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THE HORTON RIVER BREAKTHROUGH AND RESULTING GEOMORPHIC CHANGES IN A PERMAFROST ENVIRONMENT, WESTERN ARCTIC COAST, CANADA

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ABSTRACT. Dendrochronological analysis and radiocarbon dating show that a breakthrough to the sea occurred along the lower course of the Horton River after 1640 AD. At the breakthrough site, the Horton River flowed 10 m above sea level so that river erosion and delta building would have been rapid. By 1826, when the coast was mapped by the expedition of Dr. John Richardson, the Horton Delta had a surface area of about 10 to 15 km^2, approximately one third of the present area. Construction of the delta has protected the adjacent sea cliffs from wave erosion. Attention is paid to the nature of geomorphic change in a permafrost environment and the role of river and sea ice in affecting changes.

Introduction

Horton River which now flows into Franklin Bay, formerly discharged into Harrowby Bay (Fig. 1) about 60 km northwest of the present mouth (Mackay 1958, 1981). Development of the Horton River delta since breakthrough has influenced the accumulation of eroded sediments from cliffs to the north and south of the delta and the rate and nature of the geomorphic processes on the cliffs which are now protected from wave attack by deltaic sedimentation. Special interest attaches to this site because it is in an area of continuous permafrost dating of the breakthrough event has

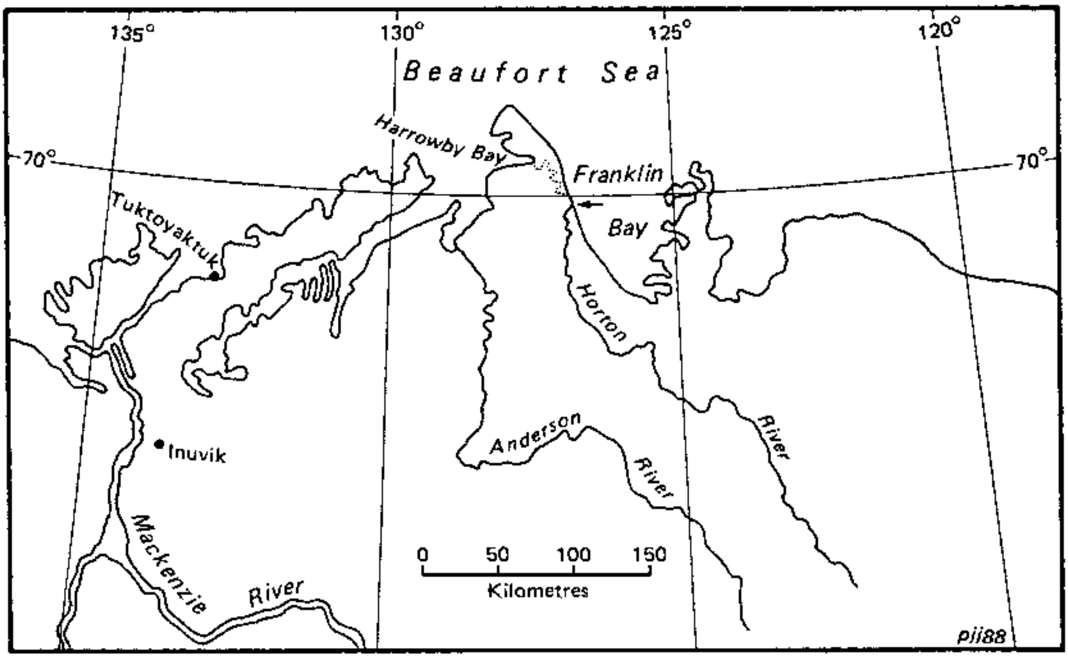

Fig. 1. Location map. The arrow in Franklin Bay points to the Horton Delta. The Old Horton Channel is marked by a fine dotted line connecting the mouth of Horton River with Harrowby Bay to the northwest.

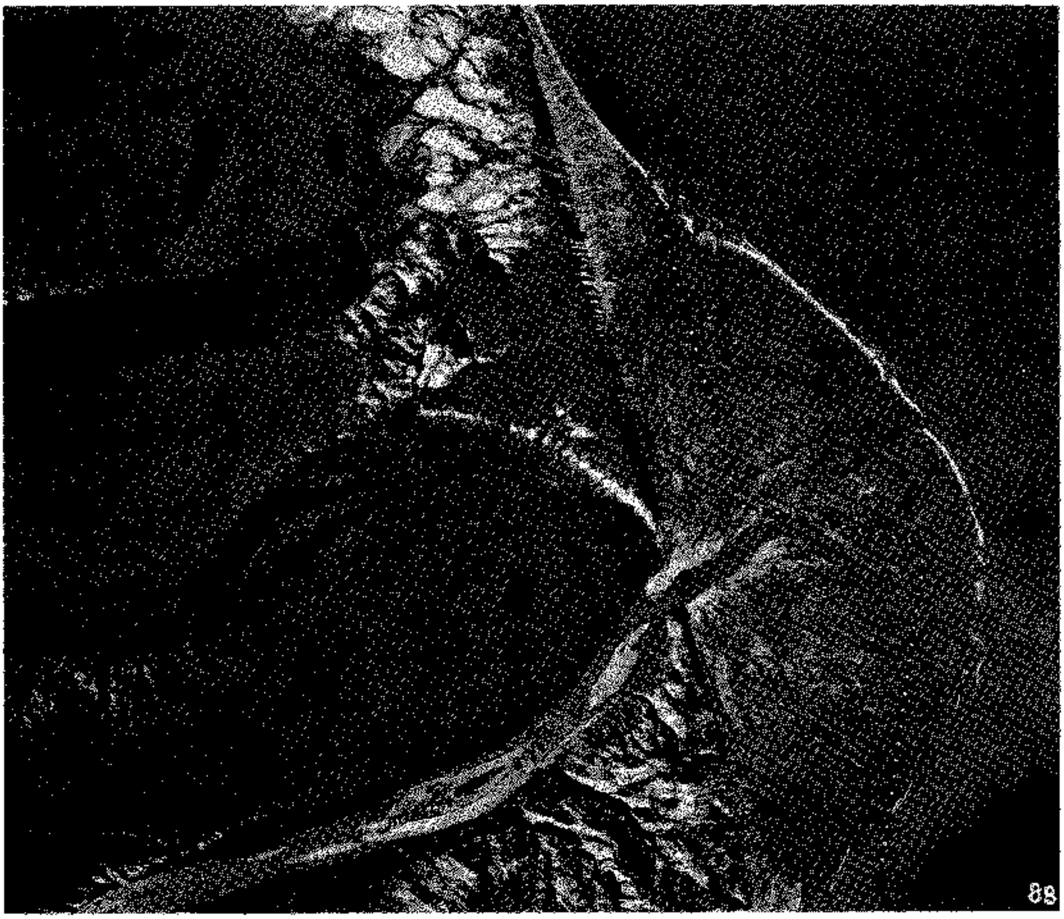

Fig. 2. Air photograhps (A19216–87 and 88) of the modern Horton Delta area. The numbers 1, 2, 3, 4 refer to radiocarbon and dendrochronological dated sites as given in Fig. 4. The 1826 route of Richardson's party is plotted from an unpublished 1826 field survey (see text).

probably been bracketed, and rates of geomorphic change can be estimated. The regional geomorphology has been discussed by Mackay (1958) and Rampton (1988) and the geology by Yorath *et al.* (1975).

