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**GEOLOGICAL SURVEY OF CANADA**
**OPEN FILE 8713**

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**Version 1.1**

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## Abstract

This Open File presents national-scale mapping of ground ice conditions in Canada. The mapping depicts a first-order estimate of the combined volumetric percentage of excess ice in the top 5 m of permafrost from segregated, wedge, and relict ice. The estimates for the three ice types are based on modelling by O'Neill et al. (2019) (https://doi.org/10.5194/tc-13-753-2019), and informed by available published values of ground ice content and expert knowledge. The mapping offers an improved depiction of ground ice in Canada at a broad scale, incorporating current knowledge on the associations between geological and environmental conditions and ground ice type and abundance. It provides a foundation for hypothesis testing related to broad-scale controls on ground ice formation, preservation, and melt. Additional compilation of quantitative field data on ground ice and improvements to national-scale surficial geology mapping will allow further assessment and refinement of the representation of ground ice in Canada. Continued research will focus on improving the lateral and vertical representation of ground ice required for incorporation into Earth system models and decision-making. Spatial data files of the mapping are available as downloads with this Open File.


## Purpose

The Ground ice map of Canada presented in this Open File depicts a first-order estimate of the combined volumetric percentage of excess ice in the top 5 m of permafrost from segregated, wedge, and relict ice. Excess ice is defined as the "volume of ice in the ground which exceeds the total pore volume that the ground would have under natural unfrozen conditions" (Harris et al., 1988). This estimate stems from integrating qualitative assessments of the modelled abundance of these three ice types (O'Neill et al., 2019). This document provides information on the methodology for the map compilation, and a description of files included in this Open File.

## Files

**1_of_8713_v1_1 Ground ice map of Canada.pdf** – *Wall map/poster*
**2_Ground_ice_abundance_v1_1** – *Geospatial files (Geotiff) for Ground ice map of Canada ice abundance*
**3_relict_ice_v1_1** – *Geospatial files (Geotiff) for relict ice abundance with v1.1 fix*
**4_segregated_ice** – *Geospatial files (Geotiff) for segregated ice abundance from O'Neill et al.* (2019)
**5_wedge_ice** – *Geospatial files (Geotiff) for wedge ice abundance from O'Neill et al.* (2019)
**6_modified_surf_mat** – *Geospatial files (Geotiff) for surficial materials from O'Neill et al.* (2019)
**7_PF_zones_lines** – *Geospatial files (Shapefile) for permafrost zones in Canada (modified from Heginbottom et al. (1995))*
**8_Ground ice map v1_1 simple.png** – *Simplified Ground ice map of Canada with legend*

## Methods

The map compilation steps were: (1) assign numeric value ranges (estimated % excess ice in upper 5 m of permafrost) to each qualitative class from O'Neill et al. (2019) for each ice type (relict, segregated, wedge); (2) by map algebra, sum numeric values to derive an integrated (total) ice content; and (3) apply a classification to produce the legend for the integrated map.

### *(1) Assigning numeric values to individual ice types*

The numeric values assigned to each ice type from O'Neill et al. (2019) are shown in Figure 1.

**Ground ice abundance**
**(Est. % excess ice volume in top 5 m of permafrost)**

| | None | Negligible | Low | Medium | High |
|---|---|---|---|---|---|
| RELICT | 0 | >0-2 | >2-5 | >5-10 | >10 |
| SEGREGATED | 0 | >0-2 | >2-5 | >5-10 | >10 |
| WEDGE | 0 | >0-2 | >2-5 | >5-10 | >10 |

Figure 1. Numeric classification of qualitative ground ice classes from O'Neill et al. (2019).

The classification breaks in Figure 1 are based partly on published values available from the literature, and on expert knowledge (Table 1, Appendix). The studies in Table 1 are reported because (1) the volumetric contribution from specific ice types was explicitly stated or could be estimated from the information provided and simple assumptions, and (2) the studies commonly reported average values for surficial material units or broader geographic areas, making them appropriate to inform this type and scale of modelling. For the purposes of the classification, it is assumed the soil pore space is ice saturated, such that relict, segregated, and wedge ice contribute to excess ice. To derive volumetric ice content from these data, pore space must be estimated.

