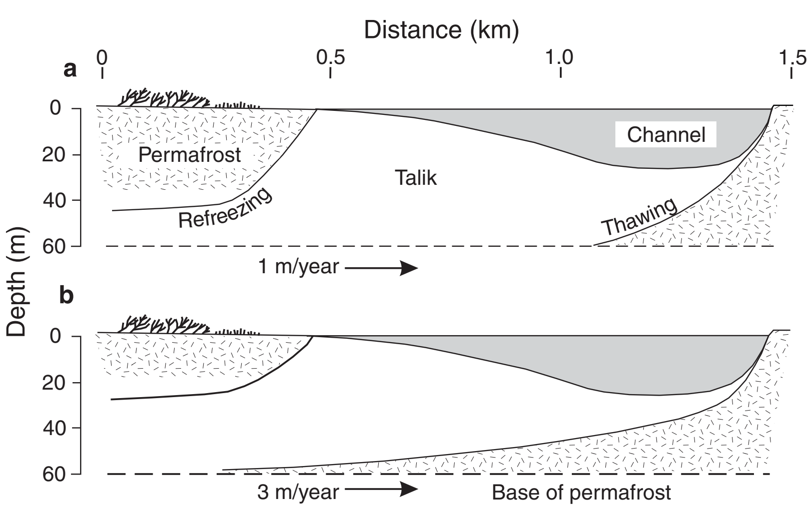

Figure 5.

Predicted talik developed beneath a major distributary channel having migration rates of ***a****) 1 m/year and* ***b****) 3 m/year. In both profiles, refreezing decelerates as willows with associated warmer ground temperatures follow the channel migration. Thawing decelerates as the frost table falls below the channel thalweg. Increasing migration rate increases the proportion of channel underlain by permafrost. Average annual ground temperatures used to calculate refreezing are shown in Figure 4b.*

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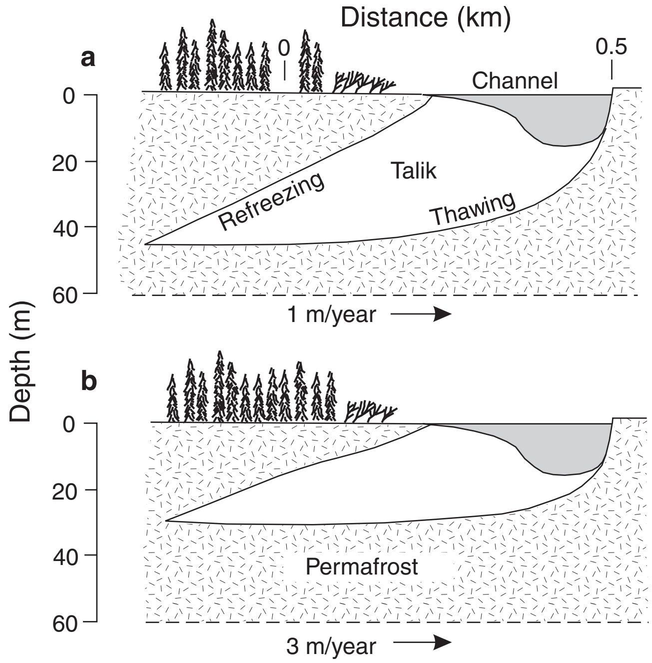

*Figure 6. Predicted talik developed beneath a secondary channel having migration rates of 1 m/year **a**), and 3 m/year **b**). Because the channel is much narrower than in Figure 5, thawing decelerates more quickly and refreezing begins sooner, resulting in a talik which does not breach permafrost. Ground temperatures for refreezing are also lower because of the establishment of forest. Average annual ground temperatures used to calculate refreezing are shown in Figure 4c.*

For a laterally stable channel in the Mackenzie Delta, Smith (1976) indicated that a through-permafrost talik will exist for any channel wider than about 70 m; however, migration increases the width of channel required to produce a through-talik. A 200 m wide channel with a willow-to-spruce succession approximating conditions at the site studied by Smith (1976) is shown in Figure 6. In this case, the talik refreezes well before it reaches the base of permafrost for both the 1 m/year and 3 m/year migration rates. Even for the 1 km wide channel shown in Figure 5, with 3 m/year of migration, thaw does not penetrate permafrost beneath the channel. On the other hand, repeated passages of migrating channels over the same location will limit the maximum depth of the base of permafrost.