Dating the breakthrough

Historical evidence

The present river mouth was mapped in 1826 by the explorer Dr. John Richardson (Richardson, 1828). The boat route followed by Richardson's party is plotted on an air photograph in Fig. 2. The route is redrawn from an unpublished field map by E.N. Kendall, Richardson's surveyor (Scott Polar Research Institute, Cambridge, England, E.N. Kendall file MS 248/495). The route crossed the northern half of the delta where it came within about one kilometre of the present shore. The near shore route in Fig. 2 is probably fairly accurate, because a field sketch of the Horton mouth (Richardson 1828, plate 25) shows details of two landscape features, a low rocky spur and meander slip off terraces, which would have been hard to detect if the route had been farther seaward.

Dating driftwood

Although the lower Horton River is in the tundra, spruce trees grow about 200 km upstream from the

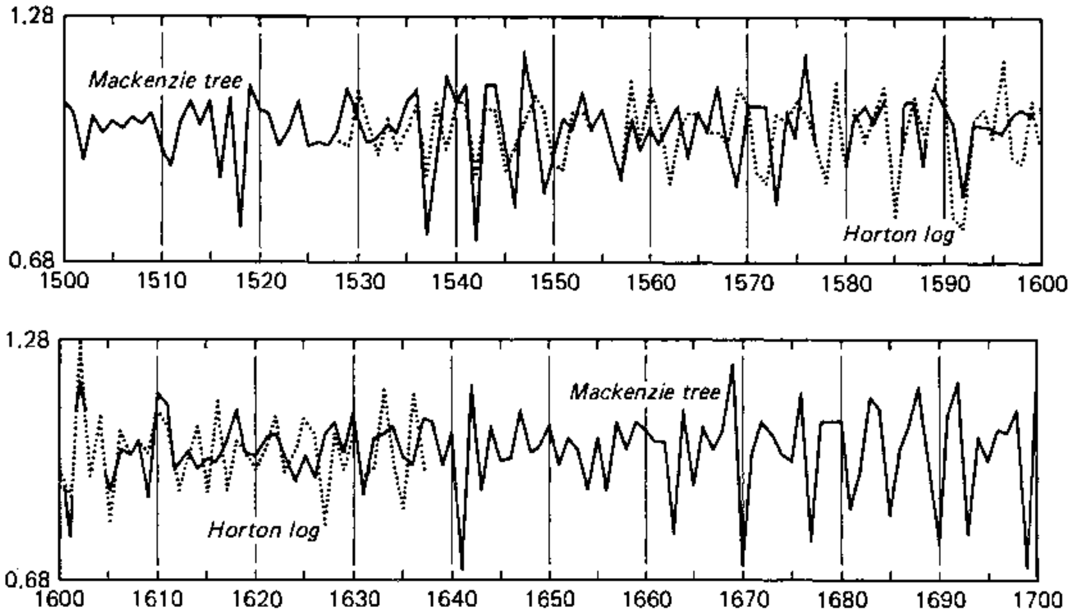

Fig. 3. Densitometric cross-dating scan (by M.L. Parker) of a piece of driftwood from site 3 (Fig. 2) along the old channel of Horton River and a single white spruce in the Mackenzie Delta near Inuvik, N.W.T. (Fig. 1) (see text).

present mouth. The Horton River at the time of breakthrough flowed about 10 m above present sea level (ASL) at the present position of the river mouth. Because all river transported driftwood on the abandoned channel would predate the breakthrough, driftwood was collected along the abandoned channel for dating purposes.

Dendrochronological analysis: A water-worn spruce log from site 3 (Fig. 2) at about 9 m ASL has been cross-dated by x-ray densitometry (analysis by M.L. Parker; cf. Parker *et al.* 1980). Ring width and ring density chronologies were obtained and these were compared with a living-tree chronology from the Mackenzie Delta (Fig. 1), using a computer cross-dating technique. The maximum density method produced a good match and a date of 1526 AD for wood near the pith (Fig.

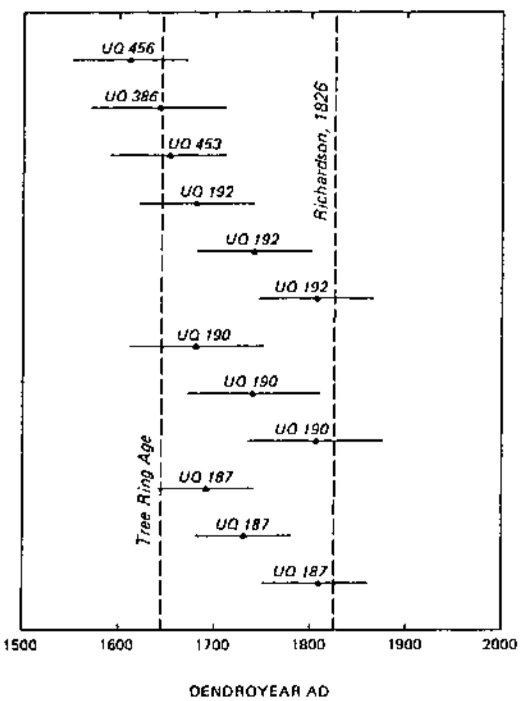

Fig. 4. Radiocarbon dates for sites along the Old Horton Channel (Fig. 1). The dendroyears have been corrected according to Stuiver (1982). For each radiocarbon date there may be more than one dendroyear. The lines on each side of the dots represent one standard deviation. UQ−187 was collected at site 1 in Fig. 2; UQ−190 at site 2; UQ−192 at site 3; UQ−386, UQ−453, UQ−456 at site 4.

