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Permafrost Development in the Intertidal Zone at Churchill, Manitoba: A Possible Mechanism for Accelerated Beach Uplift

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ABSTRACT. Boreholes drilled in the Beech Bay area during July to November 1929 indicated that a sill of permafrost had extended below the high-water line, tapering in depth towards low water. The boreholes revealed thick layers of fine sediments on top of deep underlain bedrock. Recent borings determined the upper limits of permafrost in 1981. Examination of the data shows that there has been a permafrost expansion into the emerging tidal zone. These observations suggest an additional mechanism for accelerated uplift of coastal exposed "soft" sediments: the vertical expansion of refrozen, water-saturated silts and clays as new permafrost forms. The existing rates of isostatic uplift are enhanced by the process.

Key words: permafrost, active zone, isostatic uplift, Beech Bay, Churchill, Hudson Bay

RÉSUMÉ. Des carottes prises dans la région de la baie Beech entre juillet et novembre 1929 ont indiqué qu'un seuil de pergélisol s'étendait au-dessous du niveau des hautes mers, diminuant en profondeur en approchant le niveau des basses mers. Les carottes révèlant des couches épaisses de fins sédiments reposant sur un profond sousbassement. Des carottes récentes ont déterminé les limites supérieures du pergélisol en 1981. L'étude des données signales une expansion du pergélisol dans la zone intertidale surgissante. Ces observations suggèrent un mécanisme additionnel accélérant la levée des sédiments "mous" exposés le long des côtes par l'expansion verticale de vases et de glaises saturées d'eau et congelées à nouveau sous de nouvelles formes de pergélisol. Le taux de levée isostatique est augmenté par le processus.

Mots clés: pergélisol, zone active, levée isostatique, baie Beech, la baie d'Hudson

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INTRODUCTION

Along the coastal regions of Hudson Bay, recently uplifted beach sediments are subjected to the intrusion or recession of permafrost. As submerged sediments are elevated into the tidal zone, they are subject to radiational cooling. At some unique point in the tidal zone or beach, a significant but small negative seasonal energy balance is achieved in relation to incoming radiation, which results in the development of permafrost in the subsurface strata.

The existence of permafrost in the arctic intertidal zone was recorded by Owens and McCann (1970): "... the frost table extends into the intertidal zone such that it can prevent the reworking of large amounts of beach material." Other studies on beaches in the Arctic Archipelago (McCann and Hannel, 1971; Sadler and Serson, 1981) clearly demonstrate the presence of permafrost extending through the tidal zone into the Arctic Ocean. The existence of 'relict' permafrost under the Arctic Ocean has also been reported (French, 1976; Vigdorchik, 1980). At Pen Island near the Ontario-Manitoba border, Kershaw (1976) reports finding permafrost in the intertidal zone during July and August. The concept of ice uplift has been used by Rampton (1976) to explain geomorphological features in the Mackenzie Valley: "Low terraces of non-glacial origin and composed mainly of silt are present along the East Channel of the Mackenzie River and along most major rivers...Non-glacial terraces in this area result from two processes: (1) the down-cutting of streams to lower base levels, and (2) heaving as a result of permafrost aggradation in river alluvium." Whether there is an active enlargement of pore size leading to some degree of massive ice formation in the marine or fluvial beaches in the Churchill region is not known, although ice-cored mounds up to 2 m in height are present on the flats between Akudlik and Beech Bay.

Accordingly a study of Beech Bay near Churchill, Manitoba was initiated during August and September of 1980 and 1981 with the following objectives: 1) determination of the present extent of permafrost within the beach and present tidal zones, in order to contrast the findings with those of a previous study in 1927-32 (Palmer, 1927); and 2) an examination of the potential effects of permafrost development on the rate of beach uplift.