The numeric value (>10%) for the 'High' classes accounts for known patterns of ice distribution and content with depth. Though segregated ice in fine-grained sediments can contribute >20% excess ice content to the upper 1-2 metres of epigenetic permafrost (Kanevskiy et al., 2013; Morse et al., 2009; O'Neill and Burn, 2012; Table 1) ice enrichment declines with depth (French and Shur, 2010; Pollard and French, 1980), such that the average ice content in the top 5 m of permafrost is typically lower than just below the permafrost table. For example, low ground ice abundance (up to 5% excess ice content) on the legend could result from ice-rich sediments (e.g., 20% excess ice) in the top metre of permafrost overlying ice-poor sediments in the 4 m below. Therefore, we consider >10% as high abundance for segregated ice in the top 5 m of permafrost.

Similarly, though wedge ice can account for as much as 50% of upper permafrost volume in Yedoma (ice-rich Pleistocene syngenetic deposits) in Alaska (Kanevskiy et al., 2013), reported volumes from epigenetic permafrost deposit types represented on the national-scale surficial geology mapping are much lower (Table 1), so we also use 10% as a break for high wedge ice abundance.

There are few reports on the volumetric abundance of relict ice over landscape units, likely due to its discontinuous distribution, and because studies commonly take place opportunistically where it is exposed. In terrain cored with relict ice, the abundance is variable (Jorgenson et al., 2008), and in specific locations where ice bodies are present, the upper several metres of permafrost may be essentially pure ice. Reported values for relict ice and massive segregation-intrusive ice exposures in cold tundra environments are between 15-20% (Table 1) in the upper 10 m, so >10% is also considered high relict abundance (Figure 1). The lack of distributed data on relict buried glacier ice abundance highlights the need for additional assessments on its abundance and spatial continuity in glacial sediments.

*(2) Deriving integrated ice content*

The three rasters were summed using raster addition in a geographic information system (ESRI® ArcMap™). To accomplish this, the rasters were reclassified; pixels were assigned the numeric values of the upper range for each class and ice type shown in Figure 1, except for the 'High' class. As an example, 'Low' was given a value of 5. Pixels with 'High' abundance were assigned a value of 15 for the purposes of the calculation. The pixel values for the three layers were then summed to produce a new raster integrating the three ice types.

*(3) Legend classification*

Figure 2 presents the classified legend for the Ground ice map of Canada integrating the three ice types.

**Ground ice abundance**
**(Est. % excess ice volume in top 5 m of permafrost)**

| | None | Negligible | Low | Medium | High | Very high |
|---|---|---|---|---|---|---|
| **TOTAL** | 0 | >0-5 | >5-10 | >10-20 | >20-30 | >30 |

Figure 2. Legend for the Ground ice map of Canada integrating the three ice types.

The legend includes six classes, from 'None' (0%) to 'Very high' (>30%) (Figure 2). The value (>30%) for the 'Very high' class is between the highest class depicting percent visible ice in the upper 10-20 m of ground on the Permafrost Map of Canada and the Circum-Arctic Map of Permafrost and Ground ice Conditions (>20%) (Brown et al., 2001; Heginbottom et al., 1995), and the highest class (>40%) depicting excess ice volume in the top 5 m for ground ice mapping of Alaska (Jorgenson et al., 2008).

On the presented map, the 'Very high' ice class occurs where relict ice is modelled in conjunction with segregated and wedge ice. Permafrost areas in the 'None' class may still include excess ground ice, because ice-rich deposit types may not be represented at the scale of the national surficial geology mapping (O'Neill et al., 2019; Wolfe et al., 2021).

## Version 1.1 update

We identified an issue in the relict ice script that caused the maximum extent of previously inundated terrain to be incorrectly coded in some areas. This caused preservation of relict ice in some areas in the version 1.0 output where it should have melted according to the model rules (Figure 3). The maximum extent of marine and glacial lake inundation is established in two ways in the model: (1) using limits presented on the Glacial Map of Canada (Prest et al., 1968), and (2) using data on deglaciation (Dyke et al., 2003). The extent of inundation from these two sources largely overlaps. However, the issue identified causes omission of the extent of inundation from (2) where it is outside (beyond) the inundated area represented in (1). Therefore, relict ice was modelled as preserved in some areas where it should not be.

In this Version 1.1 update, we provide the corrected relict ice GeoTIFF, and update files to reflect the change on combined ice abundance files. Figure 3 identifies, in red, the areas affected by this update.

