

Ice content in permafrost in the Kivalliq Region, Nunavut: Digitization and analysis from historic drilling program

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ABSTRACT

The Kivalliq Region on mainland Nunavut west of Hudson Bay, Canada is an area of interest for major infrastructure projects. Proposals include a 450-km all-season road between Arviat and Chesterfield Inlet as well as the Kivalliq Hydro-Fibre Link which would connect the region to electrical power and extended high-speed internet service from Manitoba. Permafrost and ground-ice data are crucial to responsible development in the region, yet little data are available. We introduce a newly digitized database containing geotechnical, cryostratigraphic, and geospatial data created from paper reports of a field drilling campaign completed in 1975–1977 by the Polar Gas consortium of companies in support of a proposed, but never realized, pipeline running from Melville Island to Ontario via the Kivalliq Region. The section from the Nunavut-Manitoba border to Baker Lake is discussed here. We found that (1) boreholes in alluvial and glacial sediments are substantially more likely to contain ice-rich permafrost than boreholes in glaciofluvial sediments, and (2) boreholes below the maximum postglacial marine limit are more likely to be ice-rich than those above the marine limit, but (3) caution is necessary in interpretation of visible ice content data from this dataset. The newly digitized data have some weaknesses, but also contain considerable useful data on permafrost and ground ice.

1 INTRODUCTION

Ground ice content is an important property of frozen ground that affects the stability of infrastructure. Ground ice is the most critical factor of potential thaw settlement. Recent advances in modelling of ground ice (e.g., O'Neill et al. 2019, 2024) have considerably improved our ability to predict the distribution of ground ice; however, direct observations are still useful for land-use planning in permafrost and for validation of model results. Unfortunately, direct observations of ground ice are relatively difficult to obtain.

The Kivalliq Region of Nunavut is home to two active mines (MeadowBank-Amaruq and Meliadine) and is also a region of interest for development. Proposed projects include a 450 km all-season road from Arviat to Chesterfield Inlet as well as the Kivalliq Hydro-Fibre Link (KHFL) project (Nulik Corporation 2023; McCuaig et al. 2022), which proposes to connect the region to electrical power and extended high-speed internet service from Manitoba. Permafrost and ground-ice data are crucial to responsible development in the region, yet there are few relevant studies. Much of the published work about permafrost in the Kivalliq Region comes from a set of related studies working within about 20 km of Rankin Inlet. LeBlanc and Oldenborger (2021) report on ground temperatures and give descriptions of sediments and ground ice in seven boreholes, and Faucher et al. (2024) use laboratory measurements to study ground ice in a shallow (< 2.5 m) subset of three of these boreholes. Remote-sensing, geophysical, and machine learning studies of the same area investigated sensitivity to thaw subsidence (Oldenborger et al. 2020, 2022). Outside the Rankin Inlet area, McCuaig et al. (2022) have mapped surficial geology and described ground ice and permafrost in the KHFL corridor along the coast of Hudson Bay and inland from Rankin Inlet to Baker Lake. These studies

provide permafrost information for the region but cover only a small fraction of the area and all are below the upper limit of post-glacial marine inundation in the region (McMartin et al. 2022).

From 1975 to 1977, the Polar Gas consortium of companies completed a drilling program in support of planning and construction for a proposed, but never realized, pipeline from the Canadian Arctic Archipelago to Ontario via the Kivalliq Region of Nunavut. The entire drilling program included logs and sample data from nearly 500 boreholes which, heretofore, have been available only in a few paper copies. The Polar Gas Project (PGP) Drilling Program included 72 boreholes in the Kivalliq Region between the Nunavut-Manitoba border and Baker Lake (Figure 1). These data represent the only available permafrost and geotechnical investigation along a north-south transect for large portions of the Kivalliq Region, yet they have not been digitized or evaluated by modern practitioners or academics.

