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**Abstract:** Parks Canada and the Geological Survey of Canada conducted a collaborative field project in 2007 and 2008 at the York Factory National Historic Site of Canada to characterize current permafrost distribution and support the development of management plans. Seven boreholes were drilled and instrumented to document the ground thermal regime. Ground electrical conductivity surveys were also conducted to further characterize permafrost throughout the site. The results indicate that the distribution of permafrost is discontinuous, and where present, it is generally less than 15 m thick and warmer than −1°C. Permafrost is present in areas where vegetation clearing has probably resulted in reduced snow cover. Permafrost is generally absent where re-establishment of willows has promoted deeper snow cover and higher mean annual ground temperatures.

**Résumé :** En 2007 et 2008, Parcs Canada et la Commission géologique du Canada ont collaboré à la réalisation d'un projet sur le terrain au lieu historique national du Canada York Factory, afin de caractériser la répartition actuelle du pergélisol et de soutenir l'élaboration de plans d'aménagement de ce lieu historique national. Sept puits ont été forés et instrumentés pour documenter le régime thermique du sol. Des levés de la conductivité électrique du sol ont également été réalisés dans l'ensemble du lieu historique national du Canada York Factory, dans le but de caractériser davantage le pergélisol. Les résultats indiquent que le pergélisol est discontinu et que, lorsqu'il est présent, son épaisseur ne dépasse pas 15 m et la température y est supérieure à −1 °C. Le pergélisol se trouve dans des zones où le défrichement a vraisemblablement eu pour effet de réduire la couverture de neige. Habituellement, le pergélisol est absent aux endroits où le rétablissement de la végétation de saules a favorisé une couverture de neige plus épaisse et des températures moyennes annuelles du sol plus élevées.

## INTRODUCTION

York Factory, established in 1684, is perhaps the oldest place in Canada where permafrost has played a role in building maintenance. Hudson's Bay Company (HBC) records documenting excavations to depths of 25 feet at the present York Factory site liken the frozen ground encountered to solid rock (Donaldson, 1981). Artisans responsible for construction and maintenance were well aware of permanently frozen ground and the need to compensate for heave or settlement of building foundations, and thus modified building techniques accordingly (Donaldson, 1981). With preservation of this National Historic Site now a major concern of Parks Canada, permafrost will also play a role in the preservation strategy. Frozen ground can be an effective preservation medium for artifacts. On the other hand, thawing of ice-rich frozen soil is likely to weaken the ground, cause subsidence, and alter surface drainage. York Factory lies within the permafrost zone of Canada but is sufficiently south that the distribution of permafrost is not continuous. To understand how permafrost (as well as ongoing impact of climate change) may affect preservation, it is necessary to determine its present distribution and thermal condition.

Recent research on the distribution and sensitivity of permafrost at York Factory is part of a multidisciplinary approach to "Saving York Factory", a project led by Parks Canada. The objective of this project is to develop a management plan for the York Factory National Historical Site of Canada by identifying and assessing the environmental threats to the site, including permafrost degradation. The Geological Survey of Canada (GSC) collaborated with Parks Canada in 2007 to drill and instrument a suite of boreholes for ground temperature measurement and ground ice determination. These instrumented boreholes also contribute to the GSC's ongoing efforts to enhance the national permafrost monitoring network and to better characterize the current thermal state of permafrost in the region. Geophysical surveys allowed permafrost distribution inferred from the boreholes to be extrapolated throughout the site.

This report describes the fieldwork conducted in 2007 and 2008. Thermal data from the first year of thermal monitoring is presented along with results obtained through the geophysical surveys. These data are utilized to present a preliminary characterization of permafrost at York Factory.

## REGIONAL SETTING

Established as a National Historic Site in 1936, York Factory is one of the oldest and most important HBC trading posts, having operated from 1684 to 1957. York Factory (57.0°N, 92.3°W) is located on the peninsula between the estuaries of the Nelson and Hayes rivers, on the southwest coast of Hudson Bay in Manitoba (Fig. 1) and lies within the Hudson Bay Lowlands physiographic region. Although the HBC had a presence at the mouth of the Hayes River starting


**Figure 1.** Location of York Factory.

in 1684, today's site is the third location of the York Factory post, established in 1788 following the inundation of the previous two posts farther downstream (Donaldson, 1981).

The peninsula is characterized by parallel beach ridges and bars that record coastal emergence during earlier stages of glacial rebound. The overall relief is gently sloping toward Hudson Bay, on the order of 1 m/km, with raised beaches, palsas, and peat plateaus responsible for the local relief of up to about 1 m. The combination of the generally flat landscape and raised beaches causes poor drainage. As a result the low-lying areas between the raised features are waterlogged marsh and fen. The York Factory National Historic Site of Canada is situated approximately 10 km inland from Hudson Bay on the north side of the Hayes River, adjacent to a steep, 10 m high riverbank, eroding at approximately 0.5 m/yr (Skaftfeld et al., 2005).