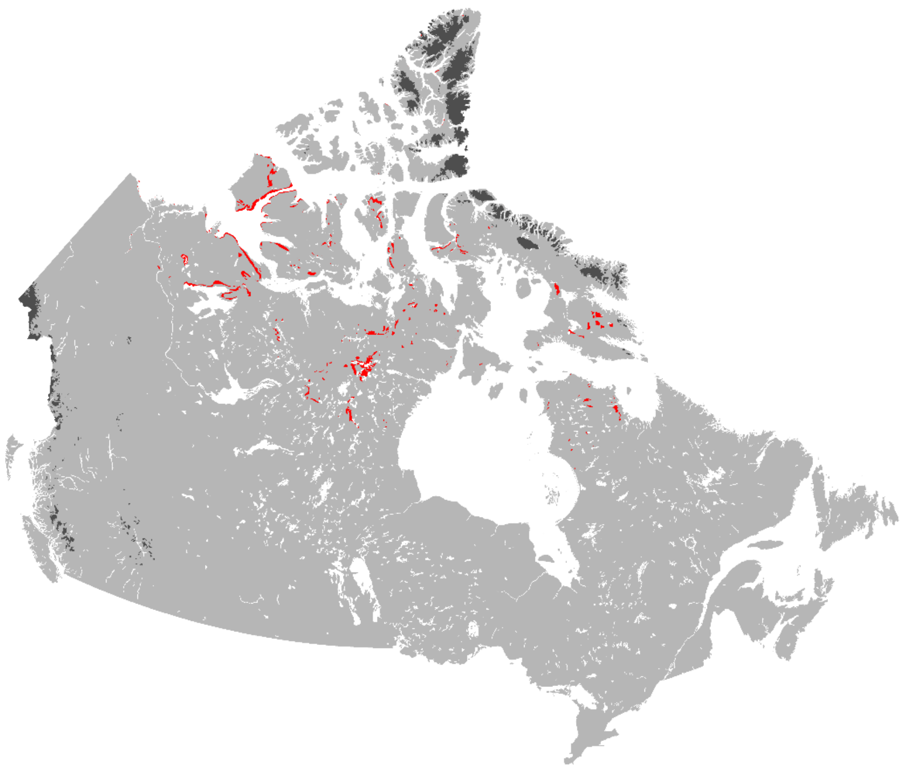

Figure 3. Map showing areas affected by Version 1.1 update of relict ice output. Red areas no longer include modelled relict ice due to the correction of maximum limits of inundation.

## Use of Ground ice map of Canada v. 1.1

The map presents broad-scale ground ice conditions in Canada, providing a first-order assessment of regional variations in ground ice content. Because of the scale of the underlying data layers and processes represented in the modelling, the map may not accurately reflect site-scale ground ice conditions at specific locations. In particular, biome distributions are highly generalized and the scale of the surficial geology dataset used in the model is 1:5,000,000, such that localized variation in surficial geology may not be well represented. For example, areas mapped as bedrock or till veneer around Yellowknife, NT include ice-rich glaciolacustrine deposits that are not represented (Wolfe et al., 2014). Similarly, areas mapped as bedrock near Salluit, NU contain ice-rich marine clays and tills that are not mapped at the national scale (Allard et al., 2011). Further comparisons of modelled ice abundance with field observations are available in a ground ice atlas (Wolfe et al., 2021).

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## Appendix

Table 1. List of references including information on volumetric ground ice abundance for specific deposit types or geographic regions. EI = excess ice; VIC = volumetric ice content. The depth interval reported refers to the top of permafrost.