From the paper copies of PGP drilling reports (EBA 1975, 1976, 1977), we digitized geospatial, cryostratigraphic, stratigraphic, and other geotechnical data into an internal database, greatly expanding the permafrost data in readily useable formats for this region. In this paper, we examine visible ground ice characteristics of these boreholes in the context of publicly available datasets of surficial geology (Geological Survey of Canada 2017a, b, c, d, e) and postglacial marine transgression limits (McMartin et al. 2022) to illustrate the potential of this newly digitized database.

2 KIVALLIQ REGION

The area considered in this paper is a part of the Kivalliq Region of mainland Nunavut on the western coast of

Hudson Bay. During the Wisconsin glacialiation, the entire region was covered by the Laurentide Ice Sheet, which retreated from the region 6–8 ka (Dyke 2004). The ice sheet caused substantial isostatic depression, and the region was partially covered by a marine transgression that extended about 90–400 km inland of the current coast (Dyke 2004; McMartin et al. 2022). The median elevation of the marine limit is 140 m, but due to a range of deglacial ages and proximity to a former ice-load centre causing substantial glacio-isostatic rebound the elevation of the marine limit varies from 132 to 170 m asl through the study area (McMartin et al. 2022). The PGP pipeline route traverses the marine limit in multiple locations (Figure 1), and the surficial geology is a complex mixture of alluvial, glacial, glaciofluvial, and marine deposits with bedrock outcrops (Geological Survey of Canada 2017a, b, c, d, e). The region is within the continuous permafrost zone (Heginbottom et al. 1995).

3 METHODS

The PGP Field Drilling Program took place from 1975 to 1977 (EBA 1975, 1976, 1977), and covered the entire proposed pipeline corridor from northern Melville Island to Longlac, Ontario (Figure 1). While the full drilling program included nearly 500 boreholes, only the 72 located in the Kivalliq Region between the Nunavut-Manitoba border and Baker Lake, Nunavut will be discussed in this paper. The terminal depth of boreholes in this region ranges from 2.5 to 13 m, and more than 75% of boreholes reach more than 5.5 m depth. Boreholes were drilled using a rotary wireline diamond drill. Drilling techniques used in 1975 often yielded poor core recovery, as heat generated at the cutting face, especially when drilling through coarse materials, combined with unrefrigerated drilling fluid, substantially thawed samples and caused the fine matrix to be washed away. In 1976 the PGP drilling program added a refrigeration unit which maintained the circulating drilling fluid at a temperature below 0 °C. This improved core recovery such that they “effectively cut and retained core in almost every soil type encountered in [the Kivalliq region]” (EBA 1976). However, sample recovery was still poor where frozen material was not well ice bonded. For some locations that were stone-free, they also used a Cold Regions Research and Engineering Laboratory (CRREL) permafrost drilling system.

PGP technicians recorded logs of soil type, visible ground ice content, and ground ice type. They estimated visible ice content to the nearest 5%. We recognize that visible ice content has weaknesses as a measure of ground ice, and we consider that in our analysis (see discussion). In addition to estimated percent visible ice content, PGP technicians used a simple ground ice description system common in North America (Table 1) based on a hybrid of ice content (assessed visually) and basic cryostructure. This approach remains in use among practitioners, but a more cryostructure-focused description is also commonly used among academics (cf. Murton and French 1994). Technicians extracted samples at selected depths and subsets of samples were analyzed for various properties.