Terrain development is the combined result of the continual emergence of land at a rate of 1.0 to 1.3 m per century (Simpson, 1972) and sedimentation by the Nelson and Hayes rivers (Tarnocai, 1982). As a result permafrost at York Factory is relatively young: radiocarbon dating of driftwood extracted from the bank of the Hayes River by Simpson (1972) indicated that the minimum age of emergence is between 1055 and 1930 BP. The Quaternary stratigraphy at the site consists of alluvial silt approximately 4 m thick (Tarnocai, 1982) overlying laminated, grey marine silt and clay to depths greater than 15 m. A shallow cover of peat interlayered with alluvium as a result of inundation overlies these sediments (Tarnocai, 1982). Simpson (1972) described the terrain in which York Factory is located as a levee, consisting of alluvium deposited immediately inland of the riverbank during flooding. Much of this zone is no longer inundated by the Hayes River and is characterized by being fairly level and slightly better drained than terrain farther inland.

The climate is typified by long, cold winters and short, cool summers, and is cooler than would be expected at similar latitudes because of the proximity of Hudson Bay. Sea ice often persists through July, cooling the surrounding terrain (Rouse, 1991). Ball (1983) analyzed York Factory climate records kept from 1774 to 1910. The mean annual air temperature (MAAT), calculated using the 34 complete years of record for York Factory over this period, is –6.9°C. No recent climate data exists for the site. The closest Environment Canada climate stations, located 200 km northwest at Churchill and 170 km southwest at Gillam, post 1971–2000 climate normals of –6.9° and –4.2°C, respectively. York Factory has presumably warmed since 1910 to a MAAT intermediate between the Churchill and Gillam values.

York Factory is found just within the southern limit of the continuous permafrost (90–100%) zone as mapped by Heginbottom et al. (1995) and the same mapping denotes a volumetric ground ice content of up to 15%, largely based on physiography. However, very limited data are available in this region to substantiate these designations. Early records during construction and maintenance of York Factory mention buildings being adjusted to compensate for uneven settlement (Donaldson, 1981) which indicates the likely presence of excess ice in frozen soil. Observations during the construction of Thompson (about 375 km inland from York Factory) in the late 1950s and early 1960s indicate that the distribution of permafrost is discontinuous (Johnston et al., 1963). Research by Dyke (1988) on the aggradation of permafrost along emerging coastlines in the Churchill River estuary indicates that under climatic conditions probably colder than York Factory, permafrost will form, but is very sensitive to surface conditions, in particular the presence of vegetation and tendency for snow accumulation.

## METHODS AND SITE SELECTION

Anticipating that ground temperature would be influenced by past land clearing, airphotos dating back to 1925 were analyzed for changing vegetation patterns. Comparison of 1983 coverage with 2006 Google Earth coverage (Fig. 2) was used to locate areas where vegetation cover had more recently changed. Five borehole locations, 1P–5P, were selected based on these more recent changes (*see* Fig. 2, 3 and Table 1 for rationale).

To characterize the natural ground thermal regime in the region, two sites were selected beyond the area occupied by York Factory. One borehole (1TCT) was drilled in a poorly