| Reference | Ice content % | Type | Depth interval | Sediments | Location | Comments |
|---|---|---|---|---|---|---|
| **SEGREGATED ICE** | | | | | | |
| (Morse et al., 2009) | 24 | EI | top 1 m | Uplands (till/glacial/drained lake basin) | Richards Is., NT | |
| (O'Neill and Burn, 2012) | 20 | EI | top 1 m | Till | Illisarvik, Richards Is., NT | |
| (Kokelj and Burn, 2003) | 10-15 | EI | top ~1 m | Till/fan deposits | near Inuvik, NT | |
| (Kokelj and Burn, 2005) | 27-41 | EI | top 0.5 m | Silty loams | Mackenzie Delta, NT | |
| (Burn, 1988) | ~20* | EI | top 3 m | Glaciolacustrine silts/silty clay | Stewart River valley, YT | *Assumed 0.5 porosity and all pores filled with ice, estimated from Fig. 6 |
| (Kanevskiy et al., 2013) | 34* | EI | top 3-4 m | Marine (silty deposits & sandy gravel) | western Alaska Coastal Plain, AK | *Assumed 0.5 porosity and all pores filled with ice |
| (Kanevskiy et al., 2013) | 27* | EI | top 3-4 m | Marine (silt and silty clay) | eastern Alaska Coastal Plain, AK | *Assumed 0.5 porosity and all pores filled with ice |
| (Pollard and French, 1980) | 9.2 | EI | top 9.5 m | Various | Richards Is., NT | EI = 14.3% of upper 9.5 m and wedge ice constitutes 36% of all excess ice. So segregated ice = 9.2% (0.64*14.3) assuming only wedge and segregated excess ice occur. |
| (French et al., 1986) | 10-30 | EI | top ~3.5 m | Shale, shale fragment, fines | Sabine Peninsula, Melville Is., NU | Up to 70% EI in 0.7 m interval at top of permafrost |
| (Dallimore et al., 1996) | 8-16 | EI | top ~10-15 m | Silty sands and diamictons | Northern Richards Is., NT | Ice-rich ground with ground ice forms <50 cm thick |
| (Calmels et al., 2008) | ~25-35* | EI | top ~5 m | Glacio-marine silt and clay | Umiujaq, QC | *Assumed 0.3 to 0.4 porosity and all pores filled with ice, estimated from Fig. 5. |
| **WEDGE ICE** | | | | | | |
| (Pollard and French, 1980) | 12 | VIC | top 4.5 m | Various | Richards Is., NT | Average of low centred polygons (16%) and other tundra areas (8%) |
| (Bernard-Grand'Maison and Pollard, 2018) | 3.81 | VIC | top 5.9 m | Various | Fosheim Peninsula Ellesmere Is., NU | ice-rich silty-clay marine sediments, local fluvial, glacial and glaciofluvial deposits |
| (Bode et al., 2008) | 4.6-7.3 | VIC | top 3.5-4 m | Fine-grained sand and silt | Taglu Is., NT | Airphoto interpretation and ground penetrating radar |
| (Dallimore et al., 1996) | 6.5 | VIC | top 5 m | Undifferentiated preglacial sediments, diamicton, lacustrine | Northern Richards Is., NT | Conservative estimate (complex ice wedge forms and smaller polygons omitted) |

| | | | | | | |
|---|---|---|---|---|---|---|
| (Kanevskiy et al., 2013) | 14 | VIC | top 3-4 m | Silty deposits and sandy gravel | Beaufort Sea Coast Alaska western primary surface, AK | |
| (Kanevskiy et al., 2013) | 12 | VIC | top 3-4 m | Silt and silty clay | Beaufort Sea Coast Alaska eastern primary surface, AK | Highest volumetric wedge ice content (28%) in 5-7 m bluff, >5m wide wedges |
| (Kanevskiy et al., 2013) | 1-22 | VIC | top 3-4 m | Fine-grained, organic rich soils | Alaska Coastal Plain lake basins, AK | Average in old basins (8%) higher than average in young basins (3%) |
| (Couture and Pollard, 1998) | 1.8-3.5 | VIC | top 5.9 m | Fine-grained sediments below marine limit | Fosheim Peninsula Ellesmere Is., NU | |
| (Kanevskiy et al., 2013) | 50 | VIC | top 3-4 m | Eolian silt | Camden Bay area, AK | Yedoma |

| **RELICT / INTRASEDIMENTAL/ MASSIVE ICE** | | | | | | |
|---|---|---|---|---|---|---|
| (Kanevskiy et al., 2013) | 19 | VIC | top 7-10 m | Stratified inclusions sand/gravel | Kaktovik at Barter Is., AK | Interpreted as buried glacial ice |
| (Couture and Pollard, 1998) | 16.2 | EI | top 5.9 m | Underlying fine-grained marine sediment. | Fosheim Peninsula Ellesmere Is., NU | Massive segregation/intrusive ice bodies. 16.2% of terrain units where ice type occurs. Mean top of massive ice at 3.5 m |
| (Dallimore et al., 1996) | 9 | EI | top ~10-15 m | Diamicton, sands | Northern Richards Is., NT | Various massive ice bodies – genesis not interpreted. Up to 20% in one 14 m high exposure segment |

| **ALL ICE TYPES** | | | | | | |
|---|---|---|---|---|---|---|
| (Lantuit et al., 2012) | 29 | Visible VIC | Various | Various | Beaufort coasts, NT | Ground ice content based on field observations of exposures, published values, boreholes and cores, geophysics, terrain analysis from remotely sensed datasets, and largely the Circum-Arctic map of permafrost conditions (Lantuit et al., 2012, p. 388) |
| (Lantuit et al., 2012) | 14 | Visible VIC | Various | Various | Canadian Archipelago | As above cell |
| (Pollard and French, 1980) | 14.3 | EI | top 9.5 m | Various | Richards Is., NT | |