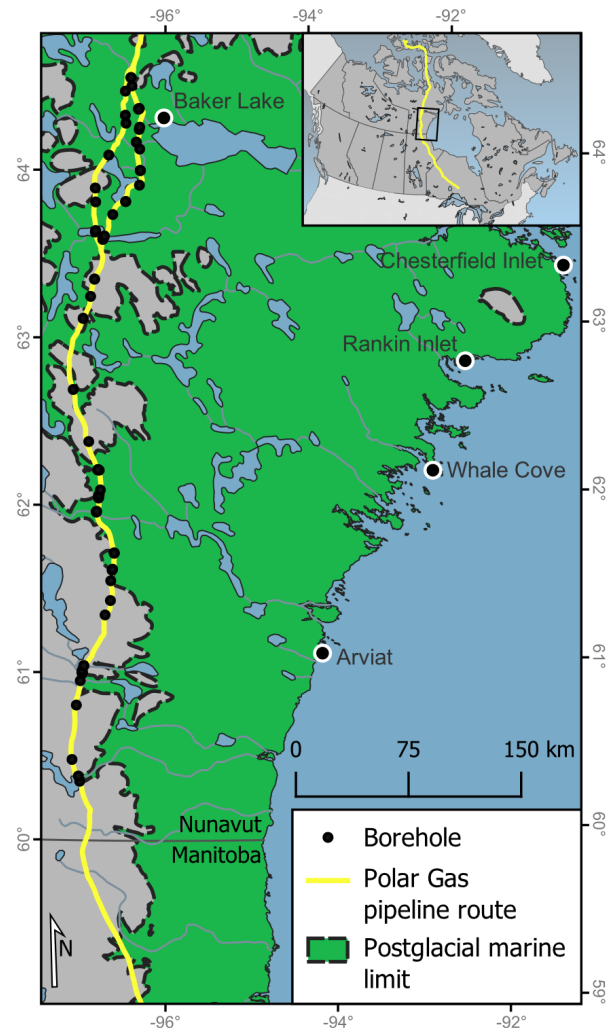


Figure 1. Map of the PGP pipeline route and borehole locations through the Kivalliq Region of Nunavut, Canada. Note that some borehole locations are too close together to be individually resolved at this scale. The full pipeline route is shown on the inset map. Postglacial marine limit at 132–170 m asl from McMartin et al. (2022).

We manually transcribed text and numeric data from PGP Drilling Program reports without using optical character recognition software. There were two broad types of information: (1) data from drilling logs, including literal soil descriptions, soil classification codes using the Unified Soil Classification System, ground ice description codes (Table 1), and visible ice content; and (2) data from laboratory analyses conducted on samples from boreholes, including gravimetric water content, field-moist density, particle size distribution, and Atterberg limits. We manually traced the PGP proposed pipeline route from index maps in the PGP drilling program reports using QGIS software (QGIS 2023). We used the index maps for initial borehole placement, then refined locations using photographs and air photos in the PGP reports. We detected some errors in the paper reports. These errors were rare (less than 1%) and appeared to be dominantly typographical errors made during the

compilation of borehole logs in reports. Where data were very likely erroneous, we used our judgement and available context (i.e., other data from the reports) to correct errors whenever possible. In circumstances where we judged that context was insufficient to make a confident correction, the offending data were removed and left blank.

Table 1. Ground ice description scheme used in PGP reports (EBA 1975, 1976, 1977). Where borderline or mixed classifications existed PGP technicians used dual symbols. A similar scale is described in French and Shur (2010).

Visible ice content category	Ground ice description code	Description
Ice not visible	Nf	Poorly bonded or friable
	Nbn	No excess ice, well bonded
	Nbe	Excess ice, well bonded
Visible ice < 50% by volume	Vx	Individual ice crystals or inclusions
	Vc	Ice coatings on particles
	Vr	Random or irregularly oriented ice formations
	Vs	Stratified or distinctly oriented ice formations
Visible ice > 50% by volume	ICE+	Ice with soil inclusions
	ICE	Ice greater than 2.5 cm thick without soil inclusions

We overlaid borehole locations on surficial geology maps of the region produced at a scale of 1:125,000 (Geological Survey of Canada 2017a, b, c, d, e). Because these maps have a high categorical resolution relative to the number of boreholes, surficial geology categories were downgraded from detailed subcategories (e.g., glaciofluvial sediments – ice-contact sediments) to broad categories (e.g., glaciofluvial sediments). Downgrading generally retained a proportionally representative sample of surficial geology subtypes, though alluvial sediments were somewhat biased towards locations with a marine sediment subtype. We assigned boreholes to surficial categories based on a spatial join using QGIS software (QGIS 2023). We classified boreholes as either above or below the maximum marine limit defined by McMartin et al. (2022), which they assessed with a moderate to high level of confidence for this region. This limit also affects the surficial materials present (e.g., no marine or wave-washed sediments are present above the limit) and, therefore, the ground ice type and content.

