Modelled ground ice conditions in the Kivalliq region, Nunavut, Canada

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ABSTRACT

Significant infrastructure development is proposed in the Kivalliq Region, Nunavut, including a 1,200 km long hydroelectric/fibre optic link to southern Canada. Knowledge of ground ice conditions is important to mitigate the effects of climate change and permafrost thaw on infrastructure. Nevertheless, only limited information exists in this region. The Geological Survey of Canada (GSC) has developed updated ground ice mapping for Canada and tested the modelling framework at regional scales using more detailed surficial geology mapping. The ground ice modelling depicts the estimated relative abundance of relict (buried glacial) ice, segregated ice, and wedge ice in the upper five metres of permafrost. Here we present modelling for the Kivalliq region based on standardized 1:125,000 scale surficial geology mapping. Such modelling is useful at a reconnaissance level and to guide more detailed ground ice investigations. Relict ice is predicted over limited areas above the postglacial marine limit. High segregated ice abundance occurs in fine-grained marine deposits within the limit of inundation. Modelled segregated ice abundance is medium or low in thicker till deposits. Wedge ice abundance is negligible or low due to the dominantly thin and coarse-grained surficial cover, and (relatively) limited time since subaerial exposure of the terrain following deglaciation near the coast. Overall, the highest ice contents are predicted above marine limit in thick, fine-grained till deposits. Areas with high relict ice abundance coincide with evidence of ice-cored terrain in satellite imagery, and modelled segregated ice is in general agreement with the limited field observations from the region.

1 INTRODUCTION

Permafrost is warming and thawing in response to climate change (Smith et al. 2022). Land use planning and adaptation requires knowledge of ground ice due to its role in the stability of permafrost terrain under warming conditions (Doré et al. 2016). The Kivalliq region in Nunavut is undergoing significant development, but fundamental information on ground ice and permafrost is lacking in the region. Preliminary investigations on permafrost temperatures and ground ice conditions (LeBlanc and Oldenborger 2021; McQuaig et al. 2022), permafrost hazards (Forbes et al. 2014), and thaw sensitivity based on remote-sensing imagery analysis (Oldenborger et al. 2022b) have begun addressing this knowledge gap. Most of these studies were focused near the communities of Rankin Inlet and Arviat. Herein, modelled regional-scale ground ice abundance is presented to contribute to foundational permafrost knowledge in the region and complement ongoing field-based investigations (e.g., Faucher et al. 2024). The specific objectives are to 1) estimate the abundance and distribution of excess ice in upper permafrost from relict (buried glacial), segregated, and wedge ice, 2) present patterns in ground ice abundance and associations with surficial geology and environmental conditions, and 3) discuss the accuracy of the predictions based on available information on ground ice, limitations of the modelling, and implications given proposed development in the region.

1.1 Study area

The study area extends from the Manitoba/Nunavut border (60°N) to beyond Baker Lake, NU (65°N) along the western coast of Hudson Bay, and inland to 98°W (Figure 1). The region was covered by the Laurentide Ice Sheet during the Wisconsin glaciation. Following deglaciation, which

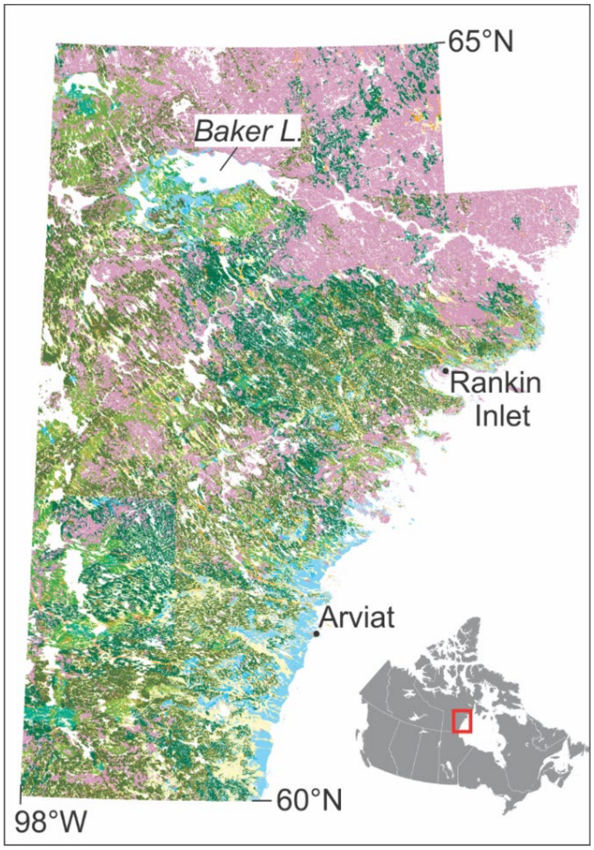

Figure 1. Study region surficial geology compilation. Pink = bedrock; all green shades = tills; blues = marine and lacustrine; yellows = alluvial; oranges = glaciofluvial; purples = glaciolacustrine deposits.