PERMAFROST THICKNESS IN THE VICINITY OF MIGRATING CHANNELS

Migration of the bend in a major channel shown in Figure 7 has been determined by tracing previous channel positions visible on this aerial photo. Channel positions prior to 1950 can be traced as faint scars in the medium grey-toned, willow-covered area landward of the present point bar. Their age can be roughly estimated by assuming that the migration rate for the 35 year time span documented in Figure 7 (about 6 m/year) is representative of the past. The boundary of dark forest adjoining the willow area outlines a former position for the inside of the bend. Although the traces of former channel positions lack the same channel curvature as the present bend, the old channel scars mark incremental positions that appear to be directly related to movement of the bend from this prior position. Therefore it is concluded that the present willow-covered area has aggraded at about the same rate as the outer bend.

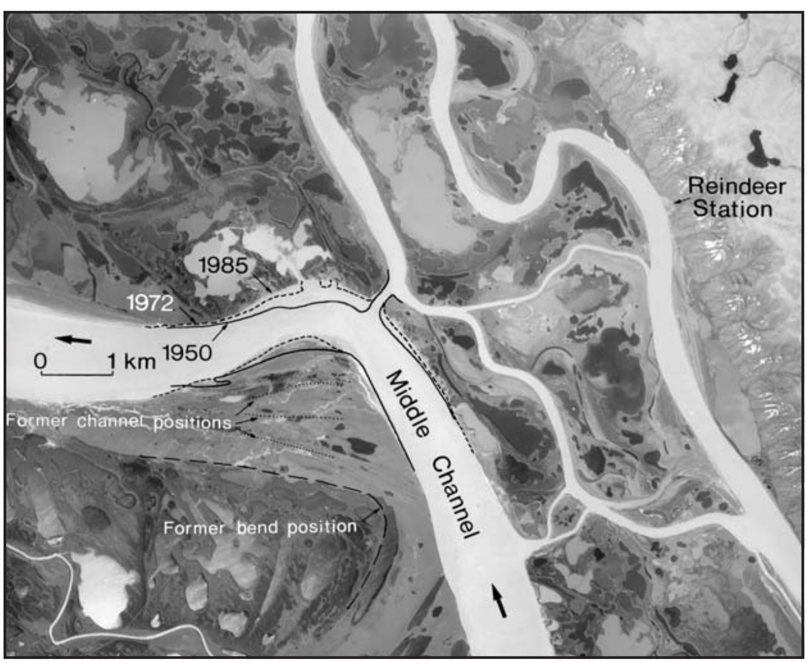

Figure 7.

A 1985 aerial photo showing migration of a major bend in Middle Channel, east central Mackenzie Delta. Former shorelines for 1972 (dashed) and 1950 (solid) are indicated. NAPL A26726-19

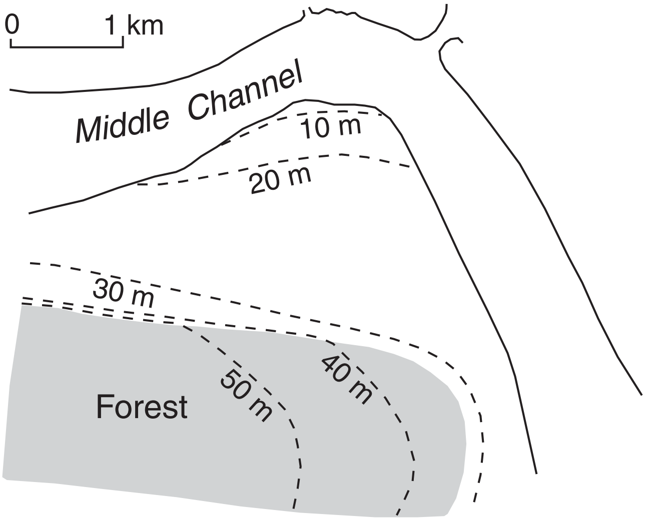

Figure 8. Predicted permafrost thickness (in metres as shown by dashed lines) beneath the zone of point bar deposits for the major bend in Figure 7. The thickness contours parallel former channel margins. The warming effect of lakes is not taken into account.