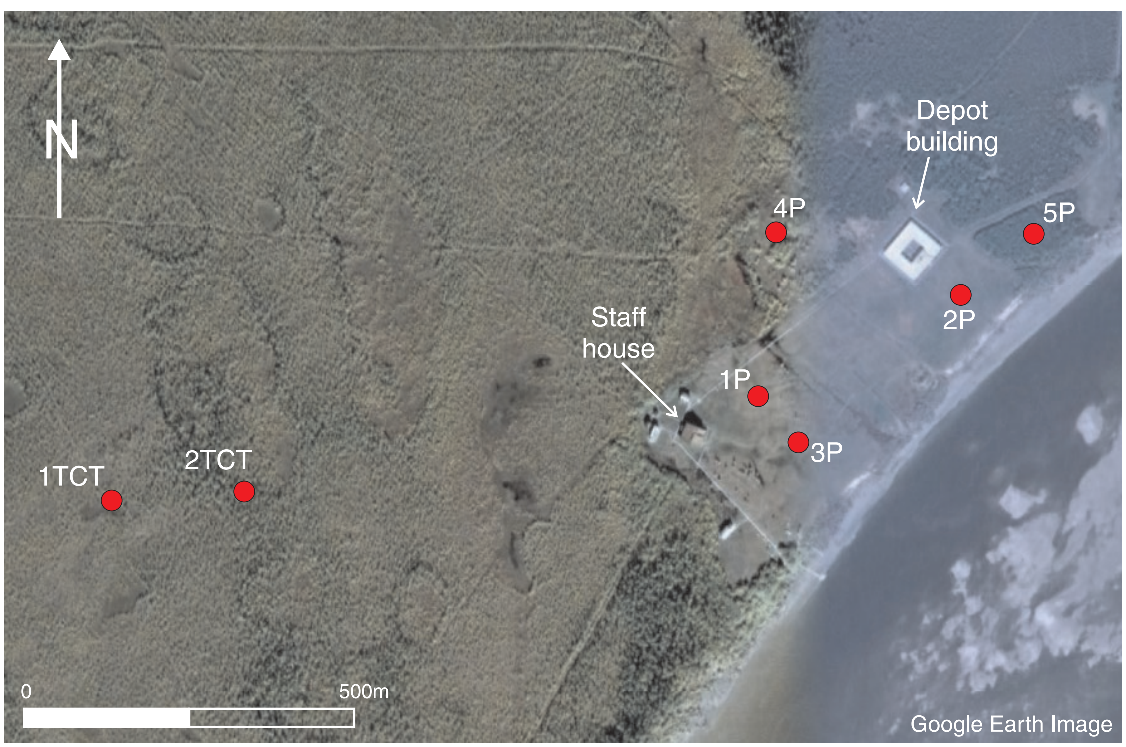


**Figure 2.** Location of boreholes and temperature cables.

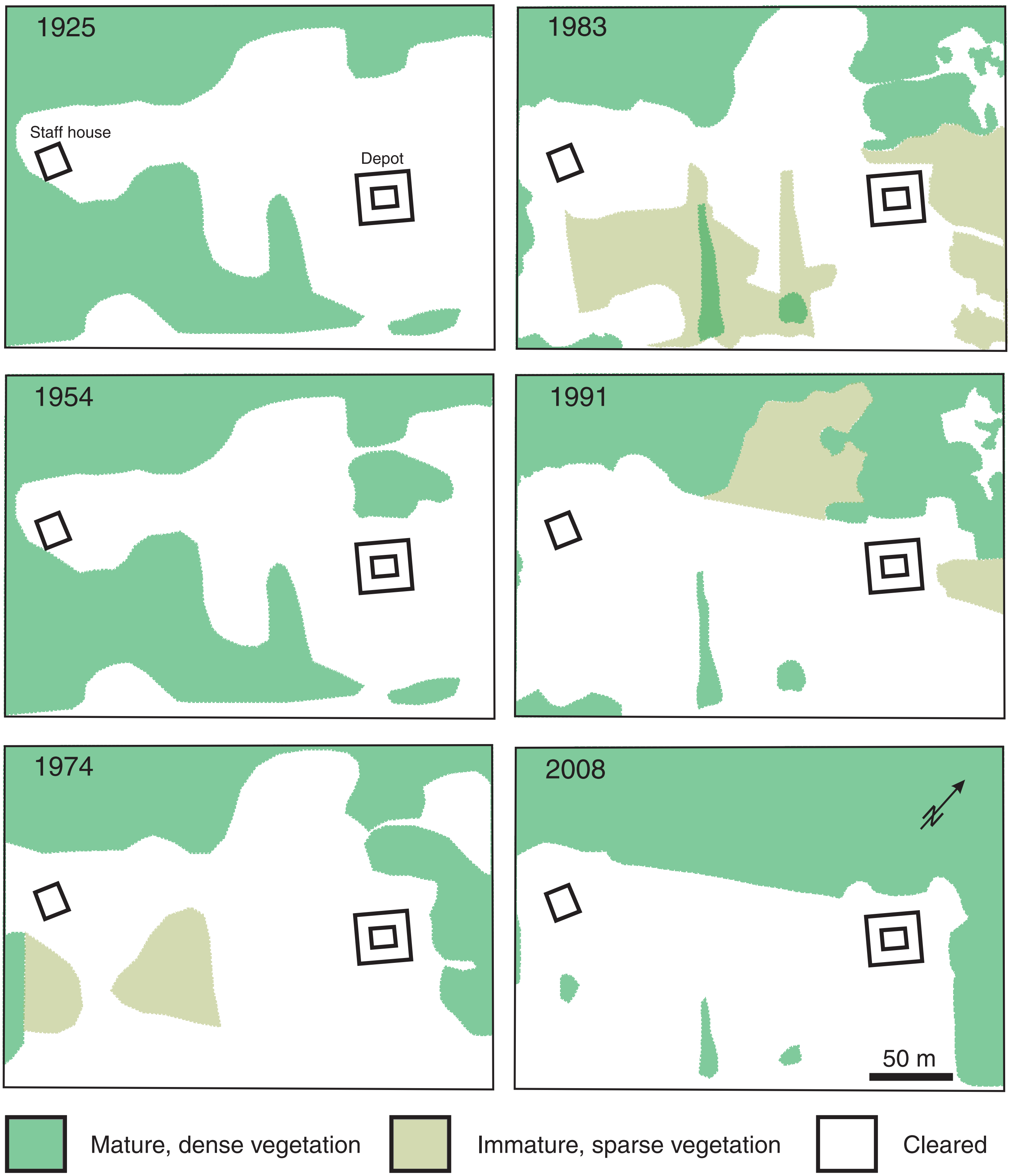


**Figure 3.** Vegetation changes observed from imagery available from 1925 to present.

**Table 1.** Borehole details

| Borehole ID | GPS location (northing/easting) (Zone 15V, NAD83) | Thermistor depths (m) | Rationale |
|---|---|---|---|
| 1P | 6317800 / 0542119 ± 7m | 0.5, 1, 1.5, 2, 4, 7, 12 | Area appearing grassy (cleared) in 1983 and 2006 |
| 2P | 6317878 / 0542270 ± 5m | 0.5, 1, 1.5, 2, 4, 6, 10, 15 | Area covered with low shrubs in 1983 but grassy (cleared) in 2006 |
| 3P | 6317766 / 0542150 ± 4m | 0.5, 1, 1.5, 2, 4, 7, 12 | Lower-lying area appearing to have a shrub cover in 1983 but grassy (cleared) in 2006 |
| 4P | 6317924 / 0542128 ± 3m | 0.5, 1, 1.5, 2, 4, 6, 10, 15 | Area appearing to have a low shrub cover in 1983 but covered in broken forest in 2006 |
| 5P | 6317924 / 0542325 ± 5m | 0.5, 1, 1.5, 2, 4, 6, 10, 15 | Area appearing to have immature vegetation cover in 1983 but mature cover in 2006 |
| 1TCT | 6317712 / 0541632 ± 4m | 0.5, 1.5, 2, 4, 6, 10, 15 | Inter-beach fen |
| 2TCT | 6317724 / 0541732 ± 4m | 0.5, 1, 1.5, 2, 4, 6, 10 | Raised beach bog |

drained inter-beach fen, and the other (2TCT) in a bog in the slightly drier, raised beach environment. Figure 2 and Table 1 provide the location and site characteristics of each borehole location.

A Ranger 24 drill utilizing a solid-stem auger was engaged by Parks Canada to drill boreholes to 15 m depth from September 18 to 25, 2007. Sheets of plywood were placed beneath the drill to minimize ground disturbance. Observations of the subsurface conditions were made during the drilling. The observations included soil type, moisture content, presence of ice bonding, visible ice content, and presence of organics. In addition to every auger flight, grab samples were taken when the soil conditions changed. These were sent to the GSC for laboratory analysis. The holes were preserved for temperature measurement with one inch PVC casing, and the annulus backfilled with native soil and silica sand. Multisensor temperature cables were installed in each borehole (*see* Table 1 for details). Thermistors utilized were YSI 46004, which have an accuracy of ±0.1°C. Eight-channel dataloggers manufactured by RBR Ltd. were connected to all cables to record temperature at 8-hour intervals. The measurement system allowed for a resolution of ±0.01°C. Data were acquired from the loggers in September 2008. Manual readings of cables were done in July 2008 during a site visit by GSC personnel. In addition, a weather station, which collects on-site snow depth and air temperature data, was installed in June 2008.