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occurred between 9 and 6 14C ka BP, the land was inundated up to about 170 m above the modern sea level by the postglacial Tyrell Sea, which extended up to 150 km inland (Dyke 2004). Isostatic rebound following deglaciation drove emergence and subsequent permafrost development within inundated areas.

Surficial geology includes exposed bedrock, glacial tills, marine, glaciofluvial, glaciolacustrine, lacustrine, and alluvial deposits. Organic deposits, 30 to > 100 cm thick, occur in pockets in flat areas, and predominantly overlie fine-grained materials (Arsenault et al. 1981; McMartin 2002; Forbes et al. 2014). Topography is subdued and comprises bedrock hills and eskers, moraines, and drumlins that are widespread in the region (McMartin et al. 2021).

The study area is within the continuous permafrost zone. The mean annual air temperatures (1981–2010) at Arviat, Rankin Inlet, and Baker Lake are -9.3, -10.5, and -11.3 °C, respectively (Environment Canada 2023). At Rankin Inlet, annual mean ground temperatures near the top of permafrost range from -9.5 to -5.5 °C (LeBlanc and Oldenborger 2021). Annual mean ground temperatures at Baker Lake in 1998–2003 were about -7 to -8 °C (Smith et al. 2005).

Limited information exists on ground ice conditions. Faucher et al. (2024) observed high excess ice contents in two cores from marine sediments with individual samples having up to 85% excess ice. Lower excess ice contents occurred in a dominantly till core. McQuaig et al. (2022) estimated volumetric ice content visually from cores drilled along the proposed infrastructure corridor. Samples from organic and finer-grained marine sediments had moderate to high ice contents (up to 50–60%) comprising mainly segregated ice. Fluvial sands and silts had moderate ice contents (10–20%), whereas coarser grained till and glaciomarine deposits had low ice contents (5–10%). Elevated segregated ice content is also inferable from the presence of solifluction lobes over some fine-grained deposits (e.g., Oldenborger et al. 2022a).

Polygonal ground, interpreted as ice wedge polygons, are mapped extensively along the proposed Kivalliq Hydro-Fibre Link in coarse-grained glaciofluvial, beach ridge, and nearshore marine sediments, and in fine-grained fluvial, offshore marine, and organic deposits (McQuaig et al. 2022). Well-developed polygons are observed in marine sediments overlain with organic material near Arviat (Forbes et al. 2014). Ice wedge polygons are also mapped in various deposits near Rankin Inlet (McMartin 2002; Oldenborger et al. 2022a). However, there are no known volumetric estimates of wedge ice in the region.

2 Methodology

Sixteen 1:125,000 scale Canadian Geoscience Maps formed the surficial materials compilation used for the modelling (Geological Survey of Canada 2017a–n, 2018a, b). These maps conform to the Geological Survey of Canada's Surficial Data Model, which standardises legends and digital formatting for the mapped units (Deblonde et al. 2019). Original vector polygon shapefiles were combined and converted to raster with pixel size of 250 m. The pixel size was chosen to preserve small surficial geology units and cartographic detail around waterbodies with complex shorelines. As with the surficial materials compilation for the *Ground Ice Map of Canada* (GIMC), till units were classified into fine and coarse-grained dominant textures based on underlying bedrock geology (O'Neill et al. 2019). As a result, 33 surficial units are mapped in the study area, which comprise bedrock, and multiple till, alluvial, marine, lacustrine, glaciofluvial, and glaciolacustrine units (Figure 1).

Surficial units that appear on the national-scale mapping retain their model parameter values from the GIMC. Units that are not represented are assigned parameters based on a review of surficial geology-ground ice associations informed by the surficial geology map unit legends and observations from prior investigations, including those west of the study region in the Slave Geological Province (e.g., Dredge et al. 1999).