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METHODS

Bore holes drilled between July and November 1929 (Map 34, Hudson Bay Terminus Test Borings, Resident Engineer's Office, Churchill, Manitoba) indicate that a sill of permafrost extends below the high-water line, tapering in depth towards low water. The area was surveyed and referenced to Churchill benchmark IGY #2 (grid ref. 341144, 1972 Photomap, Churchill) together with a transect through each location, C and D (Fig. 1).

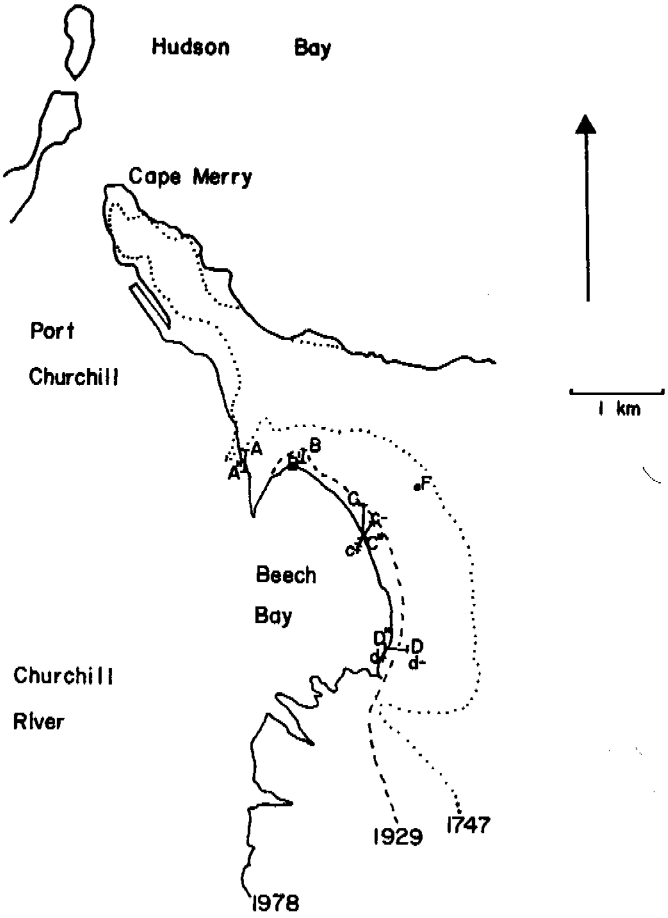

FIG. 1. Beach zones in the vicinity of Churchill, Manitoba, showing high-water lines for 1747, 1929 and 1978 and locations of bore hole transects A, B, C, D, and bore hole F on Beech Bay.

The upper limit of the permafrost was established by borings using a 4 m long hand auger, and sediments were collected and examined for the presence or absence of ice crystals. The sediments were also subsequently analysed for moisture content, pore space and texture. The texture of the mineral sediments was determined by a hydrometric technique based on differential rate of settling of sediment particles dispersed in a water column (Savigny, 1979; Watson *et al.*, 1973). The location of the current borings was established relative to the previous drilling sites but also extended farther into the tidal zone as well as farther inland (Fig. 1).

Rates of beach formation were established by scaled projections from 1747 (Robson, 1752) and 1929 charts, and from an aerial photograph taken in 1978. In addition, maps and surveys from 1908, 1927a,b, 1949, 1958, 1960, and 1973, and aerial photographs taken in 1929, 1932, 1969, and 1978 were examined for tidal zone shift (see Appendix). To support the dating of the former beach lines, tree-ring cores were taken from an area of white spruce (*Picea glauca*) that has developed in an area adjacent to the old 1747 high-water line.