Two geophysical surveys were completed in July 2008 over a grid covering the present cleared area and extending up to 60 m into the shrub-dominated margins. The Geonics EM31 and EM34 instruments were used, both of which measure the electrical conductivity of the ground beneath the instrument by an induced electromagnetic field. The EM31 measures the conductivity to about 6 m depth, and the EM34, with a coil spacing of 10 m, penetrates to a depth of 15 m. The amount of unfrozen moisture in the ground is the main influence on the conductivity readings. Completely frozen ground will be the least conductive; moist, thawed ground will be the most conductive; and ground just below freezing but still warm enough to contain some unfrozen water will have intermediate conductivity.

## RESULTS

Changes in vegetation cover since 1925 over the area surveyed in 2008 are shown in Figure 3. The most significant changes are the encroachment of willows north and east of the Depot building, whereas the area between the riverbank, the staff house and the Depot building has been increasingly cleared over time.

Observations during drilling indicated that permafrost was present at 1P, 2P, 3P, and 4P, and unfrozen conditions were observed in the remaining boreholes. Ice lenses (and therefore presence of excess ice) were also observed in the frozen sediments.

A continuous record of ground temperature is available from October 2007 to September 2008. The annual range in temperature at each depth (temperature envelope) is shown in Figure 4. The ground temperature profiles can be used to determine if permafrost is present, and the approximate permafrost thickness. Where permafrost is present, the maximum depth of summer thaw (base of active layer) was determined from the maximum temperature profile. For the non-permafrost sites, the depth of seasonal frost penetration was determined from the minimum temperature profile. The thermal condition of the ground at all borehole sites is summarized in Table 2.

The ground temperatures indicate that permafrost is extensive over the presently cleared area, confirming the observations during drilling. Permafrost is present at four of the five boreholes (1P through 4P) located on the NHS, with mean annual ground temperature (MAGT) ranging between –0.2 and –0.9°C at depths of 6 to 7 m. At the permafrost sites where the MAGT was warmer than –0.5°C, the base of permafrost ranged from approximately 13 to 15 m depth, whereas at 1P, the ground is likely frozen to