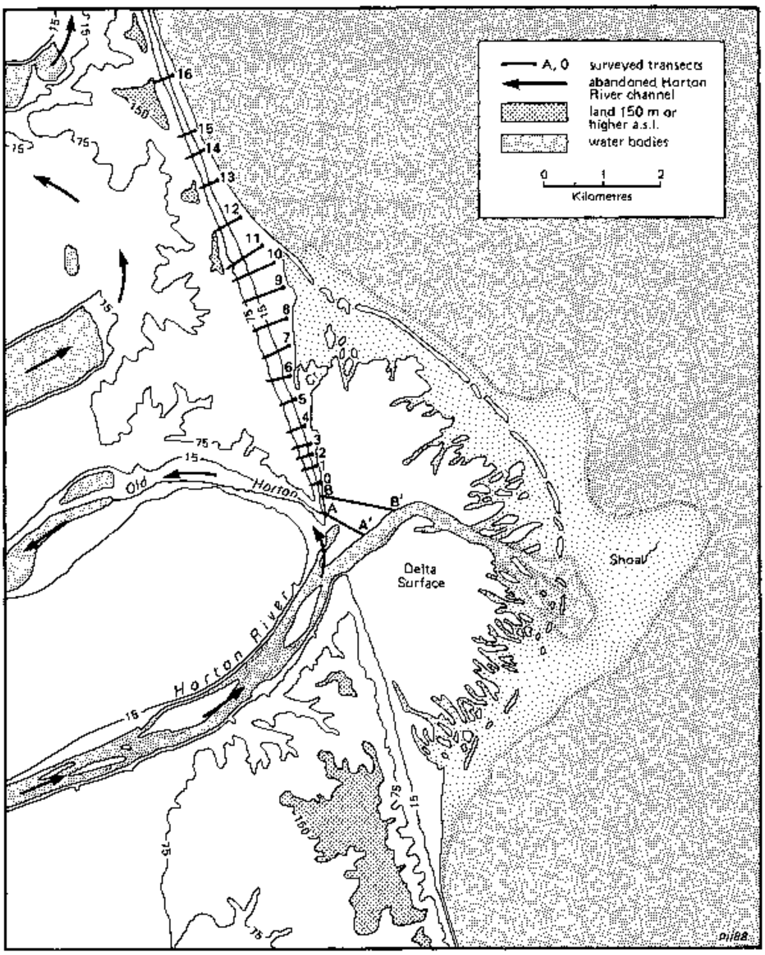

Fig. 5. The Horton Delta showing the surveyed transects (0–16) and two profiles A–A' and B–B'.

3). The outermost identifiable ring grew in 1638 AD, but as the log was water-worn from downriver transport, the breakthrough date would then be at least after 1640 AD.

Radiocarbon dating: Six radiocarbon dates have been obtained for driftwood along the abandoned channel at altitudes of about 9 to 10 m ASL. The radiocarbon dates, converted into dendroyears AD using the calibration curves of Stuiver (1982) are plotted in Fig. 4. All of the radiocarbon dates are compatible with the dendrochronological breakthrough date after 1640 AD. Although some pieces of driftwood could have been transported by people for fuel or other purposes, the cumulative radiocarbon evidence suggests a breakthrough after 1640.

Sediment Sources

Bedrock geology of cliffs and immediate hinterland

Mesozoic sedimentary rocks underlie the Anderson Plain physiographic region which includes the lower Horton River area (Yorath *et al.* 1975). The Lower Cretaceous Horton River formation with plastic concretionary shale underlies much of the lower course of the Horton River. The cliffs adjacent to Horton Delta consist of Upper Cretaceous Amundsen Gulf Group shales (Mason River and Smoking Hills Formations). Almost all the shale that is exposed in the cliffs appears to belong to the lower 150 m of the Mason River Formation. As described by Yorath *et al.* (1975), soft moderately fissile to fissile and blocky shales are included in this part of the formation. Two cliff forming units are present: the so-called unit 4 of the Lower

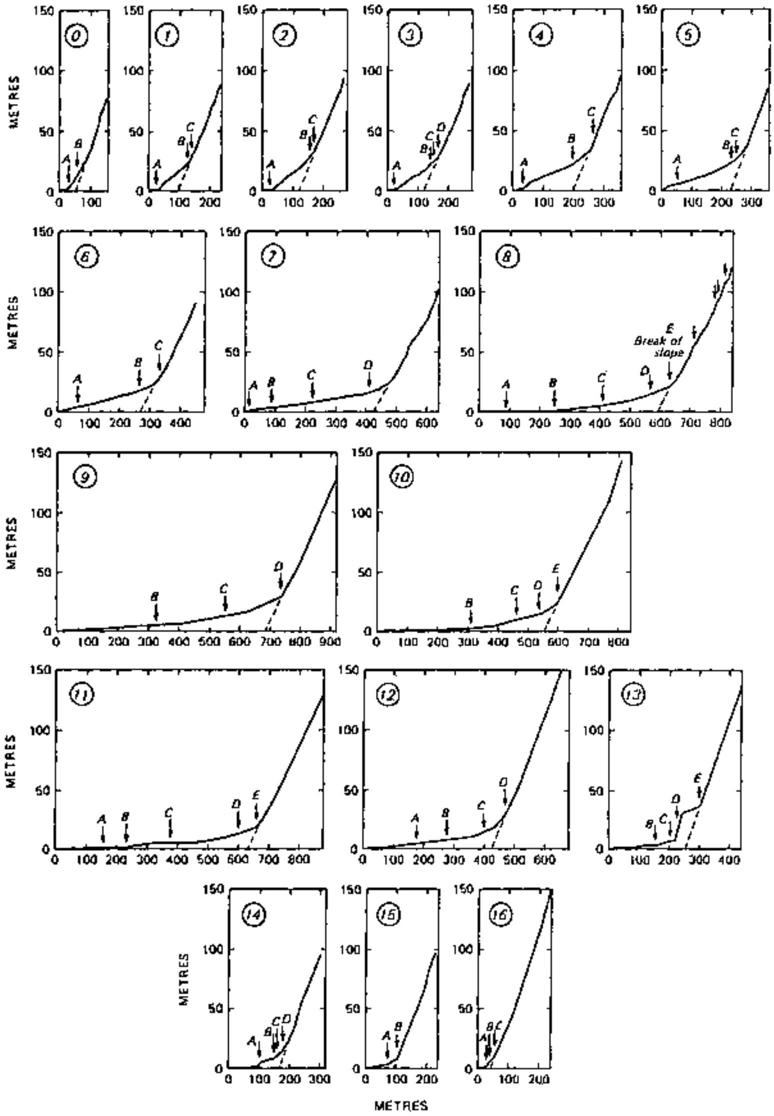

Fig. 6. Transect profiles 0 to 16.