RESULTS

Figures 2 and 3 illustrate the 1929 sill of permafrost tapering to a point in or beyond the tidal zone. In the original study the

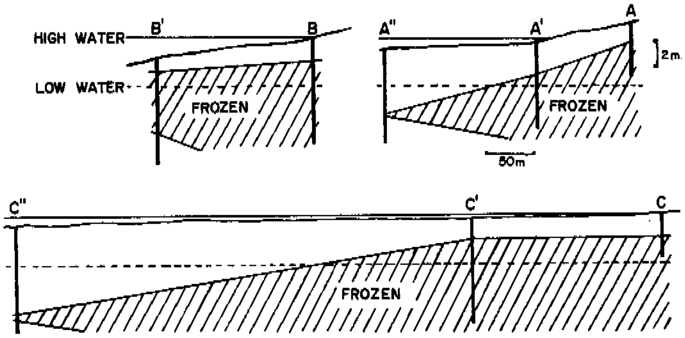

FIG. 2. Vertical sections of transect A, Port Churchill and transects B and C on Beech Bay showing 1929 high-water lines and tapering permafrost sills underlying the tidal zone. Redrawn from Map 34, Hudson Bay Terminus Test Borings, with permission of the Canada Harbours Board Archives, Port Churchill.

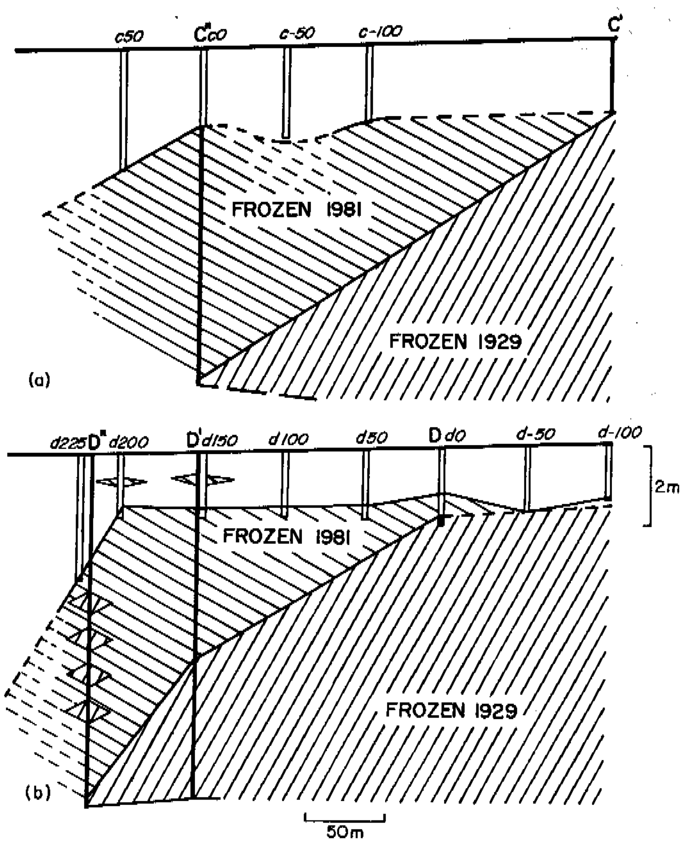

FIG. 3. (a) Vertical section of transect C, Beech Bay, Churchill, Manitoba, showing 1981 depths of active layer and location of 1929 permafrost sill. (b) Vertical section of transect D, Beech Bay, Churchill, Manitoba, showing 1981 depths of active layer and location of 1929 permafrost sill.

area near transect C consisted of three bore holes (C, C′, C″) spaced over approximately 250 m. In 1981 at transect C, there had been a marked decrease in the depth of the active layer since 1929. Along transect C (Fig. 3a), the bore hole that was located farthest into the tidal flats (C″), indicated a depth of the upper permafrost table of 8.24 m. The point was re-drilled in 1981 and permafrost was found at 1.85 m. A second hole drilled 50 m towards the low-water mark revealed permafrost at a depth of 2.81 m. At 100 m inland, permafrost was found at 1.79 m. Progressing inland from the original boring, there have been developments such as peat accumulation and hummock formation which impede local drainage, resulting in water-saturated fens and bogs.

The active layer has increased since 1929 into the saturated areas upslope, indicating probable thermokarst developments. As one moves inland beyond the bogs to the region of bore hole F (1929; Fig. 1), the slope becomes steeper, enhancing surficial drainage and resulting in a uniform development of 1.1 m peat. In 1929 the active layer at F was 1.37 m thick; in 1981 it remained virtually unchanged at 1.42 m.