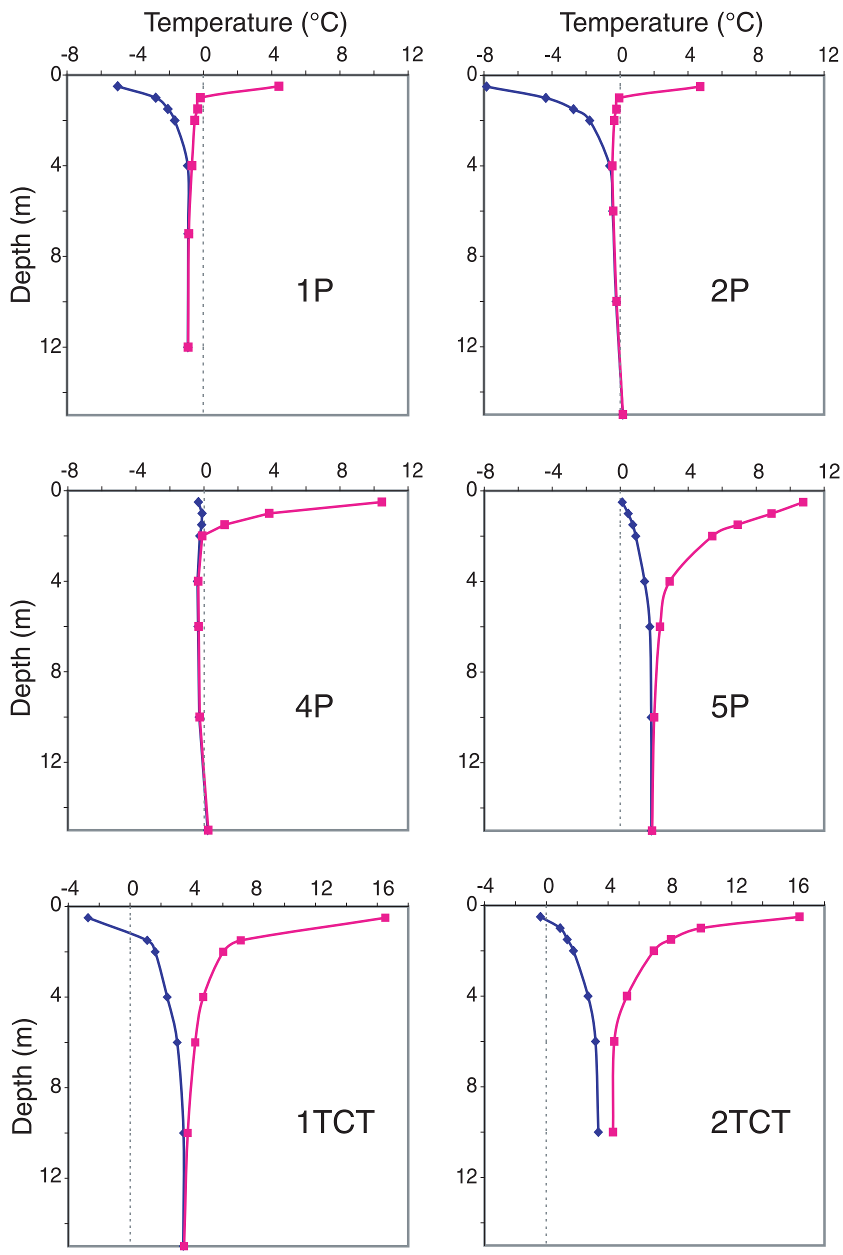


**Figure 4.** Temperature envelopes for each cable location based on data from October 15, 2007 to September 9, 2008.

**Table 2.** Summary of ground temperature measurements

| Borehole ID | MAGT * (°C) | Depth of MAGT measurement (m)** | MAGT at base of active layer (°C) | Depth to base of active layer (m) | Depth of seasonal frost penetration (m) | Depth to base of permafrost (m) |
|---|---|---|---|---|---|---|
| 1P | -0.9 | 7 | -0.8 | 0.98 | n/a | > 12 |
| 2P | -0.4 | 6 | -1.0 | 1.0 | n/a | 13 |
| 3P | -0.2 | 7 | -0.6 | 1.1** | n/a | 15*** |
| 4P | -0.3 | 6 | -0.2 | 1.95 | n/a | 12.8 |
| 5P | 1.8 | 15 | 2.3 | n/a | 0.3*** | n/a |
| 1TCT | 3.6 | 10 | 2.9 | n/a | 1.35 | n/a |
| 2TCT | 3.9 | 10 | 3.5 | n/a | 0.65 | n/a |

* Mean Annual Ground Temperature at level of zero annual amplitude,
** Approximate depth of zero annual amplitude,
*** Value extrapolated from measured values

greater depths but insufficient temperature data are available to determine the permafrost depth. Permafrost is absent at site 5P, located in the thickest willows. Here the MAGT at 15 m is 1.8°C. Permafrost is also absent at the undisturbed locations (1TCT and 2TCT) with MAGTs at 10 m depth of 3.6°C and 3.9°C for the fen and bog site, respectively (Fig. 4 and Table 2).