With an estimate of the age gradient across the willow-covered area, thickness of permafrost can be calculated. Permafrost growth will be controlled by the same succession of bank conditions as shown in Figure 5 with willow determining the average annual ground temperature until the forested area is reached; however, the time of forest establishment is not known, thus making the period that the forest determined the ground temperature difficult to include. For the sake of illustration, it is assumed that the forest was established when the channel position coincided with the bend outlined by the forest. Earlier channel positions within the forested area appear to be truncated at the forest edge, suggesting that an abrupt change in permafrost thickness across this boundary will occur. Notwithstanding these difficulties, Figure 8 has been prepared so that permafrost thicknesses over the entire area can be shown. It is intended only as an indication of the variation of permafrost thickness possible in an alluvial environment.

ISLANDS

Throughout much of its length, the Mackenzie River ranges from 1 km to 5 km in width. Islands and unvegetated bars commonly exist in the wider reaches. These islands and bars migrate downstream, as erosion removes the upstream end and sedimentation adds to the downstream end. Upstream

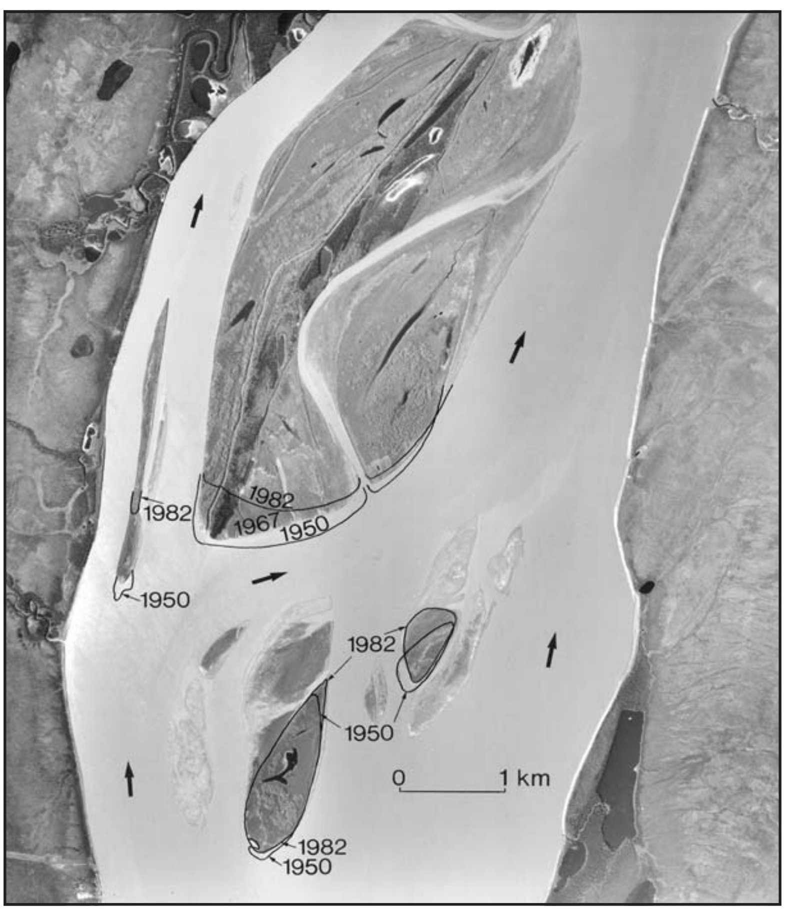

Figure 9.