Member, which contains siliceous and ferruginous dolomite concretions, and the lower part of unit 6 of the Middle Member, which contains interbeds of brown ferruginous shale and is locally blocky. The former appears to be the major cliff former as it is 25 m in thickness and outcrops both north and south of the mouth of Horton River.

Granulometry and soil mechanical properties of sediments derived from the cliffs

Fifty-nine sediment samples from seventeen transects (0 to 16) orthogonal to the cliffs (Fig. 5) were analysed for grain size distribution and Atterberg limits. When uppermost and lowermost samples taken from each of transects 0 to 16 are compared the average plasticity index is greater at the lowermost site (28 compared with 15) and the average median grain size is smaller (4.7 φ compared with 2.5 φ). This suggests that fluvial transport is dominant. However, individual slopes such as 1, 3 and 6 show no consistent trend. Both mass wasting from upslope and river ice action at breakup contribute to these trends. Of the 29

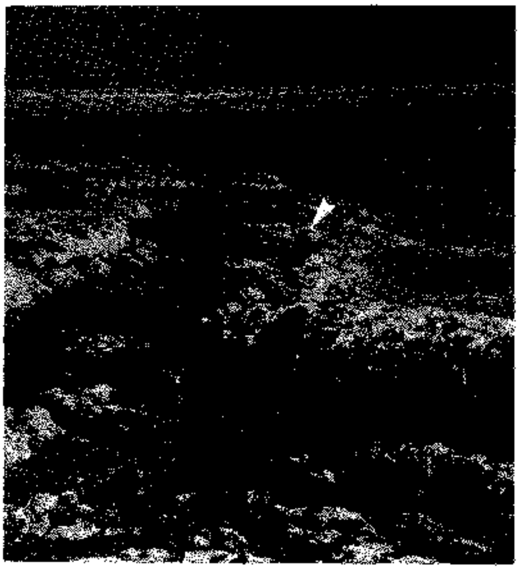

Fig. 7a. Debris flow flanked by two large levees. Arrow points to a person for scale.

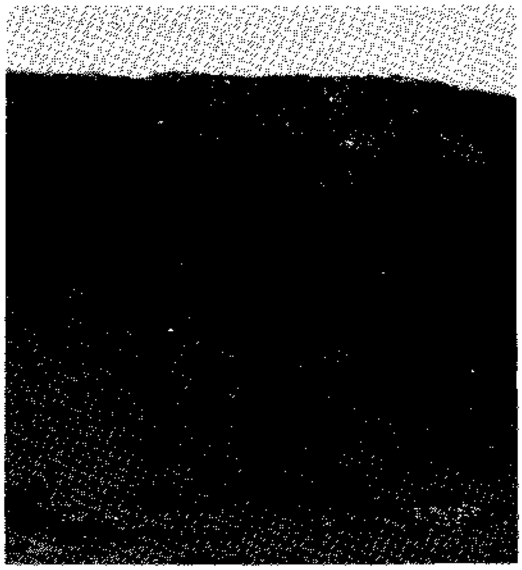

Fig. 7b. Thaw of a large exposure of high ice content massive ice at a cliff top. The ice is covered by a till. The total height is about 5 m.

samples taken from transects 0 to 8 only 16 provided meaningful Atterberg limits—the other 13 were gravelly sand or sandy gravel and contained too few fines. Of the 30 samples taken from transects 9 to 16, 29 provided Atterberg limits. Substantially more fines were present in the northernmost slopes, especially in samples taken from the upper part of the transects. These slopes are developed in the Lower Member of the Mason River Formation.

There appear to be four groups of transects (Fig. 6).

(1) Transects 0 to 3. These slopes are steep and short, basally undercut by stream action and influenced at their base by river ice push.

(2) Transects 4 to 6. These slopes are longer and less steep because they are not undercut by stream action. They are, however, influenced by river ice push.

(3) Transects 7 to 12. These are the longest and lowest gradient slopes. Downslope sorting by fluvial action is best displayed here. Neither the effects of basal undercutting nor of river ice push are evident in these slopes.

(4) Transects 13 to 16. These slopes are steep and short, with sediments well sorted by fluvial transport.

Geomorphic Processes on the Cliffs

General

The general conditions governing geomorphic processes along the Beaufort Sea coast are: the water content of the active layer, heavily influenced by snowmelt and thawing of segregation ice; near surface freezing and thawing; frost shattering of bedrock in permafrost by downward water movement and freezing; impedance of drainage by permafrost and low evaporation rates; thaw consolidation giving excessive pore pressures; accumulation of large snowdrifts in the gullies; and wind action.

Nature of the sediments

The modal soil category on the Horton cliff transects is an inorganic silt of high compressibility. The plasticity averages 25 but reaches up to 50 in places. The low shear strength associated with those sediments gives rise to debris flows with well developed levees (Fig. 7a). The local source for much of these sediments is the thawing of massive ground ice at the cliff tops (Fig. 7b). The massive ground ice occurs beneath a till or outwash sands and gravels (Rampton 1981). The ice is usually about 2 to 6 m thick. The fortuitous location of the

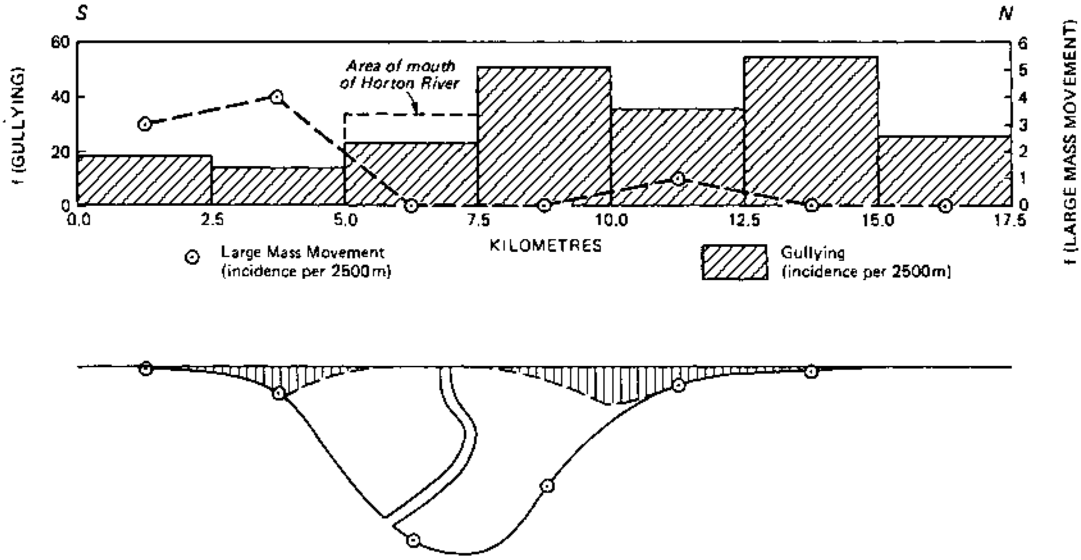

Fig. 8. Air photo interpretation of large mass movements and gullies along the cliffs fronting the Horton Delta.