A repeat study undertaken at 1929 transect D (Fig. 3b) reveals similar changes over time. The 1932 boring farthest into the tidal zone (D″) revealed an ice lens at 4.60 m and permafrost at a depth of 7.62 m. The current study (D″) found permafrost at 3.05 m (the actual site of the re-boring was approximately 10 m farther into the tidal zone). Twenty-five metres farther inland (at d200) permafrost was found at 1.30 m and a lens of ice was noted at .76 m. The 1929 borings at D′ indicated permafrost at 3.66 m, while the current study found permafrost at d150 at 1.19 m. Progressing inland at 50-m intervals, we located the ice surface at 1.40 m (d100), 1.57 m (d50) and 1.27 m (d0). The latter boring (D) had a recorded depth to permafrost at 1.68 m in 1929. Again the depth to the present permafrost table increased as we progressed inland into the water-saturated fens and bogs (1.65 m [d-50] and 1.52 m [d-100]).

Coincident with the permafrost development, the beach zone has extended by approximately 1 km since 1747 (Fig. 1). This amounts to an uplift of 3.4 m over 233 years — a rate of 1.45 m·100 yr^{-1} — along transect D.

Figure 4 illustrates the transect D vertical profile of Beech Bay. In the area where the permafrost sill begins to taper, there is a 'beach ridge', or terrace feature, that rims the entire bay. It is most prominent in the southern extremes and becomes indistinguishable on the northwest shore.

Tree-ring analysis indicated that the maximum age of forest stand at the 1747 tide line was 160 years. This is consistent with the time available for forest succession (230 years) since emergence from marine conditions. The present treeline is elevated 2.43 m along transect D and 2.92 m along transect C. Both measurements use the high-water line as datum.

DISCUSSION

This study examines the depth of the active layer by measuring the depth to the top of the permafrost sill under Beech Bay. The drilling was completed in early September 1981 at the period of peak depth of thaw of the active layer in the Churchill region (Brown, 1973; Brown Beckel, 1957; Jordan, 1979; W. Rouse, pers. comm. 1981). The seasonal timing is coincident with the 1929 drilling.

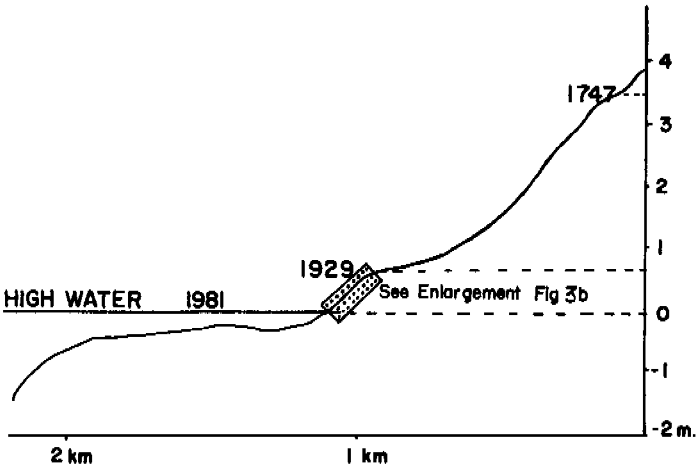

FIG. 4. Vertical section of Beech Bay along transect D, showing high-water line for 1981, and estimated high-water lines for 1929 and 1747.

As in 1929, a sill of permafrost exists under the beach on Beech Bay and tapers within the current tidal zone. The sill has extended seaward since 1929, paralleling the shift of the tidal zone that results from isostatic uplift. This cannot be considered a fossil permafrost from the period before the Tyrrell Sea inundation (Mackay, 1971, 1975; Vigdorchik, 1980). The expanding edge of the permafrost is continually achieving a new balance with the cool terrestrial climate as land emerges from the marine environment. In 1980, there was clear evidence of an active frost table throughout the tidal zone. Frost-heaved boulders were common in the shallow waters, mud boils occurred in the ridges near low tide, and thermal contraction cracks existed on the submarine ridges.