Ground ice type description codes used by PGP technicians include semi-quantitative information on visible ice content. Whereas they recorded detailed information on ice disposition (e.g., Vr – random or irregularly oriented ice formations – visible ice < 50% by volume), we downgraded these into broader categories that refer only to the visible ice content (e.g., visible ice < 50% by volume). This includes the visible ice content categories from Table 1, as

well as additional categories for (1) unfrozen sections, (2) “frozen” material that they noted was cryotic but made no other notes about ground ice in that section, and (3) material for which they made no notes on freezing or ice characteristics. PGP reports indicate that because of the use of unrefrigerated drilling fluid in 1975 there were poor sample returns when drilling through coarse fragments, and many of these cases were assigned to these additional categories. The “frozen” category is assumed to refer to material that was identified as frozen during drilling, but for which returns were insufficient to evaluate ice richness. Thus, this category represents underestimates in the other frozen categories. With the 1976 drilling season, PGP staff introduced refrigerated drilling fluid and the “frozen” category was no longer used. We calculated wet-basis gravimetric water content (w_w ; g water g⁻¹ field-moist soil) from dry-basis gravimetric water content (w_d ; g water g⁻¹ dry soil) using the following relation from Phillips et al. (2015):

$$w_w = w_d / (1 + w_d) \quad [1]$$

4 RESULTS

PGP Drilling staff noted that in 15 boreholes in the region (about 21%) they did not encounter frozen ground. Of these 15 boreholes, 14 were drilled in the first year of the drilling program when they were still using unrefrigerated drilling fluid. It is likely that in many cases permafrost was present but the drilling technique caused thawing and technicians were not able to recognize the presence of frozen ground.

Reported visible ice contents from boreholes where frozen ground was detected ranged from 5 to 90%, with a median of 15%. Wet-basis gravimetric water content ranged from 0.02 to 0.95 g water g⁻¹ field-moist soil, with a median of 0.17 g g⁻¹ and a mean of 0.25 g g⁻¹. Only a subset of samples included measurements for water content. The relationship between water content and visible ice content is shown in Figure 2. There are about 40 of over 1,200 data

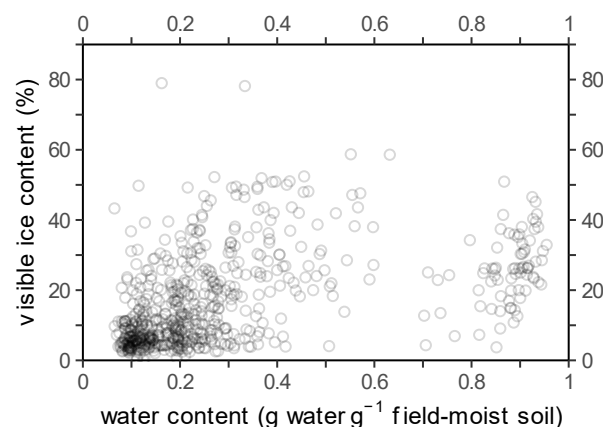


Figure 2. Scatterplot of wet-basis gravimetric water content vs visible ice content. A water content of 1 would indicate pure water or ice. To reduce overlapping of data points, water content (originally measured to the nearest 0.01 g g⁻¹) was randomized to ± 0.005 g g⁻¹ and visible ice content (originally estimated to the nearest 5%) was randomized to $\pm 2.5\%$ from the original values.

points where the ground ice description code indicates there is no visible ice, yet a visible ice content of 5, 10, or 15% is recorded.