A 1967 aerial photo of a major alluvial island and smaller island bar complex about 90 km downstream of Fort Good Hope. Channel currents are indicated by arrows. The upstream end of the major island is undergoing erosion by the current moving from left to right against the shore. Shoreline positions for vegetated islands in 1982 and 1950 are shown. NAPL A19947-7

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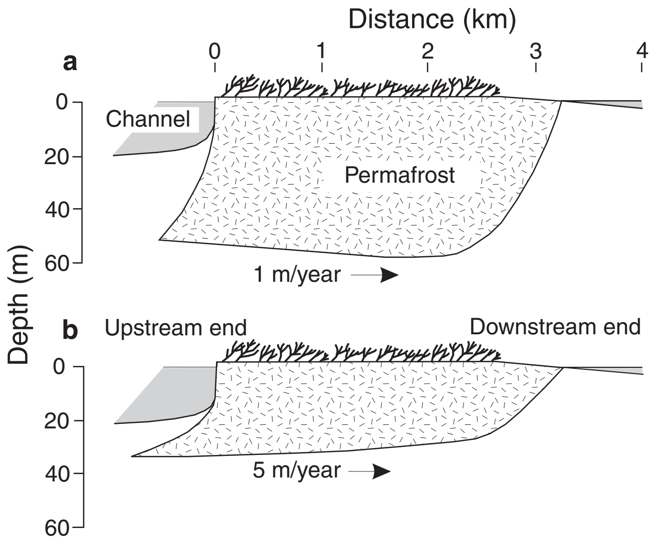

*Figure 10. Cross-sections showing predicted permafrost distribution beneath migrating islands in the Mackenzie River for channel migration rates of 1 m/year **a**) and 5 m/year **b**). The temperature distribution used ranges from 4°C for the river to -4°C on the downstream bar, warming to -1°C for the willow-covered majority of the island. Increasing migration rate reduces the maximum thickness of permafrost which can develop which in turn reduces the amount by which permafrost can underlie the migrating channel.*

migration, where sedimentation adds to the upstream end and channel erosion removes the downstream end, is also possible. The direction in which erosion takes place depends on the positioning of a channel and shoal water with respect to an island. Downstream erosion is occurring in the location shown in Figure 9 where the main channel flows from the bottom left side of the figure to the top right side, subjecting the upstream end of the large island to significant erosion.

The theoretical distribution of permafrost beneath the longitudinal cross-section of a large island such as that shown in Figure 9 is illustrated in Figure 10. Permafrost aggrades rapidly beneath the downstream unvegetated end of the island, which is migrating downstream, but then diminishes in growth rate in the upstream direction with establishment of vegetation. On a large island, rate of migration fails to alter greatly the amount that permafrost extends beyond the shore of the island beneath the river. Deeper growth permitted by slow migration is compensated by a greater depth of thaw occurring close to the upstream or eroding end.

AN EXAMPLE OF TEMPERATURE CHANGE

As a final example of change in the alluvial environment, the effect of erosion and sedimentation on ground temperatures beneath unvegetated bars is examined. Lack of subsurface data for unvegetated bars in the Mackenzie valley restricts discussion to the Mackenzie Delta front where considerable data are available. This area also provides one of the most dynamic sedimentary environments of the entire river system. Unvegetated bars are large and are susceptible to open ocean wave action and delta-channel migration. This, combined with the coldest average annual air temperatures in the Mackenzie valley, gives the delta front the widest range of ground temperatures and the most rapidly changing permafrost distribution in the Mackenzie valley.