massive ground ice at the tops of the bluffs is an important factor in determining the size and volume of debris flows that debouch onto the fan delta. This is because an active thaw slump, such as that in Fig. 7b, may retreat 5 to 10 m in a single summer to release hundreds of cubic metres of watery debris with varying amounts of sand, gravel, and boulders into gully heads. Thus, the thaw of massive ice complements the role of snow-melt, derived from large snowbanks in the gullies, in initiating and nourishing debris flows.

Analysis from air photographs

The incidence of gullying and large mass movement phenomena has been analysed along a 17.5 km section from south of the Horton Delta to the north. The greatest incidence of large mass movement (rotational slumping, slides and large debris flows) occurs south of Horton River mouth; maximum incidence of gullying occurs to the north (Fig. 8). It is not immediately apparent why the dominant erosional activity should differ as both areas coincide with maximum available relief zones (150–160 m) and they are both protected from wave action at their base by deltaic sediment accumulation. Beyond the coastal areas protected by deltaic sediments, both to the south and north, short, steep gullies, spaced at an average of one per 100 m, are characteristic (Fig. 9a).

Frost shattering of bedrock cliffs in permafrost

The seaward facing bluffs fronting Horton Delta have been backwearing from coastal erosion and mass wasting for thousands of years. Because the bluffs are in permafrost, it follows that the bedrock in permafrost beneath the active layer has not previously been subjected to weathering, and yet the upper metre of permafrost bedrock is frequently frost shattered. In explanation, studies have shown that in unconsolidated materials, there can be a thermally induced net downward migration of water from the active layer into permafrost in summer to form pore ice and ice lenses at the top of permafrost (Cheng 1983; Mackay 1983; Parmuzina 1983). At the Horton River, drilling in permafrost on a rapidly eroding 20° slope in shale (Fig. 9b) showed that the previously unweathered shale at the top of permafrost was icier than at depth. A second bedrock site gave the same result. Ice lensing at the top of permafrost with little doubt contributes to frost shattering of

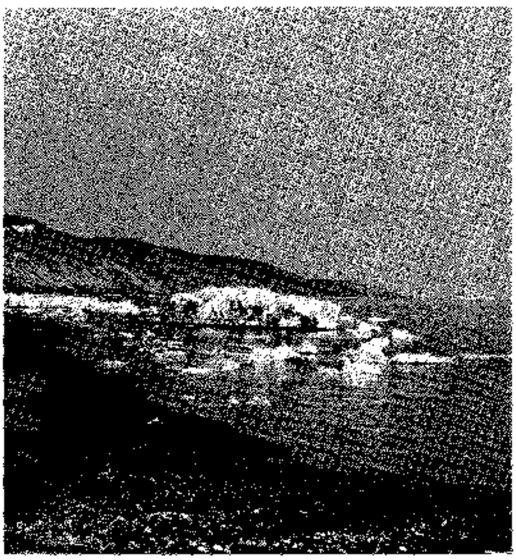

Fig. 9a. View taken from the Horton Delta, at the seaward position of transect 12 (Fig. 5) looking northwest along part of the delta to the unprotected seacliffs of Franklin Bay. Note the grounded sea ice.

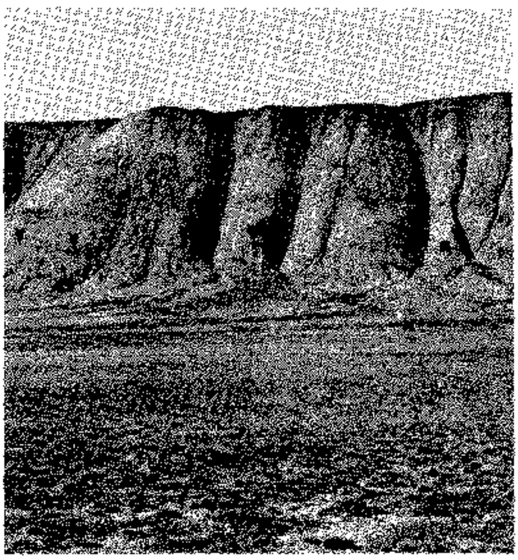

Fig. 9b. View of eroded cliffs taken from the seaward end of transect 9 (Fig. 5). The "dot" is where frost shattered shale, in permafrost, was sampled for water content (see text). The arrows mark sites of recent active layer failures.

previously unweathered shale and hence to a more rapid mass wasting of hill slopes.

Active-layer failures

Detachment failures of the active layer are common along the bare cliff slopes that front the Horton Delta (Fig. 9b). Commonly, the slopes are 20 to 30° and the active layer material is a loose frost shattered shale. The failure will often start just downslope either from a change in rock type or downslope from an ice wedge that trends along the contour. Failures tend to occur when 20 to 30 cm of loose thawed active layer material slides downslope over frozen and often ice-rich material beneath.

Ice wedges

Many ice wedges have grown along the contour of the bare backwearing bluffs such as those in Fig. 9b. On the gentler slopes of the alluvial fans (Fig. 9b), syngenetic ice wedges are growing in areas of active sedimentation. Several syngenetic ice wedges were drilled in order to estimate growth rates. Along profile 8 (Fig. 6), at the 200 m mark, the top of a syngenetic ice wedge was 0.8 m below ground level. The wedge was 0.6 m wide and was actively growing. Along profile 9 (Fig. 6, at the 350 m mark) the top of a syngenetic ice wedge was 0.6 m below ground level. The wedge was 0.95 m wide and was actively growing. The ages for the tops of the active ice wedges can hardly exceed 50 to 100 years because the flattish tops of the wedges were close to the bottom of the active layer. If so, the growth rates of the syngenetic ice wedges may average 1 to 2 cm yr^{-1} or more.