The surficial geology information was altered on one map sheet (Geological Survey of Canada 2018a) where an inconsistency during the conversion from the paper map to the standardized digital form was noted. On this sheet, areas mapped primarily as bedrock with secondary coverage of till veneer or felsenmeer were mapped as till veneer in the digitized version, in contrast to adjacent map sheets. These areas were edited in the GIS to be mapped as bedrock for consistency.

The models use an expert-system approach implemented in a GIS, and incorporate conceptual principles gained from empirically based research of ground ice. Datasets on surficial geology, deglaciation, paleovegetation distribution, permafrost, and glacial lake and marine limits are used to model estimates of the abundance of relict (buried glacial), segregated, and wedge ice in the upper 5 m of permafrost. The modelling routines are fully described by O'Neill et al. (2019). In contrast with the GIMC modelling, we use a recent (McMartin et al. 2022), region-specific geospatial dataset of postglacial inundation to simulate the melt of relict ice in previously submerged areas, rather than the *Glacial Map of Canada* (Prest et al. 1968).

The model results for the three ice types were combined using the methodology presented for the *Ground Ice Map of Canada* (O'Neill et al. 2022).

3 Results

The distribution of modelled relict ice is restricted mainly to the west of the study region, above the level of postglacial inundation (Figure 2). High relict ice abundance is predicted in fine-grained hummocky till and moraine complexes, while areas of medium abundance are modelled in fine-grained till blankets, and coarse-grained hummocky till and moraine complexes, and glaciolacustrine and glaciofluvial units. Lower abundance is modelled in other coarse-grained till units and outwash fan sediments. Since nearly all the study area has been in the herb tundra biome since deglaciation, little modelled melt of relict ice due to transitions to warmer climates and associated biomes has occurred.

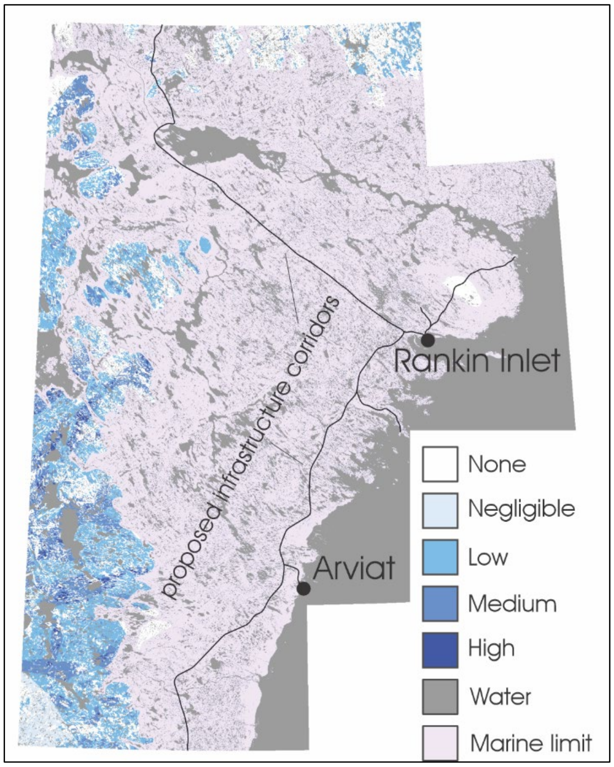

Figure 2. Modelled relict (buried glacial) ice abundance. Marine limit indicated from McMartin et al. (2022). Infrastructure routing modified from McQuaig et al. (2022).

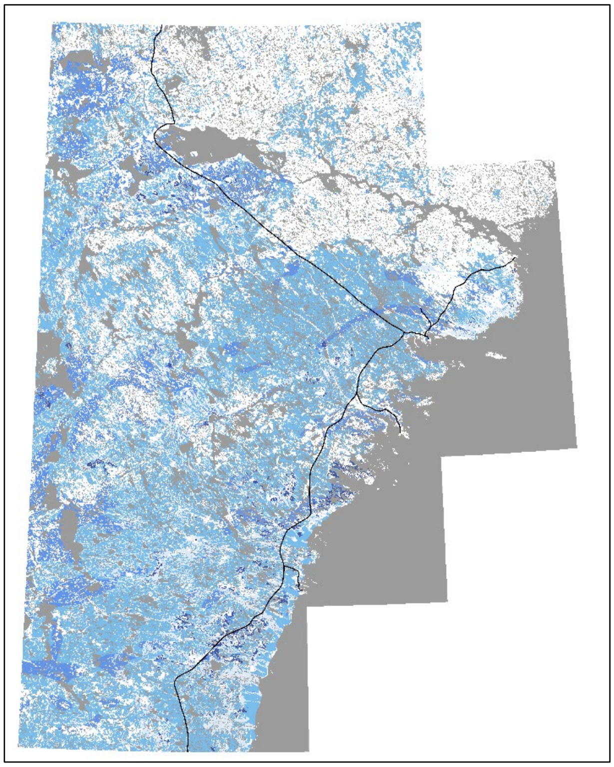
Figure 3. Modelled segregated ice abundance. See Figure 2 legend.