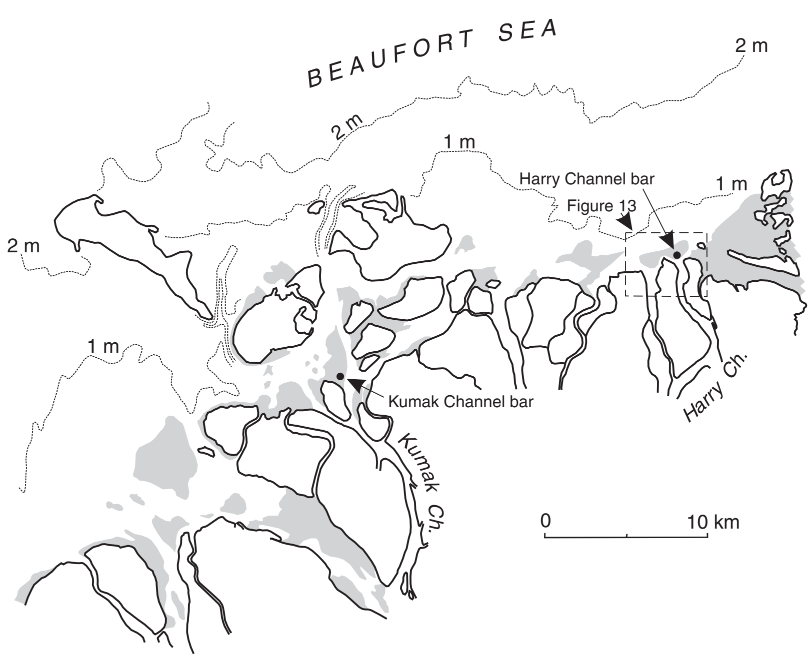

Figure 11.

Mackenzie Delta front showing areas exposed as unvegetated subaerial bars between 1950 and 1985 (grey shading). Also shown are locations of temperature cables giving temperature profiles shown in Figure 12. Dotted lines are bathymetric contours. Location of Figure 13 is shown as dashed rectangle.

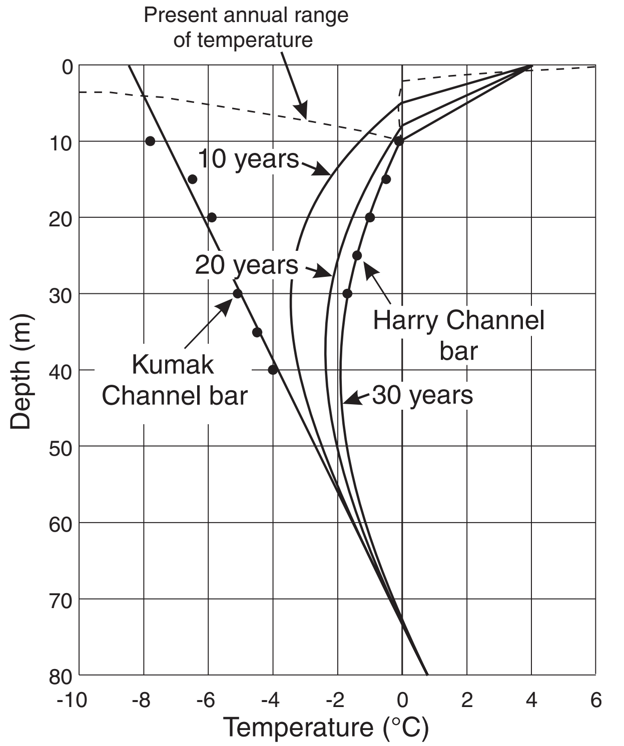

Figure 12.

Temperature profiles beneath two bars at the Mackenzie Delta front assumed to have formed at the same time. Inundation of Harry Channel bar is simulated by suddenly warming the surface temperature to 4°C. The response of the ground temperature 10, 20, and 30 years after this change is shown as a warming from the initial temperature profile represented by the profile beneath the Kumak Channel bar. Dashed lines indicate the 1992 envelope of temperature variation for the Harry Channel bar.