The ridge that rims the bay at the 1929 high-tide mark also marks the start of the taper of the permafrost sill. The ridge may be, in effect, a 'knee' that reflects the forward section of the developing sill. Throughout transects C and D the active layer is thinnest at the knee. The active layer increases inland, particularly in areas of poor drainage where thermokarst may occur. The knee itself becomes less distinct along the north shore of Beech Bay. The rate of uplift is much greater on the northeast shore of Beech Bay compared to the southeast shore (2.19 *vs.* 1.45 m·100 yr^{-1}). On the east shore, transect D extends into an open spruce woodland; transect C on the north shore extends onto a drier tundra meadow. If a greater column-height of permafrost were to develop on the tundra meadow, one would expect greater combined uplift at C. The slope at C would be greater and the knee itself would be less distinct. This is exactly what has been observed.

In the Churchill region, the estimated rate of post-glacial rebound varies with each study. The estimates based on beach ridge or tundra elevations above present sea level are generally larger than rates derived from uplift of bedrock. On the basis of radiocarbon dating of shells, Craig (1968) estimates the rate of uplift to be close to 1.83 m·100 yr^{-1}. Our investigations indicate that land currently at an elevation of up to 2.19 m was part of the tidal flats of Hudson Bay a century ago. However, Andrews (1968) estimates the rate of uplift at between .8 and 1.0 m·100 yr^{-1}, and Barnett (1966, 1970) analysed the Port of Churchill tidal gauge data from 1940 to 1968 and concluded that the current rate of uplift is .397 ± .115 m (with 95% confidence limits). Tidal anomalies in Hudson Bay resulting from winters of variable ice cover (Godin and Barber, 1980) indicate that even this estimate may need revision. However, there is support of the lower estimates: Godin and Eldring (1974) have estimated a conservative change in height of the geodetic markers at Churchill. In 1978, these markers were resurveyed by Canadian Geodetic Survey personnel, who obtained a rate of rebound of .815 m·100 yr^{-1} for the Cape Merry geodetic marker, BM 566-D. This relatively low rate was confirmed in a 1980 survey from low tide to the Cape Merry geodetic marker (A.E. Wokes, pers. comm. 1980).

In examining the lateral extension of Beech Bay, we found an unexpectedly high rate of beach formation between mean tide lines, on topographic maps based on measurements made in 1946 and 1972 (3.4 m on transect D at the 1747 beach line). The rate of beach formation expected from the isostatic uplift (.816 m·100 yr^{-1}) and the angle of beach slopes (.003 along transect D) accounts for less than half of the new beach. The additions of fluvial and marine deposits alone are unlikely to explain the uplift phenomenon, since the effect is observed from high-tide line to high-tide line, i.e. above the zone of sediment deposition.

A MODEL FOR ACCELERATED BEACH UPLIFT

Ice formation causes an increase in volume of about 1.095 times the original volume of water at temperatures between 0-80 °C and pressures below 2 Kbars. Terrestrial pressure of 2 Kbars occurs only in association with high temperatures (Fletcher, 1970; Hobbs, 1974). In soil this expansion may be partly accommodated by compression of vapour in the pore space. However, in water-saturated material resting on bedrock, the increase in volume results in a net thrust towards the surface. The composition of beach material from Beech Bay is given in Table 1.