Modelled segregated ice abundance is highest in frost-susceptible, fine-grained marine sediments that are mainly distributed near the modern Hudson Bay coastline, but also occur in smaller pockets inland within the limit of postglacial submergence (Figure 3). Medium segregated ice abundance is modelled predominantly in areas with fine-grained till units, which are differentiated in the study region based on the presence of underlying Neoarchean sedimentary rocks (Wheeler et al. 1996). In the northeast part of the study region the distribution of modelled segregated ice is limited due to the widespread occurrence of exposed bedrock (Figures 1 and 3).

Wedge ice abundance is modelled as negligible over much of the study area (Figure 4). Inland, some areas of low abundance occur in fine-grained tills and marine sediments. As with segregated ice, there is no modelled wedge ice in the bedrock-dominated northeast.

The combined ice abundance in the study region ranges from none to high (Figure 5). There are no areas modelled with very high combined ice contents.

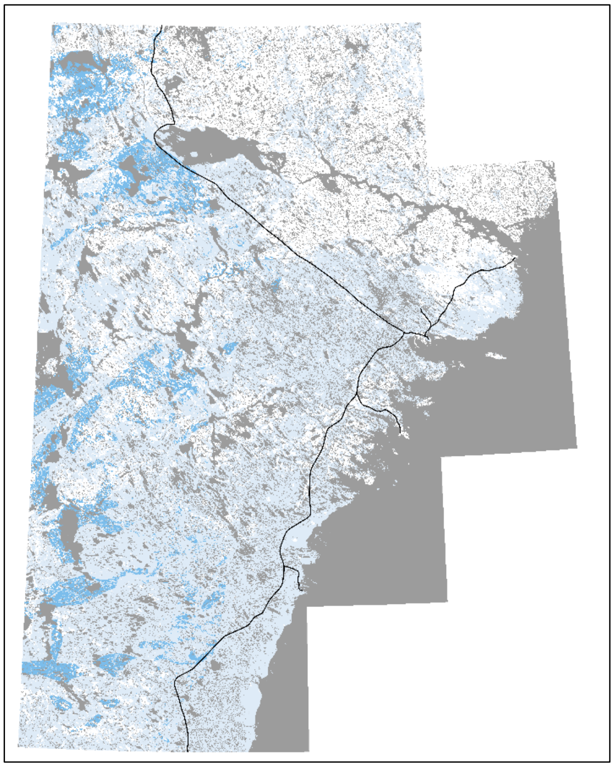
Figure 4. Modelled wedge ice abundance. See Figure 2 legend.

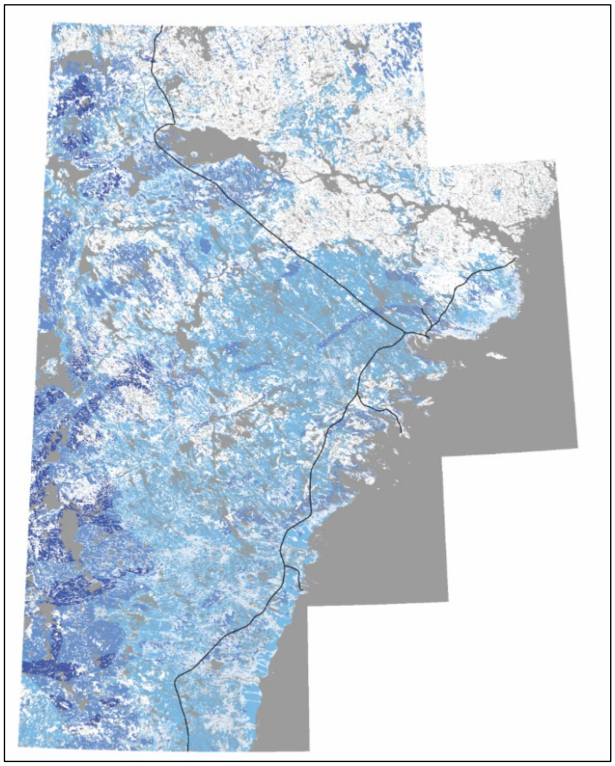

Figure 5. Modelled combined ice abundance. See Figure 2 legend.