Geomorphic processes on the delta surface

The role of river ice

The Horton River, with a length of 650 km, freezes over in September–October. Break-up, which usually takes place in late May, is the major process affecting the surface morphology of the delta. At break-up, the water level in the lower Horton may rise as much as 8 m. With a rise in water level, at the river mouth, large pans of river ice are spread over the proximal part of the delta. An ice dam is then formed on the seaward side of the coastal bluff as shown by high level ice scour marks. As the river ice moves across the delta, the surface is bulldozed, scraped, and fluted.

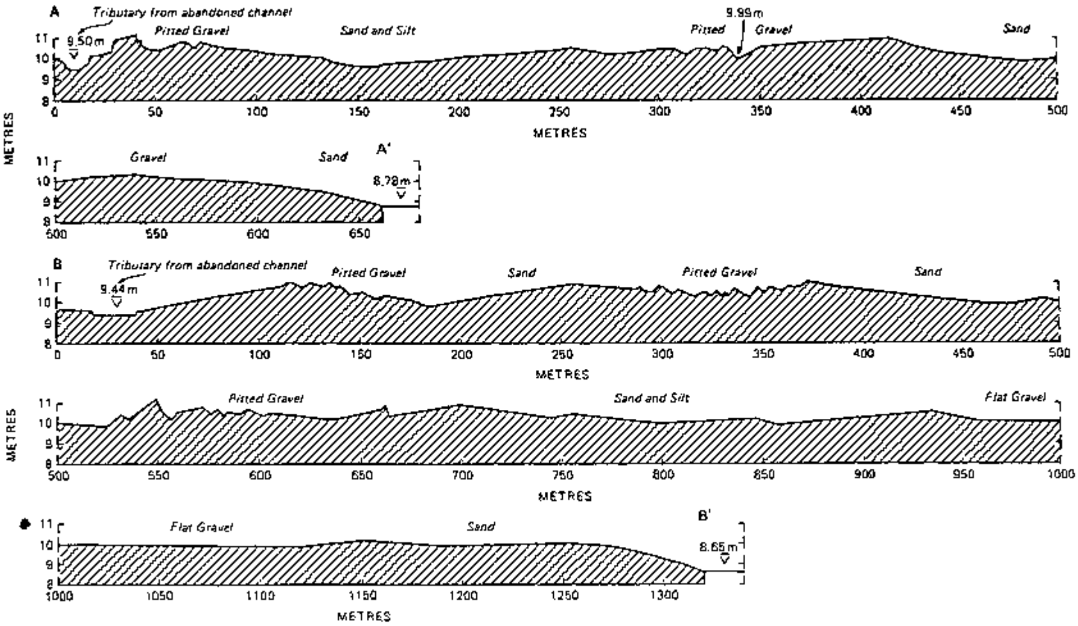

Fig. 10. Profiles A–A' and B–B' on the delta near the mouth. See Fig. 5 for location.

Sea ice

Sea ice plays a less important role than river ice. Freeze-up of sea ice is later than that of river ice by a month or more, but even so, sea ice inhibits wave action on the delta for at least six months of the year. In summer, persistent onshore winds will usually bring in sea ice to bulldoze the gravel barrier beaches. In some summers with prolonged onshore winds, the delta may be largely protected from wave action.

The delta surface

The delta surface is irregular in both topography and material. Two transects (A–A' and B–B') were surveyed (Figs. 5 and 10) across the delta. The delta is best described as a coarse grained fan-delta (MacPherson *et al.* 1987) and a number of features of the delta surface are of interest. Most striking is the occurrence of individual large boulders and the general evidence of gravel over much of the upper part of the delta surface (Fig. 11) (cf. Barnes 1982). Areas identified as pitted gravel are widespread as indicated on the cross-sections (Fig. 10). These result from ice action during the spring break-up period (Dionne 1985). The details of delta surface form with the strong differentiation between ridges of gravel and depressions underlain by silt are presumably the result of protection by ice and active erosion and sedimentation between ice pans.

The delta surface is also of interest because much of the area near where the Horton River leaves the cliffs is at least 1 m above river level within 2 km of sea level (Fig. 10) and none of the distributary channels have levees. The lack of levees is explained by the fact that when high water occurs as at breakup, much of the delta is flooded so that there is little overflow from distributary channels. In addition, flooding can also result from a rise of sea level associated with storm surges so stream flow is not confined to channels.

Delta

The estimated volume of delta development is 0.7 km^3. This figure hides some major uncertainties about the morphometry of the offshore zone because of the lack of detailed hydrographic maps. If the basin area of Horton River is 70,000 km^2 and a similar ice content in the basin and delta sediments is assumed, the sediments in the delta would represent a rate of basin-wide lowering of 33 mm per 1000 years. However, this is deceptive because

Fig. 11. Gravel heap, with a 1 m long shovel for scale, on the delta surface several hundred metres seaward of the mouth.

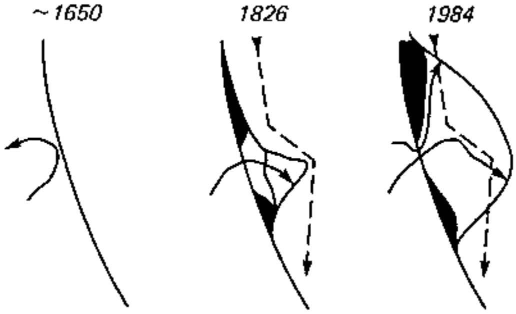

Fig. 12. The general appearance of the coast before breaktrough, about 1650 AD; the delta in 1826 (see Fig. 2); and the delta in 1984.

accelerated erosion has been confined to the lowest 100 km of Horton River, as indicated by river-thalweg steepening. Some of the Horton River lower course tributaries have pronounced knickpoints a few hundred metres to a kilometre or more upstream from their junction with Horton River. If the lowering of the Horton River channel after breakthrough is assumed to have diminished linearly from 10 m at the mouth to zero at 100 km upstream across a mean floodplain width of 500 m, the volume eroded would be approximately one third of the present delta volume. Thus, if lateral erosion is included, much of the delta volume could come from the river valley itself. Post-breakthrough erosion by the Horton and its tributaries within 100 km of the present mouth could therefore supply most of the sediment in the delta.

Relationship between Geomorphic Evidence and Dates Associated with the Breakthrough

Fig. 12 indicates the approximate appearance of the Franklin Bay coastline in 1650 (presumably before the breakthrough), in 1826, when Richardson's map was drawn and in 1984, as mapped with the aid of air photographs. If rates of delta and fan development are assumed constant, then the breakthrough on geomorphic evidence would have occurred about 1750. Evidence from tree ring cross-dating (Fig. 3), from dated driftwood (Fig. 4) and from archaeological evidence all suggest a date earlier than 1800.