Ground ice descriptions indicate that there is visible ice in more than 25% of all depth increments deeper than 0.9 m and shallower than 5 m (Figure 3). This increases to more than 35% if boreholes, where frozen ground was not recovered, are ignored. Most boreholes with frozen ground and shallow thaw depths (< 1 m) have some visible ice near the top of permafrost, and 40–50% of boreholes with frozen ground have some visible ice to depths of more than 4 m. In marine sediments PGP staff noted frozen ground in 4 of 6 boreholes; however, data on ice from them were scarce or depth intervals not well defined. Because of this lack of data, marine sediments are excluded from discussion here (not shown in Figure 3). The most ice-rich soils are found in the top 3.5 m of boreholes drilled in areas mapped as glacial and alluvial sediments, including all sections with visible ice content greater than 50%. A majority of the area along the pipeline route mapped as alluvial sediments, and of the PGP boreholes within alluvial sediments, fall in map units that have a secondary category of marine sediments. There is generally more visible ice in boreholes drilled in alluvial or glacial sediments than in glaciofluvial sediments, though no frozen soil was recovered in 3 of 7 boreholes in glaciofluvial sediments. Visible ice is present in more than 20% of depth increments shallower than 5 m in boreholes drilled in areas mapped as bedrock; however, closer examination of the individual borehole logs and descriptions reveals that all instances of visible ice are in pockets of another surficial material overlying bedrock, usually a silty to sandy till, but were mapped as bedrock in surficial geology maps.

Depth intervals with more than 50% visible ice were present only in boreholes located within the postglacial marine limit (Figure 4). There is a much greater proportion of depth intervals with visible ice in the top 2 m in locations below the marine limit than in locations above the marine limit, and also a greater proportion of boreholes that encounter frozen ground at any depth. At first examination of Figure 4 it may appear that there is substantially more visible ice distributed at depths below 3 m in boreholes above the marine limit. However, this is an artifact of the data visualization type. It is caused because the number of boreholes decreases with depth, and the boreholes that do not reach greater depths are disproportionately those where frozen ground was not detected, increasing the apparent proportion of ground ice in the remaining boreholes.

Mean grain size distribution (Table 2) indicates that all surficial geology types are dominantly sandy, but alluvial and glacial sediments had a substantially greater mean fines content (41 and 43%, respectively) than did glaciofluvial sediments (26%). This suggests that the lack of frost susceptibility of the sediments may be an important control in glaciofluvial sediments.