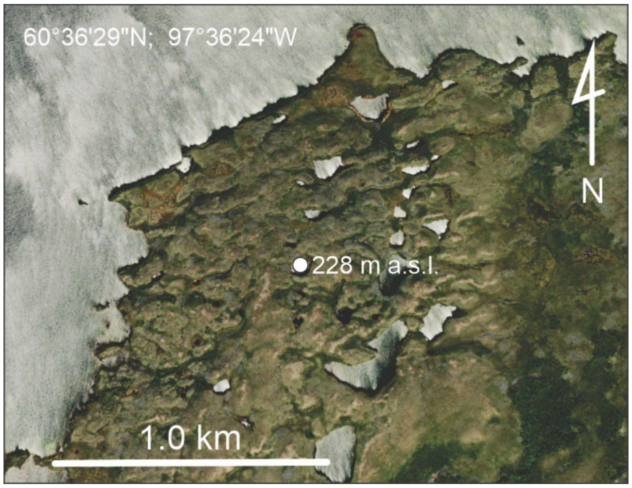

Figure 6. Interpreted ice-cored terrain in an area modelled with high relict ice abundance. Imagery from ArcGIS Earth.

4 DISCUSSION

4.1 Relict ice

Direct validation of the relict ice modelling requires information from core drilling or systematic mapping of features associated with relict ground ice, such as retrogressive-thaw slumps (Kokelj et al. 2017) or other evidence of ice-cored terrain. In our knowledge, such information is not available from the study area. However, preserved glacial ice is encountered to the west in the Slave Geological Province in hummocky tills, glaciolacustrine deltas, and glaciofluvial deposits (Wolfe 1998; Subedi et al. 2020), and that area shares many similarities with the Kivalliq region in terms of ground ice-surficial geology associations (Dredge et al. 1999).

Evidence of ice-cored terrain is visible in satellite imagery in areas modelled with high relict ice (Figure 6). This includes irregular topography and the presence of lakes with steep-sided shores in the upslope direction, which may indicate past or current melt of relict glacial ice. Much of the existing and planned infrastructure in the region is below the marine limit where postglacial inundation lasted thousands of years. Therefore, relict ice likely poses no hazard to development in these settings, unless thermal conditions at the sea-bottom were sufficient to maintain frozen ground.

4.2 Segregated ice

Modelled segregated ice is widespread except in the northern part of the study region, where bedrock dominates the surficial geology. Since the entire region is within the continuous permafrost zone and herb tundra biome, the modelled output for segregated ice is controlled by the inferred frost-susceptibility of materials based on interpretation of the dominant grain sizes (O'Neill et al. 2019). Therefore, the results largely correspond with available observations of the highest segregated ice in fine-grained marine sediments and lower contents in coarser grained till (McQuaig et al. 2022; Faucher et al. 2024). Fine-grained marine units, mainly near the coast and Baker Lake, likely pose the greatest hazards for development due to the characteristically high ice contents and potential for significant long-term settlement as permafrost thaws (e.g., O'Neill et al. 2023). Finer grained till units derived from sedimentary bedrock may also pose challenges. Otherwise, much of the region is modelled with low, negligible, or no segregated ice abundance due to the presence of coarse grained or thin unconsolidated deposits, making the consequences of permafrost thaw from segregated ice limited. Numerous lineations with no modelled segregated ice generally trend southeast and represent coarse-grained glaciofluvial deposits (eskers), which consist predominantly of sand and gravel (Phillips and LeBlanc 2024).

Some limitations exist in the modelling and uncertainties in the validity of model rules, which could be tested in this study region. For example, washing of finer grained materials to lower-lying areas occurred as the water level subsided following deglaciation (e.g., McMartin et al. 2022). Therefore, it can be expected that within an individual unit, such as a till blanket, finer material and higher segregated ice contents can be expected in lower-lying areas if the deposit has been wave-washed. The modelling does not capture this type of variation. Furthermore, in areas mapped as bedrock or till veneer with none or negligible-low modelled segregated ice abundance, smaller pockets of thicker or finer grained unconsolidated material with higher ice contents can be expected in the field, but may not be modelled due to the scale of the surficial mapping.