The electrical conductivities determined through the EM surveys are shown in Figure 5. Conductivities ranged from 5.8 to 71 mmho/m for the EM31 and from 13.5 to 38 mmho/m for the EM34. Comparison of Figure 5a and 5b shows that there is general correspondence between the two surveys. The open area between the riverbank, the staff house and the Depot building is characterized by lower conductivities. The lower conductivities are slightly more extensive on the EM31 survey than on the EM34 survey, indicating that frozen ground is probably more pervasive at shallower depths (6 m versus 15 m). From the ground temperatures and EM surveys, permafrost, where present, appears to be generally less than 15 m thick, except for a localized area near cable 1P. Higher conductivities found along the southwest and northern margins of the cleared area correspond to fen and marsh, whereas higher conductivities to the north and east of the Depot building correspond with thick vegetation cover (*see* Fig. 3). The highest EM31 conductivities along the riverbank are likely the result of salinity associated with the Hayes River estuary tidal waters.

Using the electrical conductivity measurements at the borehole locations as calibration, the EM31 survey was used to extrapolate the ground thermal regime over the site. Cables 5P (MAGT of 1.8°C) and 1P (MAGT of –0.9°C) were used as the end members in interpreting the conductivities corresponding to unfrozen and frozen ground, respectively. Cables 2P, 3P, and 4P corresponded to marginally frozen conditions, where ground temperatures were between 0 and –0.5°C. At temperatures only a few tenths of a degree below 0°C, fine-grained soils contain sufficient unfrozen moisture (Andersland and Anderson, 1978) to raise the conductivity above that expected for frozen ground. Therefore, based on the conductivity measured at sites 2P, 3P and 4P, a range of conductivities between 11 and 17 mmho/m was selected to represent a marginally frozen condition where ground temperatures ranged from 0 to –0.5°C. Based on this interpretation, a permafrost map of York Factory was constructed (Fig. 6) with the area surveyed divided into three main zones: frozen, marginally frozen, and unfrozen.

## DISCUSSION

Despite being mapped in the continuous permafrost zone (Heginbottom et al., 1995), present ground temperature measurements indicate that permafrost at York Factory is discontinuous. It is important to understand that Heginbottom et al.'s (1995) map represents conditions at a regional scale and was based mainly on physiography and climate, therefore local factors are not accounted for. At York Factory's southerly location, environmental factors, in particular the ground cover, have a large influence on the ground thermal regime. This is emphasized by examination of the permafrost map of York Factory (Fig. 6) and the 2006 image (Fig. 2) which