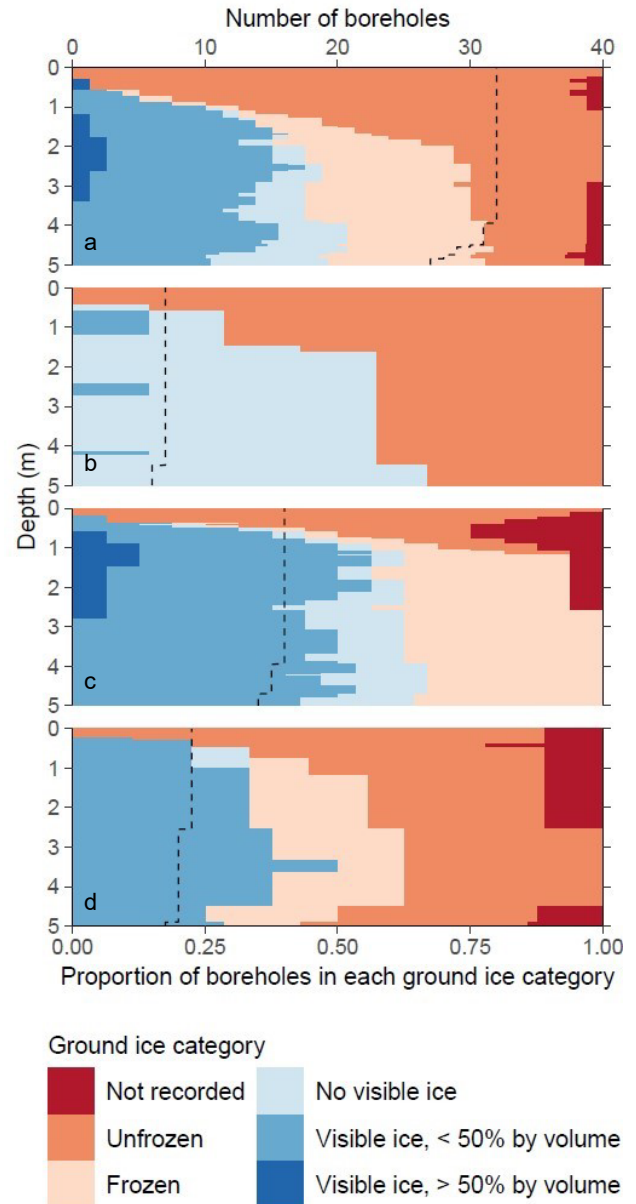


Figure 3. Proportion of boreholes falling within each ground ice category, by depth, in mapped surficial geology categories (a) glacial deposits, (b) glaciofluvial deposits, (c) alluvial deposits, and (d) thin layers of other surficial material (usually glacial deposits) overlying bedrock at locations mapped as bedrock. Using the secondary axis at the top of the figure, dashed lines indicate the number of boreholes in each category at each depth. The “frozen” category likely represents underestimates of other categories (see text). Boreholes in the marine surficial geology category are not shown because n was small and data on ground ice was limited. Figures are limited to 5 m depth because the number of boreholes drops sharply below this depth.

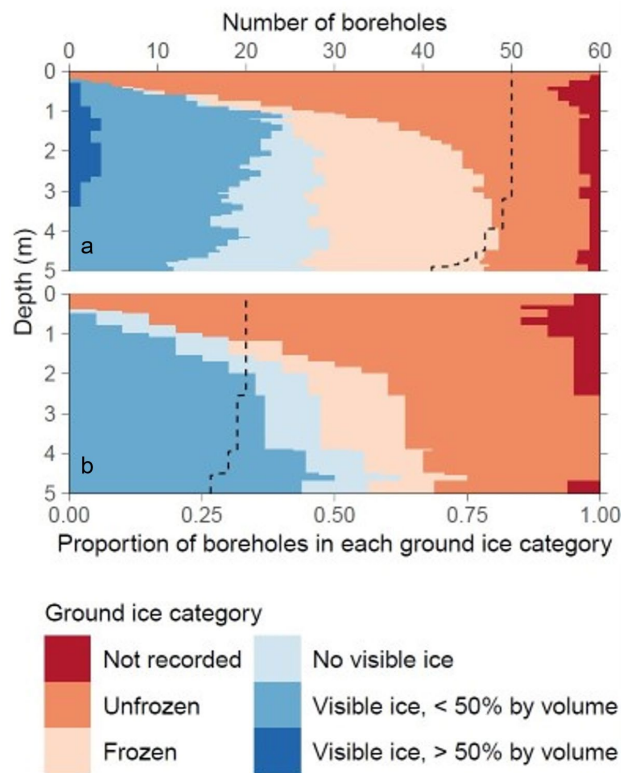


Figure 4. Proportion of boreholes falling within each ground ice category, by depth, (a) within and (b) beyond the postglacial marine limit (McMartin et al. 2022). Using the secondary axis at the top of the figure, dashed lines indicate the number of boreholes in each category at each depth. The “frozen” category likely represents underestimates of other categories (see text). Figures are limited to 5 m depth because the number of boreholes drops sharply below this depth.

Table 2. Mean grain size distribution in samples from boreholes in mapped surficial geology types.