Horton Delta

The surface area of the Horton Delta has increased from about 10 to 15 km^2 in 1826 to the present area of about 35 km^2 (Fig. 12). In 1826, much of the seaward part of the delta was building out into water depths of about 20 to 30 m, judging by present water depths at a comparable distance from the sea cliffs north and south of the Horton River mouth. The distal part of the present delta is growing out into water depths of 30 to 50 m. The preceding assumes negligible sea level changes since breakthrough (Forbes 1980; Hill *et al.* 1985). The present delta volume is 0.7 km^3. Therefore, as a rough estimate, the volume of sediment deposited since 1826 may be twice that deposited prior to 1826 AD. In any event, the depositional rate has probably remained roughly constant, so the breakthrough presumably occurred after 1640 AD, in agreement with the dendrochronological and radiocarbon evidence. A comparison of 1:25,000 maps made photogrammetrically (by K. Rood) from 1954, 1965, and 1984 photos shows little change except for a better development of the barrier bars on the seaward side of the delta. The surface area of the delta has increased very little.

Role of permafrost

All of the previous estimates of the volume of the Horton Delta and delta growth have been based tacitly upon the assumption that there is negligible excess ice in the delta. The mean annual ground temperature for one drill hole on the edge of the delta is about -9°C and the mean annual air temperature, estimated from the two nearest weather stations (Cape Parry, N.W.T. and Nicholson Peninsula, N.W.T.) is about -12°C. Therefore, permafrost will commence to grow downward wherever new delta surfaces are exposed to air temperatures. However, the water of Franklin Bay is saline; mean annual water temperature at depth of the sea water is about -1.5°C (Macdonald *et al.* 1978). The freezing point of the sea water is about -1.5°C or colder, depending upon the salinity. The Horton Delta is then building out into saline water where the density of the Horton river water should be less than that of the denser saline water at depth (cf. Bates 1953). Thus most delta sedimentation is probably into saline water. Because the freezing of sediments with saline pore water tends to inhibit ice segregation as compared to the same sediment with fresh pore water (Chamberlain 1983) it seems unlikely that Horton Delta sediments contain much excess ice. If so, then the volume of the delta should approximate the volume of the deposited material. In the older part of the delta, ice bonded permafrost has probably had sufficient time to aggrade downward to the former sea bottom but this may not be so in the distal part (cf. Osterkamp 1987; Williams 1968).

Rates of Geomorphic Change

Cliffs

The estimated volume of the fan development is approximately 0.06 km^3. However, the actual volume of sediment derived from the 2.5 km^2 catchment area is very much less than 0.06 km^3, because much of the fan volume is composed of excess ice, that is, ice beyond the saturation level. The excess ice, known as aggradational ice (Mackay 1972) forms partly as a result of the upward rise of the permafrost surface in a site of sedimentation and partly as a result of the downward movement of water into the top of permafrost in summer (Cheng 1983). A conservative estimate of the amount of excess ice for the fan portions of profiles 8 and 9 (Fig. 5) is given in Fig. 13. Holes were drilled along the two profiles to a depth of about 2.7 m. The frozen cores were then placed in vertical tubes of about the same inner diameter and allowed to thaw. The amount of supernatant (i.e.

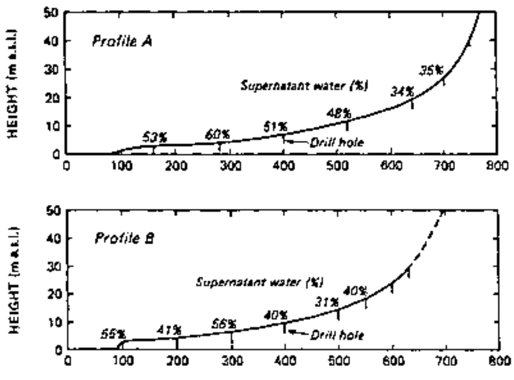

Fig. 13. Supernatant water from frozen cores, after thawing, for profiles close to 9 (profile A) and 8 (profile B) of Fig. 5.

standing) water above the saturated sediments at the bottom of the tubes was then expressed as a percent of the length of the frozen cores. The data from the two profiles suggest that at least 50% of the 0.06 km^3 of the fans is excess ice so that the volume of sediment removed from the 2.5 km^2 catchment area is probably only 0.03 km^3 or less. This implies a total degradation of about 12 m in 2–300 years. Such a rate of surface degradation is extremely high by global standards and probably the highest reported in Arctic permafrost.

The mean rate of deposition decreases downslope from the cliffs to the sea, because the profiles tend to be concave up. Fig. 14 shows the gravimetric water content and tritium content (in tritium units) for a drill hole at the 350 m mark from the sea for profile 9 (Fig. 5). The mean gravimetric water content for 18 samples was 157% and the mean bulk density was 1.1 g cm^{-3}, so the volumetric water content was considerable. The high tritium concentration above 0.7 m indicates post-nuclear testing of the 1950's and early 1960's; that at 0.8 m is marginal (Burn and Michel 1988; Michel and Fritz 1982); whereas the tritium content below 1 m indicates pre-nuclear testing. The active layer on 30 July 1986 was 32 cm deep so that the maximum late summer thickness was probably about 40 to 45 cm. Because post-nuclear tritium is found to a depth of only 70 to 80 cm, and active layer water can migrate down into the top of permafrost, the evidence from the tritium concentration suggests that sedimentation has been less than about 40 cm (80 cm – 40 cm) since 1953 or at a rate of less than about 1 cm yr^{-1} at the specific site.