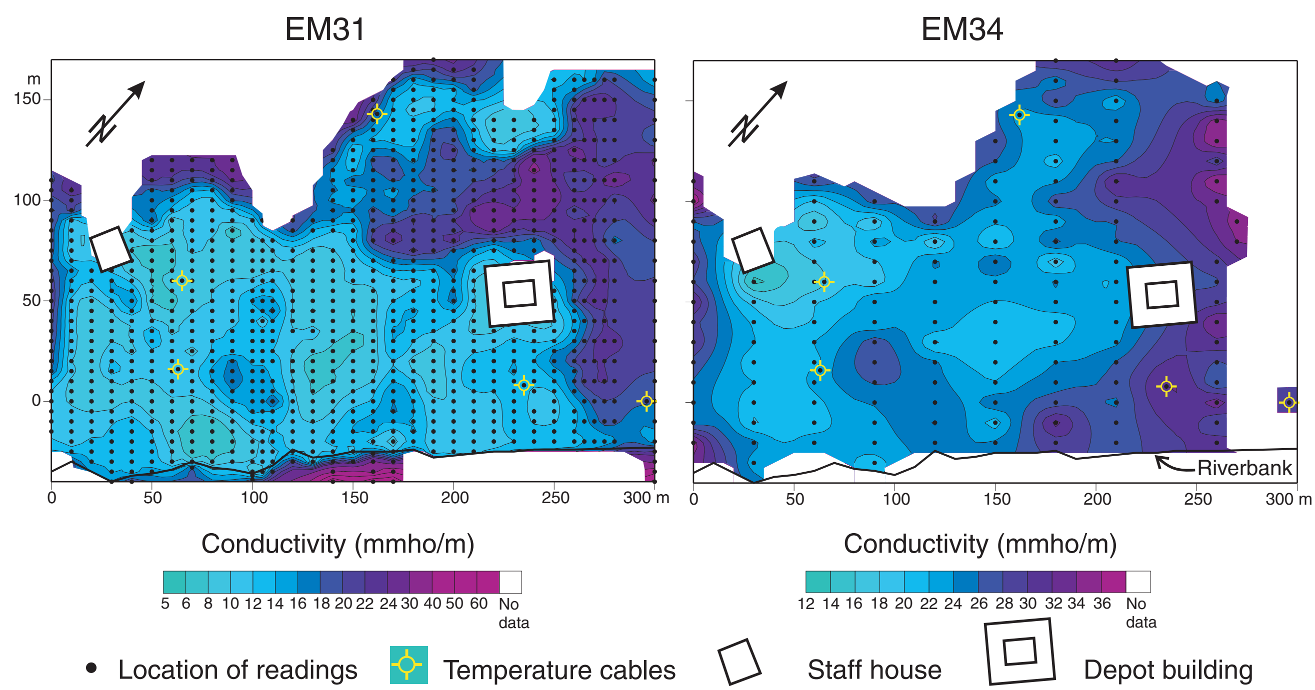


**Figure 5.** Contour maps of the conductivity readings taken with the EM31 and EM34 Geonics instruments.

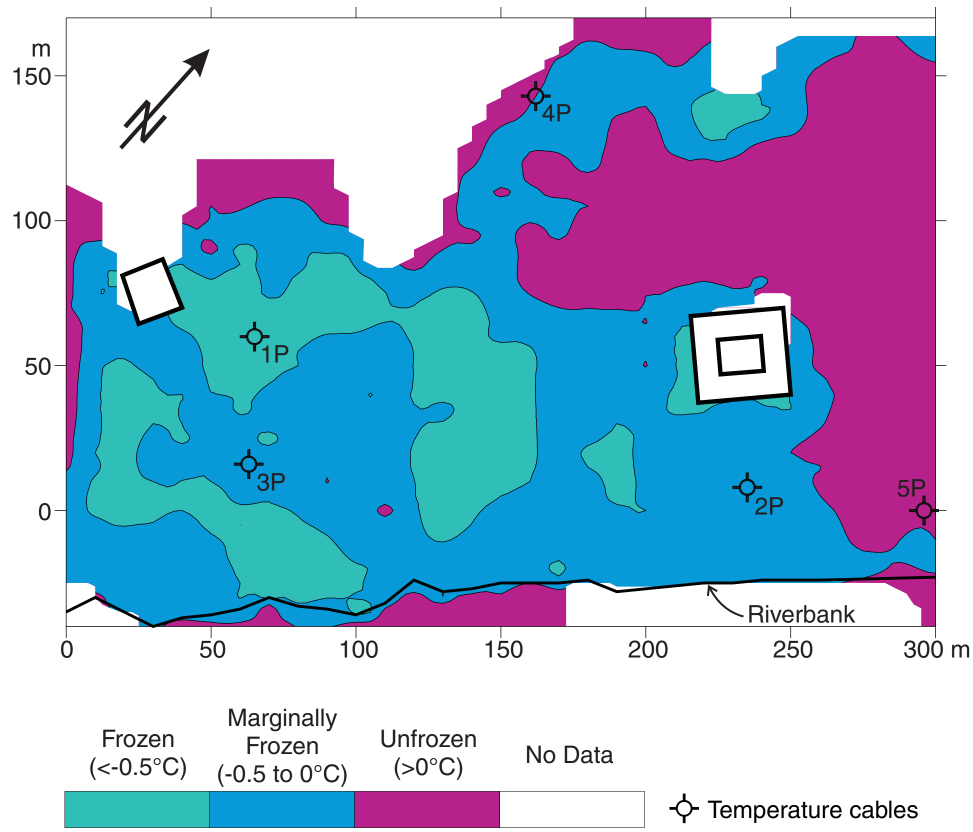


**Figure 6.** Permafrost map of York Factory interpreted from EM31 survey and ground temperature measurements. The conductivity ranges used are: frozen, 5-10 mmho/m; marginally frozen, 11-17 mmho/m; and unfrozen, >17mmho/m.

shows that the frozen and marginally frozen conditions correspond to the cleared central portion of the site, whereas unfrozen conditions correspond with vegetated areas north and east of the Depot building (Fig. 2, 3).

The correspondence between the present-day vegetation coverage at the site and the ground thermal regime points to the sensitivity of frozen ground to the ground surface conditions. Therefore today's ground thermal regime has probably evolved over the time of site occupation. Remarks recorded during the location and construction of York Factory describe the site as being heavily treed prior to development; this forest cover was subsequently exhausted by the end of the 18th century through its use as firewood and construction material (Donaldson, 1981). A thick, mature forest cover would promote the presence of permafrost given the summer shading and limitation of snow accumulation on the ground in winter. The subsequent clearing of the forest and the clearing of snow either manually or by wind would further maintain permafrost. However, younger vegetation or patchy vegetation would encourage snow accumulation which would insulate the ground from the cold winter air temperatures leading to an increase in mean annual ground temperatures (*see* for example Burgess and Smith, 2000; Throop et al., 2008).

An overlay of vegetation changes (from Fig. 3) on the permafrost map allows a comparison of the ground thermal and vegetation conditions (Fig. 7). Frozen areas correspond to areas that have the longest photographic record (83 years) of being clear of vegetation. Areas that were previously cleared but have become increasingly revegetated with willows and balsam poplar (D. Punter, pers. comm.) since approximately 1954 are now associated with no permafrost, such as the area north and east of the Depot building. Lastly, the marginally frozen portions correspond to those parts that have been cleared for the shortest period of time (since about 1991).

In addition to vegetation cover, ground temperature is influenced by drainage conditions. Simpson (1972) and Tarnocai (1982) remarked that permafrost is restricted to the slightly elevated and thus better drained areas in the vicinity of York Factory. This observation is supported by the ground temperature records from 1TCT and 2TCT, which were located in wet areas, and the elevated electrical conductivities associated with fens and marshes located at the southwest and northwest margins of the cleared area.