4.3 Wedge ice

Wedge ice abundance is modelled as either negligible or low in the study area due to the relatively short period since emergence, which is < 5000 years near the modern Hudson Bay coastline, and because modelled wedge ice accumulation is slower in the coarse-grained sediments that cover much of the study area inland. Near the coast, polygonal ground occurs in a variety of deposits and trough networks appear most developed in marine sediments (Figure 7a), which may be overlain by Holocene peat deposits between 0.4 and 1.0 m thick (Arsenault et al. 1981; McMartin 2002; Forbes et al. 2014; McQuaig et al. 2022; Oldenborger et al. 2022a).

Enhanced thermal contraction cracking and ice-wedge growth may occur in areas with organic cover, due to the thermal properties of peat and the high thermal contraction coefficient of water, which forms most of the volume of saturated peat. The modelling does not capture these conditions because the mapped surficial geology polygons represent the underlying material (e.g., marine deposits) when the peat is thinner, though its presence is indicated in the legend text of original surficial geology maps. Similarly, well-developed ice wedge troughs up to about 2 m wide are observed near Rankin Inlet in sandy nearshore marine sediments (A.M. Leblanc, pers. communication), where the thermal properties of the substrate are conducive to rapid cooling. These factors may result in a modelled underestimation of wedge ice in some locales. However, the relatively low abundance of modelled wedge ice in the region is broadly reasonable, as areas with high wedge ice abundance on the GIMC have far wider troughs and much higher polygonal densities than the polygons visible in marine sediments of the Kivalliq region, implying a much higher volumetric wedge ice content in upper permafrost (Figure 7).

Estimates of wedge ice volume in the region derived from field measurements and imagery will allow more rigorous validation efforts and improve knowledge on the volume of wedge ice in upper permafrost (e.g., Frappier and Lacelle 2021). Though the overall ice wedge volume is likely far lower in the Kivalliq region than in these regions of the western Arctic, ice wedges nonetheless may pose challenges to development due to the appreciable differential subsidence that occurs in polygonal terrain when permafrost thaws, and potential issues associated with water impoundment as runoff pathways are modified (Kanevskiy et al. 2022).

5 Conclusions

Ground ice was modelled in the Kivalliq region using 1:125,000 scale surficial geology. Modelling routines from the *Ground Ice Map of Canada* were improved to incorporate regional postglacial inundation limits. The results indicate that the highest combined ground ice

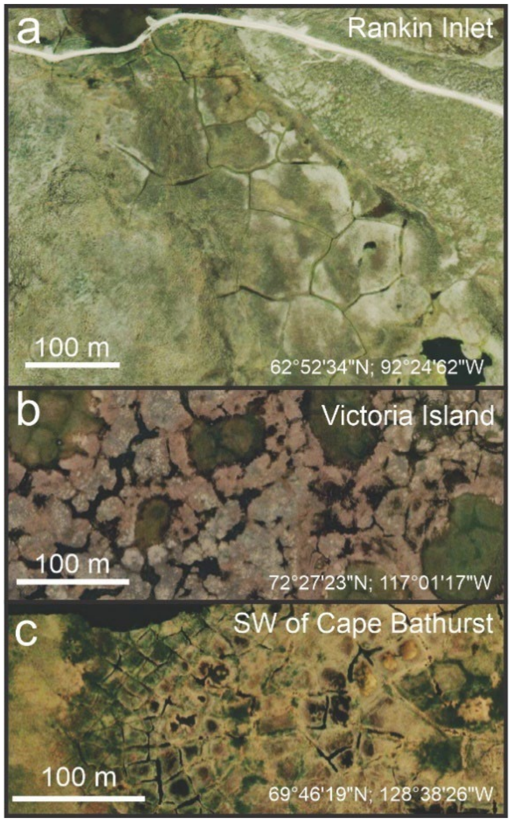

Figure 7. Polygonal ground near a) Rankin Inlet, in fine-grained marine sediments where the modelling predicts negligible abundance, and two examples where the GIMC predicts high abundance on b) northwest Victoria Island and c) SW of Cape Bathurst. Imagery from ArcGIS Earth.

abundances occur above marine limit in thick, fine-grained till units predicted to include medium or high relict ice, medium segregated ice, and low wedge ice abundance. Below the limit of postglacial submergence, fine-grained marine sediments are predicted to have high segregated ice content and include wedge ice, and likely represent the most thaw-susceptible material near the coast. Wedge ice abundance is modelled as negligible or low over the region due to the nature of surficial materials and limited time for accumulation since deglaciation and subaerial exposure as the Tyrell Sea receded.

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