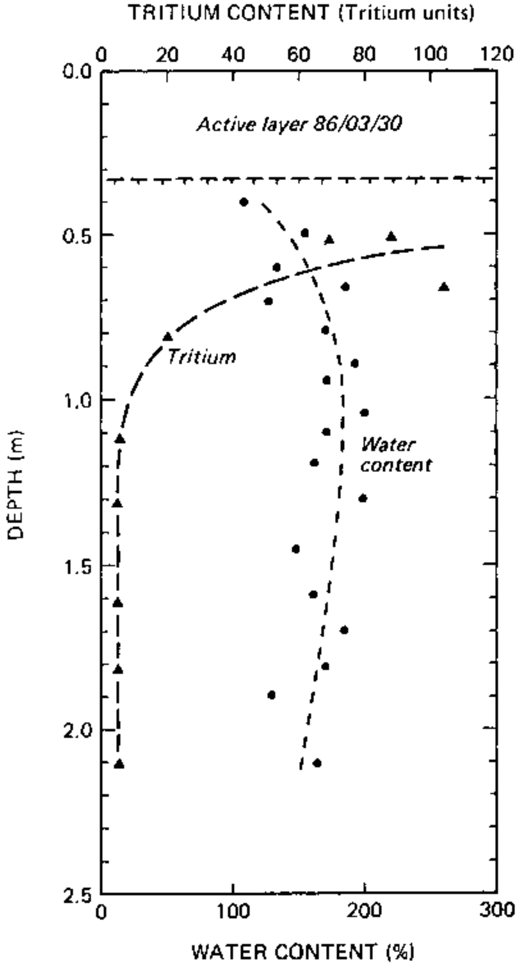

Fig. 14 Gravimetric water and tritium content for a drill hole at the 350 m mark of profile 9 (Figs. 5 and 13).

Geomorphic processes prior to the breakthrough

The shorelines immediately to the north and south of the present delta are straight with active cliff erosion, short steep gullies, slumps from undercutting by waves, a variety of localised slope features, and narrow beaches (Fig. 9a). Longshore transport tends to be southward. Because a nearly straight line can be drawn from the unprotected cliffs north of the delta, then along the wave protected cliff front of the delta, and then along the unprotected cliffs south of the delta, the pre-breakthrough cliff line was doubtless continuous, the cliffs were steep, beaches were narrow, and there were no deep embayments.

Geomorphic processes after the breakthrough

Firstly, as soon as the breakthrough of Horton River occurred it is hypothesized that the main sediment deposition consonant with the direction of longshore transport and also with the depiction of John Richardson's 1826 route was towards the south along this part of the coast. Protection of the cliff base from wave attack should therefore have commenced earliest towards the south of the river mouth. Alluvial fan sediment that would previously have been removed by wave action now accumulated behind delta sediments. In the area of maximum available relief, active extension of the gully network occurred and large scale slope failure with rotational slumping, uphill facing scarps and truncated spurs have resulted.

Secondly, the maximum relief zone north of the river mouth was protected by the build up of deltaic sediments. This allowed headward extension of the gully systems and a second locus of alluvial fan growth and debris flow activity developed. Gully enlargement facilitated the entrapment of large snowbanks which, now, may persist to the end of August. A few are sometimes perennial. Snowmelt from the large snowbanks contributes to debris flows and fan growth.

The third development has been the increased drainage density, in the form of intensified gullying, which has occurred on the protected cliffs (Fig. 8). As analysed from the air photographs, gullies occur at a spacing of roughly one every 50 metres in the protected cliffs (about twice as many as in the wave cut cliffs). It is anticipated that with the increased drainage density associated with gullying on the protected cliffs, the probability of intersecting massive ground ice and slump features at the cliff top will become greater and degradation of cliff slopes will occur behind the accumulated deltaic sediments by large scale mass movement.

The fourth development has been geocryologic: frost shattering of bedrock in permafrost; the growth of ice wedges on the bluffs and syngenetic ice wedges and aggradational ice on the alluvial fans; and the growth of permafrost in the delta.

Conclusion

The Horton River, which now flows into Franklin Bay, formerly discharged into Harrowby Bay about 60 km northwest of the present mouth. The breakthrough site is in an area with permafrost, river and sea ice. The Horton River site is then of considerable interest because the breakthrough date has probably been bracketed. Prior to the breakthrough, the west coast of Franklin Bay at the present Horton mouth was straight with sea cliffs rising precipitously 100 to 150 m above the sea. The river broke through to the sea on the undercut (outer) side of a large meander bend where river level was then about 10 m above sea level. Downcutting in the easily erodible shales would have been very rapid so the channel leading to Harrowby Bay was abandoned probably within a year. Dendrochronological analysis and radiocarbon dating of driftwood stranded on the old channel show that the breakthrough was after 1640 AD. The breakthrough was also well before 1826 when a delta, although much smaller than that of the present, was mapped by the explorer John Richardson.

The geomorphic processes on the cliffs differ, in a number of respects, from those in more temperate climates. There are numerous active layer failures on the steep bare hill slopes where 20 to 30 cm of loose frost shattered shale chips slide downslope over the frozen ice rich active layer beneath it. The upper metre or so of permafrost bedrock (shale) has become icier by the downward movement of water from the active layer in summer in response to the temperature gradient. Ice wedges have grown in many places on bare steep slopes and episodic thinning of the active layer above them often triggers slides. The melting of massive ice at the cliff tops feeds a watery slurry into gullies to initiate debris flows. Debris flows also occur downslope from many large snowbanks which accumulate in the gullies as they enlarge on the receding cliffs.

The role of river ice is paramount in determining the material and topography of the delta surface. At river breakup in late May or early June, large pans of river ice spread over the delta transporting sand, gravel, and boulders. The delta surface is littered with gravel heaps, boulders, and collapse pits and pools left by melting ice. Sea ice plays a passive role by inhibiting wave action for half of the year but some gravel may be pushed onto the barrier beaches when onshore winds drive sea ice to ground in shallow water.

The delta has a surface area of about 35 km^2 and a volume of about 0.7 km^3. If estimated rates of delta and fan development are assumed constant, then the breakthrough on geomorphic evidence would have occurred about 1750. As a rough estimate, the volume of sediment deposited since 1826 may be twice that prior to 1826 AD. A comparison of the profile of the old abandoned channel downstream from the Horton mouth with that upstream suggests that post-breakthrough downward erosion extends at least 100 km upstream from the mouth. Knickpoints on lower Horton tributaries also help to confirm upstream erosion. Vertical downcutting for 100 km upstream across the width of the floodplain with some lateral downcutting could have supplied most of the present delta volume. If sediment sources were confined, as seems likely, to the lowermost 100 km of Horton River and within 1 km on either side of the river, a specific denudation of 11.5 mm yr^{-1} occurred during the past 300 years.

The estimated volume of fan development is 0.06 km^3 which has been derived from the 2.5 km^2 catchment area of the protected cliffs. However, the fans contain a great deal of excess ice formed by permafrost aggradation accompanying fan deposition. The actual volume of sediment removed from the 2.5 km^2 catchment area is probably only about 0.03 km^3 for a total degradation of about 12 m. Depending on the timing of the Horton River breakthrough, this would be equivalent to a specific denudation of 4–6 cms yr^{-1} for the area drained by gullies in the protected cliffs.

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