Frozen, fine-grained subsurface materials commonly contain segregated ice, such as the ice lenses observed during drilling. The dissipation of water produced by the thawing

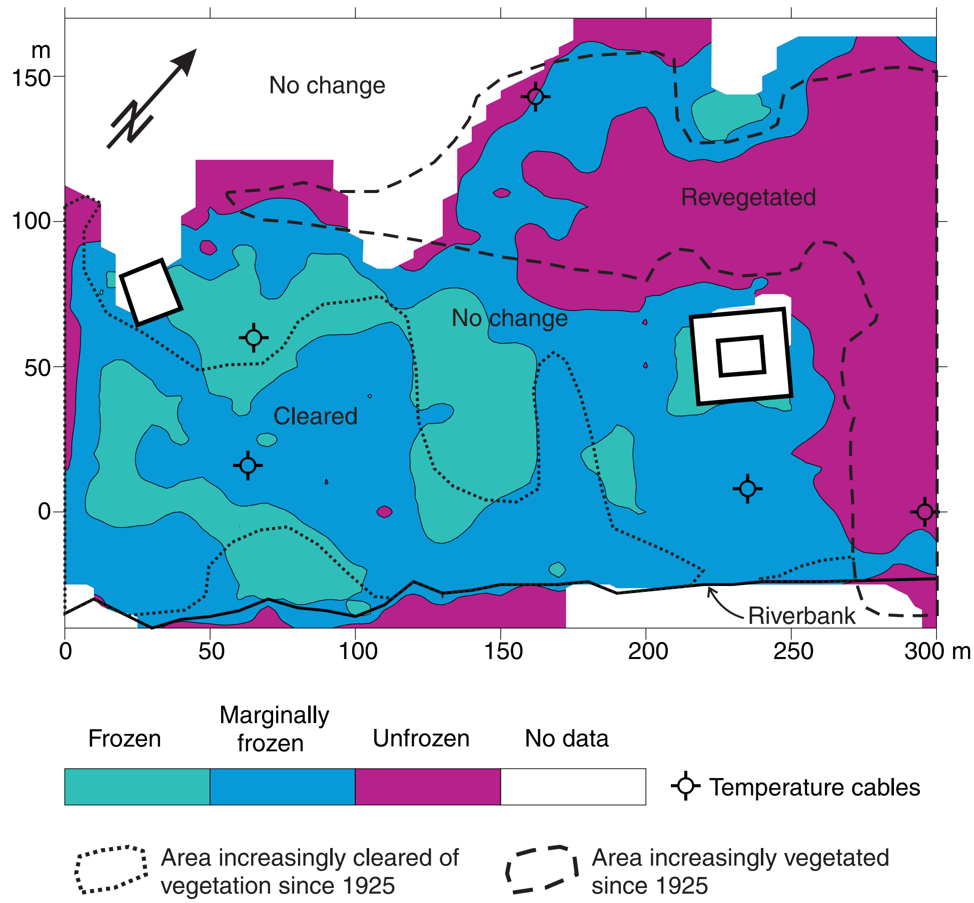


**Figure 7.** Permafrost map of York Factory NHS with main vegetation changes since 1925.

of this ice is restricted by the low permeability of the fine-grained sediments, resulting in weakening of the ground. Uneven subsidence of the ground surface can accompany thaw as has been observed at the site (Carroll, 2005) both beneath and adjacent to structures. The poor drainage conditions and subsidence of the ground can also lead to pooling of surface water, which in turn can accelerate thawing.

## CONCLUSIONS

Permafrost at York Factory is presently limited to areas that have been maintained clear of forest or shrubbery. The prominent area of thaw interpreted immediately east and north of the Depot building generally coincides with an area of shrub cover that has developed over the last three to five decades, according to analysis of airphoto coverage. Thus complete disappearance of permafrost from a previously cleared area appears to have been induced by the presence of willow and balsam poplar (and subsequent increase in snow depth) over the last few decades.

The present distribution of permafrost is related to the size of the present clear area. The present clear area is large enough to allow wind removal of snow that would otherwise accumulate at sufficient depth to result in warmer ground conditions. Thus the mapped distribution of permafrost will probably continue to be stable if the present extent of site maintenance is continued. Permafrost will likely degrade if willow encroachment is allowed. Given that the coldest MAGT is about −1°C and that adjacent sites have a MAGT of almost 4°C, a modest sustained increase in air temperature could also result in the degradation of permafrost at York Factory. However, willow growth would probably act more rapidly than climate warming to degrade permafrost. In addition to site clearing, preventing standing water by ensuring proper drainage may promote permafrost. Evidence of permafrost beneath the Depot building and the library indicates that the buildings themselves are effective at keeping ground temperatures cool. The shade provided in summer and the lack of insulation in winter translates to cooler temperatures beneath the buildings year-round.

Pending laboratory analyses of borehole soil samples, borehole and on-site air temperature data will be used to model the present distribution of permafrost. With a model of the air-ground temperature relationship established, the impact of possible warmer air temperatures on the distribution of permafrost at York Factory will be investigated.

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