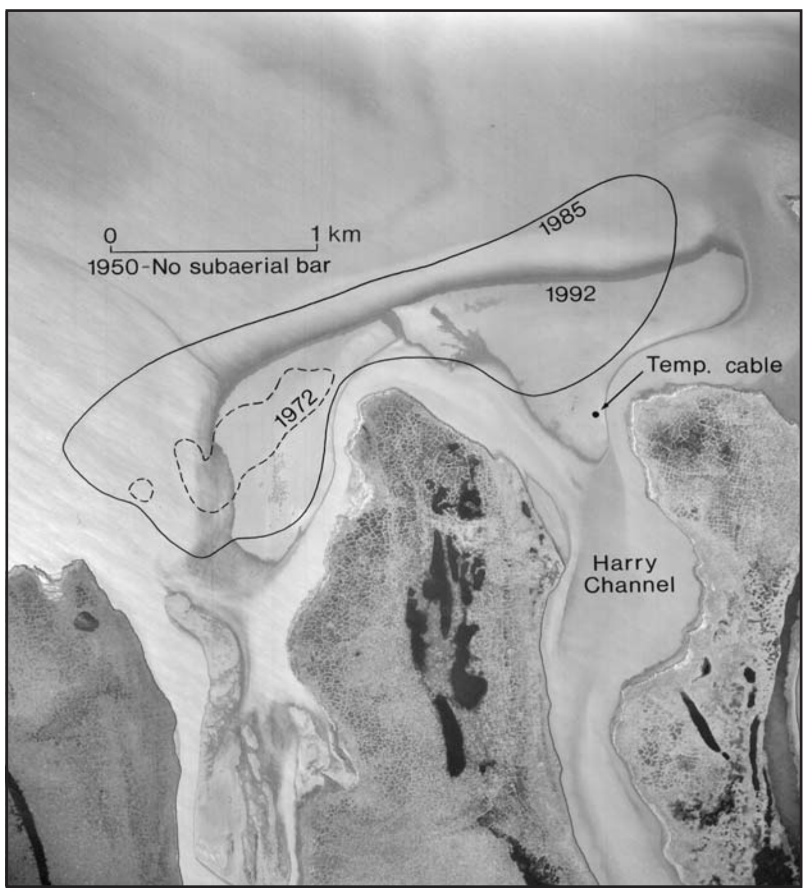

Figure 13.

Development of a bar at the mouth of Harry Channel (east side of the Mackenzie Delta) with former outlines for 1985 and 1972 shown on a 1992 aerial photo. No bar is present on aerial photography for 1950. Location of the Harry Channel bar temperature cable used in Figure 12 is indicated.

The dynamic nature of the delta front is indicated by the variability of sub-bottom temperatures in the apron of bars and shallow water (up to 1 m depth) that extends several kilometres offshore (Fig. 11). Subaerial bars are subject to cold ground temperatures because of windswept exposure and a lack of snow-trapping vegetation. Measured temperature profiles located beneath two bars assumed to have formed at the same time are shown in Figure 12. The profile for the bar at the mouth of a major distributary (Kumak Channel) has been projected to the surface to demonstrate an average annual surface temperature of -8°C to -9°C. This trend is also projected downwards to the 0°C level, giving an estimated permafrost thickness of about 75 m. This near-linear trend suggests that freezing has been uninterrupted since this location first became exposed to the estimated surface temperature. It provides a reference against which temperature profiles beneath other bars may be compared.

In Figure 12, the profile beneath a recently accreted portion of a bar at the mouth of a medium-sized distributary (Harry Channel, Fig. 11) shows much warmer temperatures. The approach to 0°C at 10 m depth suggests that thawing to this depth has occurred in the recent past. If this site was subaerially exposed for an interval of time similar to the Kumak Channel site, then the present temperature profile indicates an interval of recent submergence that is probably due to erosion of the bar. The bar has subsequently re-emerged, presumably due to accretion, and refreezing is underway.

The time elapsed since the beginning of the thawing episode for the Harry Channel bar can be estimated by using a mathematical model of temperature change and thawing in response to a sudden warming. In Figure 12 the theoretical result of warming from a subaerial -8°C or -9°C to a submerged 4°C is shown for the intervals of 10, 20, and 30 years after submergence of the bar. The profile for 30 years most closely matches the measured temperatures at the Harry Channel site. If the Harry Channel site originally had the same distribution of ground temperature as the Kumak Channel site, then the Harry Channel site appears to have been eroded about 30 years before it began to refreeze. During those 30 years, ground temperatures warmed from values similar to those at the Kumak Channel bar to almost the present values at Harry Channel. This process was accompanied by thawing, which extends to about 10 m. The bar outlines in Figure 13 suggest that re-emergence occurred after 1972, at which time refreezing would have begun. Refreezing has just been completed, as indicated by the continuously recorded subzero (degrees Celsius) temperatures (dashed envelope of temperature variation in Fig. 10) over the previously thawed depth interval. The original bar appears to have eroded, perhaps by a storm that occurred about 30 years prior to 1972, i.e. in the early 1940s.

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