TABLE 1. Mechanical analyses of core samples collected along transect D, Beech Bay, Churchill, Manitoba, 1981

	1	2	3	4	5	6	Mean ± S.D.
Spec Wt.							
(Dry)(g·cm^{-3})	2.08	2.12	2.25	2.19	1.99	2.15	2.13 ± 0.25
Texture							
Sand (%)	43.3	60.8	38.2	35.8	50.7	46.1	45.8 ± 8.3
Silt (%)	23.9	5.4	41.7	54.5	24.6	30.5	30.1 ±15.3
Clay (%)	32.8	33.8	20.1	9.7	24.7	23.4	24.1 ± 8.1

At Beech Bay, ice forms a lateral sill in the tidal zone, tapering towards low water (Fig. 3). An active zone deepening towards low water implies that this sill is in an active balance, with net heat transfer from water and loss to the atmosphere. As the land rebounds, the beach is lifted and the tidal zone will shift laterally. The permafrost sill has an equivalent development as new ice is formed towards low water. This new ice formation results in a net thrust away from bedrock, giving rise to additional uplift and lateral shift of the high-water line (Fig. 5). If the expected height of the permafrost column at the high-water line is h_0 and the original height of the column at some lateral distance ℓ towards low water is h_1, then the expected uplift at new high tide due to new ice formation is $(h_0 - h_1)y$, where y is the coefficient of expansion and $y = p.\alpha$, where p = proportion of pore space (in water-saturated material) and α = proportion of increase in volume

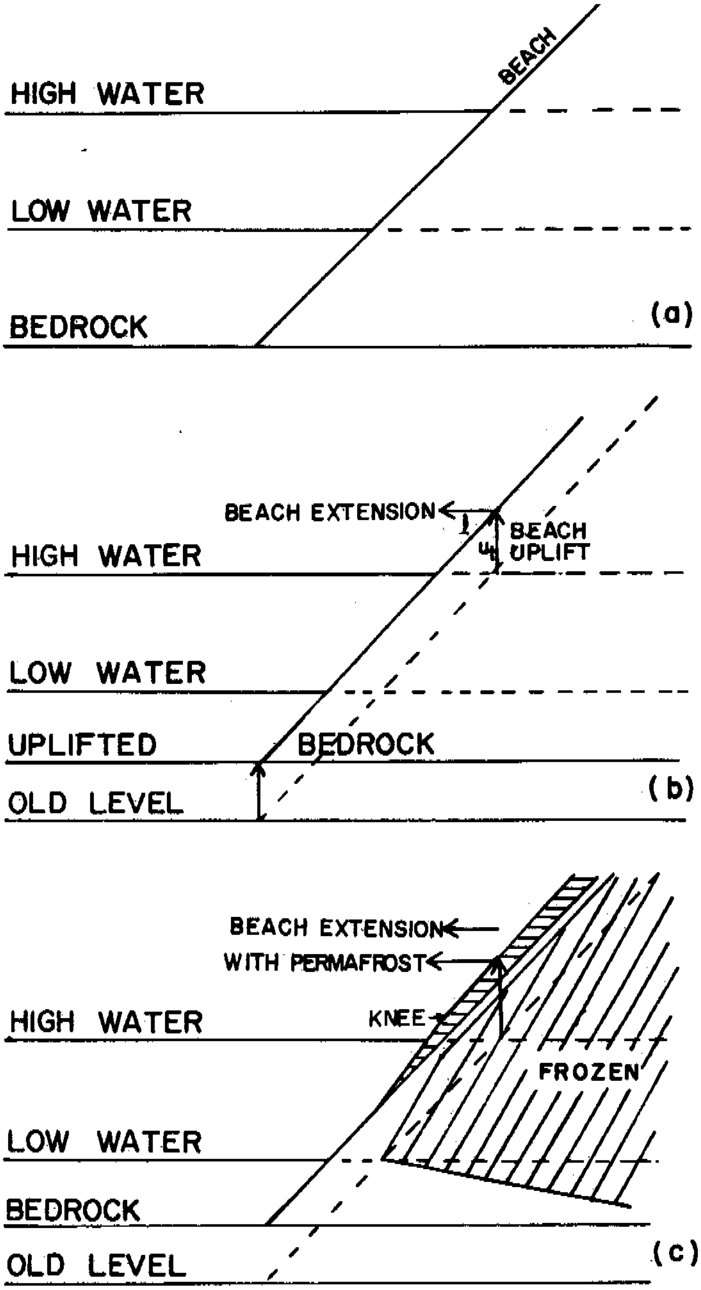

FIG. 5. Diagram of mechanism of accelerated beach uplift and lateral extension due to expansion of the permafrost column (c) following isostatic uplift of unfrozen submarine sediments (b).