Surficial material type	Sand	Silt	Clay	Gravel	<i>n</i>
Alluvial	49	34	7	10	43
Glaciofluvial	55	25	1	19	17
Marine	55	17	3	24	9
Glacial	45	38	5	13	55

5 DISCUSSION

Caution is necessary when interpreting data from these digitized reports. The purpose of the PGP Field Drilling Program was to gather information for pipeline construction, not to provide a representative sampling of the landscape to be upscaled for scientific investigations. This focus on pipeline planning means they concentrated on locations where they expected pipeline construction challenges (e.g., river crossings) and locations where they hoped to find aggregate resources. This sampling strategy is unlikely

to produce a complete picture of regional permafrost conditions. Moreover, drilling practices in the first year and dubious percent visible ice content estimates mean that some of the data should be treated with skepticism. Nevertheless, this database contains considerable useful permafrost and geotechnical data for a region with very few other observations.

The proportion of boreholes that did not include any notation of frozen ground was relatively high (about 21%) considering that the region is within the continuous permafrost zone, where 90% or more of terrain is expected to be underlain by permafrost (Heginbottom et al. 1995). This may be explained, for some, by the focus on river crossings, as some boreholes were drilled only metres from riverbanks and may be located within a talik caused by a major river, but most are likely incorrect. Nearly all boreholes for which PGP technicians did not encounter frozen ground were drilled in 1975, when they were still using unrefrigerated drilling fluid. It is likely that this caused thawing at the cutting face and permafrost was not recognized despite being present.

The association between water content and visible ice content is weak (Figure 2), particularly for the highest water contents where the volume of ice is greater than the thawed porosity of the soil and any increase in water content should cause a corresponding increase in visible ice content. Instead, we see a large scatter in visible ice content and only a weak increase. Moreover, a considerable number of the values seem to be impossible to reconcile. For example, if we assume a particle density for soil solids of 2.65 g cm^{-3} and a relatively large (i.e., conservative) thawed porosity of 0.6, we expect volumetric ice contents in excess of pore space (i.e., approximate visible ice content) of 68% and 80% for wet-basis gravimetric water contents of 0.7 and $0.8 \text{ g water g}^{-1}$ field-moist soil, respectively; however, data from the PGP Drilling Program show a range in visible ice content from only 5 to 35% for this water content range. It is unlikely that a simple routine analysis like gravimetric water content is substantially incorrect. The percent visible ice content by volume is subject to expert interpretation, and therefore could have been under or over-estimated and inconsistently recorded by different technicians over the 3 years. For instance, even when assessed by current experts, estimated visible ice content may show unreasonable scatter and poor correlation against measured volumetric ice content (e.g., Castagner et al. 2023). It is also possible that there is a scale mismatch between the two data types and the visible ice contents represent larger depth increments than the corresponding samples do. For these reasons, we opted to discuss the semi-quantitative scale (Figures 3 and 4) instead of visible ice content data from this dataset. However, if future ice content measurements are done for the region, it may still be possible to use regression models to produce a better result from visible ice content (cf. Castagner et al. 2023).

The ground ice distributions determined here are in general agreement with previous studies from the region, with minor differences. McCuaig et al. (2022) found moderate ice content in fluvial sands and silts along the proposed KHFL corridor near the coast, and Faucher et al. (2024) found that the upper permafrost was ice-rich in a core drilled in alluvial