on freezing. If the isostatic uplift in time t is written U_t, then the total amount of beach uplift in time t at location ℓ below old high tide is

$$U_{t\ell} = U_{t.} + (h_0 - h_l)\,y.$$

The expected new location of high-water line of beach with slope 'a' will occur at the point at which the old water depth w_ℓ is equal to the total beach uplift, i.e. at $w_\ell = u_{t\ell}$. Since $a = w_\ell \cdot \ell^{-1}$, we predict the new high-water line at distance $\ell = u_{t\ell} \cdot a^{-1}$. If time has been sufficient for the uplift to take the water line beyond the seaward limit of the old permafrost wedge, this becomes $\ell = u_t \cdot a^{-1} + h_0 \cdot a^{-1}$.

Applying this model to transect D, on Beech Bay, we have a measured water-saturated pore space $p = 0.370$, and expansion due to freezing of 0.095, then the coefficient of expansion $y = 0.3515$. Assuming isostatic rebound of $0.816\ \text{m} \cdot 100\ \text{yr}^{-1}$ measured on solid bedrock, we have, for the period 1747-1978, isostatic uplift $u_{t.} = 1.88$ m. If we assume that the current permafrost depth at high tide is equivalent to the known 1929 permafrost column height h_0 of 14.3 m at high tide, we have an additional uplift of 0.503 m due to permafrost formation. With beach slope at D of 0.003, we have a lateral extension due to isostasy of 626.7 m, and due to permafrost uplift of 167.5 m. This accounts for a total uplift of 2.383 m and total lateral extension of 802 m. The actual lateral shift on Beech Bay along transect D is approximately 1000 m since 1747.

The discrepancy between the real lateral extension of beach and the calculated value may relate to several factors. The estimation of permafrost column height may be variable with location, and the use of the 1929 value may be inaccurate; certainly a column of 61 m (maximum reported depth for Churchill) would give more than is needed for the observed discrepancy. Again, the assumption of a measured pore space of 0.370 would be invalid if massive ice existed at some points in the column. Refreeze and deep sediment upheave have been suggested as initiating mechanisms for the process of pingo formation (Mackay, 1962).

CONCLUSION

The evidence indicates that the permafrost sill under the beach at Beech Bay has been active at least since 1929. Permafrost development under Hudson Bay will have the general effect of increasing the rate of emergence of land through thermal expansion. As the sill increases in width, the emergence process continues within beach zones, increasing the apparent rate of uplift.

Much of the observed lateral extension of the beach is attributable to vertical expansion after refreezing. The variability in uplift estimates for the Churchill area can be explained by the hypothesis of locally differentiated uplift, which results from differential rates of permafrost column height development and from tidal anomalies (Godin and Barber, 1980).

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APPENDIX

List of Maps and Charts Used in this Study

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1908. Survey of the East Peninsula, Churchill, Manitoba, by J.E. Morrier, National Harbour Board Archives, Port Churchill, Manitoba.

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1927b. Hudson Bay Route — Plan of Churchill Harbour, to accompany Palmer, F., Hudson Bay: Report on the Selection of a Terminal Port for the Hudson Bay Railway.

1929. Hudson Bay Terminus Test Borings, Churchill, Manitoba. 1″ = 400 yds. On beach west of 16th Ave. and W St. W. National Harbour Board Archives 34, Port Churchill.

1949. Button Bay, Canada 54L/9, (1:50,000), Surveys 1947-48, Aerial Photos 1946. Department of National Defence, Canada.

1958. Camp Churchill Composite Map, ASE 70b West (1:25,000), contours 10′ in feet above mean sea level. Department of National Defence, Canada.

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