and marine undifferentiated sediments near Rankin Inlet. A majority of the area along the pipeline route mapped as alluvial sediments and a majority of the boreholes located within alluvial sediment surficial geology map units, including those that most strongly contribute to the relatively high ice content in alluvial sediments, fell in areas mapped as alluvial sediments with a significant secondary category of marine sediments, suggesting that marine sediments may be an important component of the relatively high ice content in alluvial sediment surficial units. The PGP data indicate that there is more ice at depths beyond 1.5 m in alluvium than Faucher et al. (2024) found in their core, which was in the alluvium/marine surficial geology type. McCuaig et al. (2022) found that glacial sediments along the KHFL corridor had excess ice, though typically in relatively low volumes (5–10%), but they acknowledge that they had relatively few samples. Faucher et al. (2024) noted a similar result from their core in till and marine undifferentiated sediments near Rankin Inlet. Working with data from a relatively large number of boreholes in glacial sediments (Figure 3), we note that the visible ice (< 50% by volume) is common at all depths, which could include relatively low excess ice volumes similar to those found by McCuaig et al. (2022) and Faucher et al. (2024); however, there are also boreholes where there are some intervals with > 50% visible ice, by volume, far higher than noted by either previous study. These differences in ice contents of glacial sediments do not necessarily put our results and interpretation at odds with those of Faucher et al. (2024) or McCuaig et al. (2022), as they had few samples from glacial sediments. Only a few of those from the PGP dataset showed higher ice content, and these could easily be missed in a study with a lower number of observations. In a spatially distributed examination of geological, topographic, and multispectral variables Oldenborger et al. (2022) predicted the thaw sensitivity of the ground near Rankin Inlet using a reference classification based on seasonal ground subsidence and expert knowledge on ground ice content and distribution in frozen active layer and permafrost. They found that a larger proportion (> 75%) of areas mapped as glaciofluvial sediments are thaw stable than the proportions of glacial sediments (< 75%) or alluvial sediments (about 25%), and a smaller proportion of glaciofluvial sediments have a high or very high thaw sensitivity (< 3%) than the proportions of glacial sediments (> 6%) or alluvial sediments (> 25%). The general agreement of their results with ours strengthens confidence in our findings.

Both PGP reports and McCuaig et al. (2022) note that ice-wedges are common in several materials, including coarse-grained glaciofluvial deposits, yet boreholes in glaciofluvial deposits are rarely noted to have substantial visible ice in PGP reports (Figure 3). It is common that PGP site descriptions for boreholes will note abundant ice wedges, but borehole logs that explicitly penetrate wedge ice are absent. It is possible that there was a sampling bias where PGP technicians were systematically avoiding ice wedges in their drilling. Thus, there may be substantial near-surface ground ice as ice wedges that is not accounted for in this dataset.

The presence of noteworthy visible ice in boreholes from areas mapped as bedrock highlights a difficulty inherent to

generalizing when comparing point-based measurements to complex surficial geology. These boreholes were all in pockets of other material (usually glacial deposits) too small to be mapped at the scale of the surficial geology maps. This highlights the need for caution in interpretation of these data when combined with regional surficial geology maps. Analysis of boreholes in spatially determined groupings as we have done here can give valuable impressions of trends and typical values, but where more precise or locally relevant results are desired the surficial geology type determined from maps should be compared against that inferred from the borehole stratigraphy, especially for categories with few boreholes.

6 SUMMARY

Though the Kivalliq Region of Nunavut is an area of interest for infrastructure development, heretofore the availability of permafrost data from the region has been poor. We have digitized and introduced a historic dataset of geotechnical, cryostratigraphic, and geospatial data from paper records of the PGP Field Drilling Program of 1975–77 completed in the Kivalliq Region between the Nunavut-Manitoba border to Baker Lake. Important results from this portion of the dataset include (1) the most ice-rich locations are in areas mapped as alluvial and glacial sediments, whereas those mapped as glaciofluvial tend to be ice-poor, (2) boreholes within the maximum limit of postglacial marine inundation are more likely to be ice-rich than those beyond the marine limit; however, (3) caution is necessary in interpretation of PGP data, particularly data on percent visible ice content. There are weaknesses of this dataset related to collection methods of the period, particularly where drilling methods caused sample degradation and in poor visible estimates of percent ice content, but there remains considerable potential to extract informative permafrost and geotechnical information.

7 DATA AVAILABILITY

At the time of writing, final data compilation is ongoing. We intend to release the data publicly along with additional analyses of publicly available datasets as a Geological Survey of Canada Open File, but it is not yet available. Once it is ready, it will be available to download at GEOSCAN (<https://geoscan.nrcan.gc.ca>). We intend to expand the geographic scope of the digitization project in the future.

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