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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8713**

Ground ice map of Canada

Version 1

H.B. O'Neill, S.A. Wolfe, and C. Duchesne

2020

Canada



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Publications in this series have not been edited; they are released as submitted by the author.

Abstract

This Open File presents new 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.

Recommended citations for the Ground ice map of Canada:

Both references below should ideally be cited for the Ground ice map of Canada. The first describes the modelling methodology for each ice type, and is the original reference for files 3-6 below, and the second (this Open File) describes the map compilation.

O’Neill, H.B., Wolfe, S.A., and Duchesne, C., 2019. New ground ice maps for Canada using a paleogeographic modelling approach. *The Cryosphere* 13, 753–773. <https://doi.org/10.5194/tc-13-753-2019>

O’Neill, H.B., Wolfe, S.A., and Duchesne, C., 2020. Ground ice map of Canada; Geological Survey of Canada, Open File 8713, ver. 1, 1 .zip file. <https://doi.org/10.4095/326885>

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 abundance of these three ice types from previous modelling (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

0_Report_Ground ice map of Canada_v1.pdf – *This document*

1_The Ground ice map of Canada_v1.pdf – *Wall map/poster*

2_Ground_ice_abundance.zip – *Geospatial files (Geotiff) for Ground ice map of Canada ice abundance*

3_relict_ice.zip – *Geospatial files (Geotiff) for relict ice abundance from O’Neill et al. (2019)*

4_segregated_ice.zip – *Geospatial files (Geotiff) for segregated ice abundance from O’Neill et al. (2019)*

5_wedge_ice.zip – *Geospatial files (Geotiff) for wedge ice abundance from O’Neill et al. (2019)*

6_modified_surf_mat.zip – *Geospatial files (Geotiff) for surficial materials from O’Neill et al. (2019)*

7_PF_zones_lines.zip – Geospatial files (Shapefile) for permafrost zones in Canada (modified from Heginbottom et al. (1995))

8_Marine_inundation.zip – Geospatial files (Geotiff) for maximum marine inundation limit from the Glacial Map of Canada (Prest et al., 1968), clipped to permafrost zones, indicating areas with potentially saline permafrost.

9_Ground ice map simple.png – Simplified Ground ice map of Canada with legend

10_Ground ice map simple_saline.png – Simplified Ground ice map of Canada indicating maximum marine inundation limit and areas with potentially saline permafrost.

11_Ground ice map simple.svg – Scalable vector graphics file of mapping optimized for editing in illustration/graphics software.

Methods

The map compilation steps were: (1) assign numeric value ranges (est. % 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 few 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. 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 spatial continuity.

(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, segregated: ‘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.

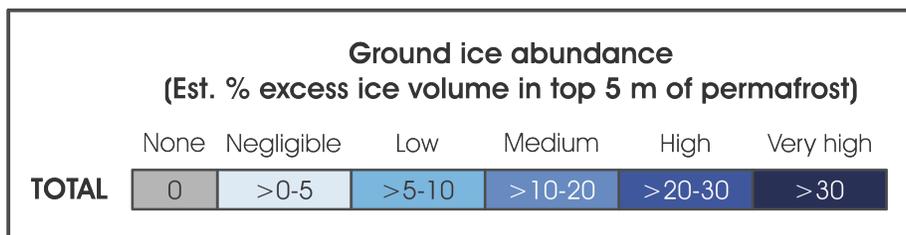


Figure 2. Legend for the Ground ice map of Canada integrating the three ice types.

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 present in high abundance 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).

Use of Ground ice map of Canada v. 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). Subsequent versions of the Ground ice map of Canada will be generated as improved datasets become available and implemented.

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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	



Ground ice in Canada

Ground ice is an important component of the permafrost environment. Its formation is responsible for characteristic features such as ice-wedge polygons, earth hummocks, pingos, palsas, and lithalsas. The melt of ground ice as permafrost thaws can trigger a suite of thermokarst processes including surface subsidence, thaw lake development, hillslope failure, and thermo-erosional gullying. Thaw of ice-rich permafrost can damage infrastructure, contribute to the mobilization of previously-frozen carbon, and alter the hydrologic regime.

Ground ice occurs in various forms in excess of the pore space of the soil. The maps in the right panel depict three common types: (1) relict ice, which may occur as large bodies of preserved glacial ice, (2) segregated ice, which may form an ice-rich zone of ice lenses, layers, and veins near the top of permafrost, and (3) wedge ice, which are downwards-tapering bodies of nearly pure ice that accumulate in near-surface permafrost. Here, relict ice is indicative of glacier ice preserved in permafrost within glacial sediments. Segregated ice forms in permafrost following the migration of unfrozen water toward frozen ground. Wedge ice accumulates over many years due to repeated cracking of the ground in winter and the infiltration and refreezing of meltwater in permafrost in spring.

The central map shows the estimated total excess ice volume in the upper metres of permafrost from relict, segregated, and wedge ice, based on modelling by O'Neill et al. (2019)¹ (see maps in right panel). The estimates of excess ice content are informed by published observations for different surficial geology and permafrost conditions, and expert knowledge.

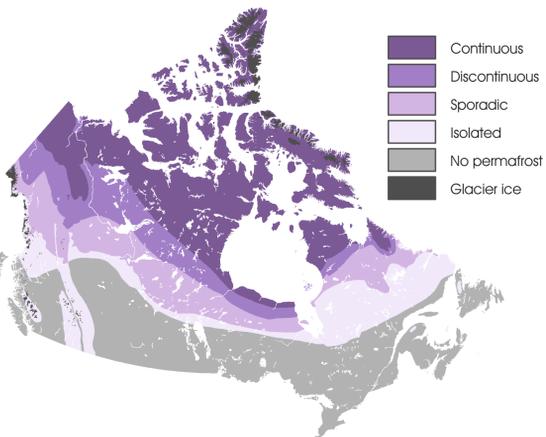
The distribution and abundance of modelled ground ice reflects the post-glacial environmental and climatic history, soil texture, and the time since terrain exposure following deglaciation. Relict ice reflects the distribution of thick glacial sediments that have remained in cold tundra environments since deglaciation. Segregated ice is widespread in Canada in areas with fine-grained, frost-susceptible soils that favour ice segregation. The highest modelled abundance occurs in areas of fine-grained lacustrine and marine sediments. Wedge ice occurs in highest abundance in fine-grained soils that were terrestrially exposed early in the Holocene and remained within tundra environments, allowing thousands of years for ice accumulation. See O'Neill et al. (2019)¹ for further information on the modelling methodology and limitations.

This map offers an improved depiction of ground ice abundance at the national-scale in Canada, incorporating current knowledge on the associations between geological and environmental conditions and ground ice type and abundance. It provides a foundation for hypothesis testing relating to broad-scale controls on ground ice formation, preservation, and melt. Additional quantitative field data on ground ice will allow further assessment and refinement of the mapping. Continued research will focus on improving the lateral and vertical representation of ground ice required for incorporation into Earth system models and decision-making.

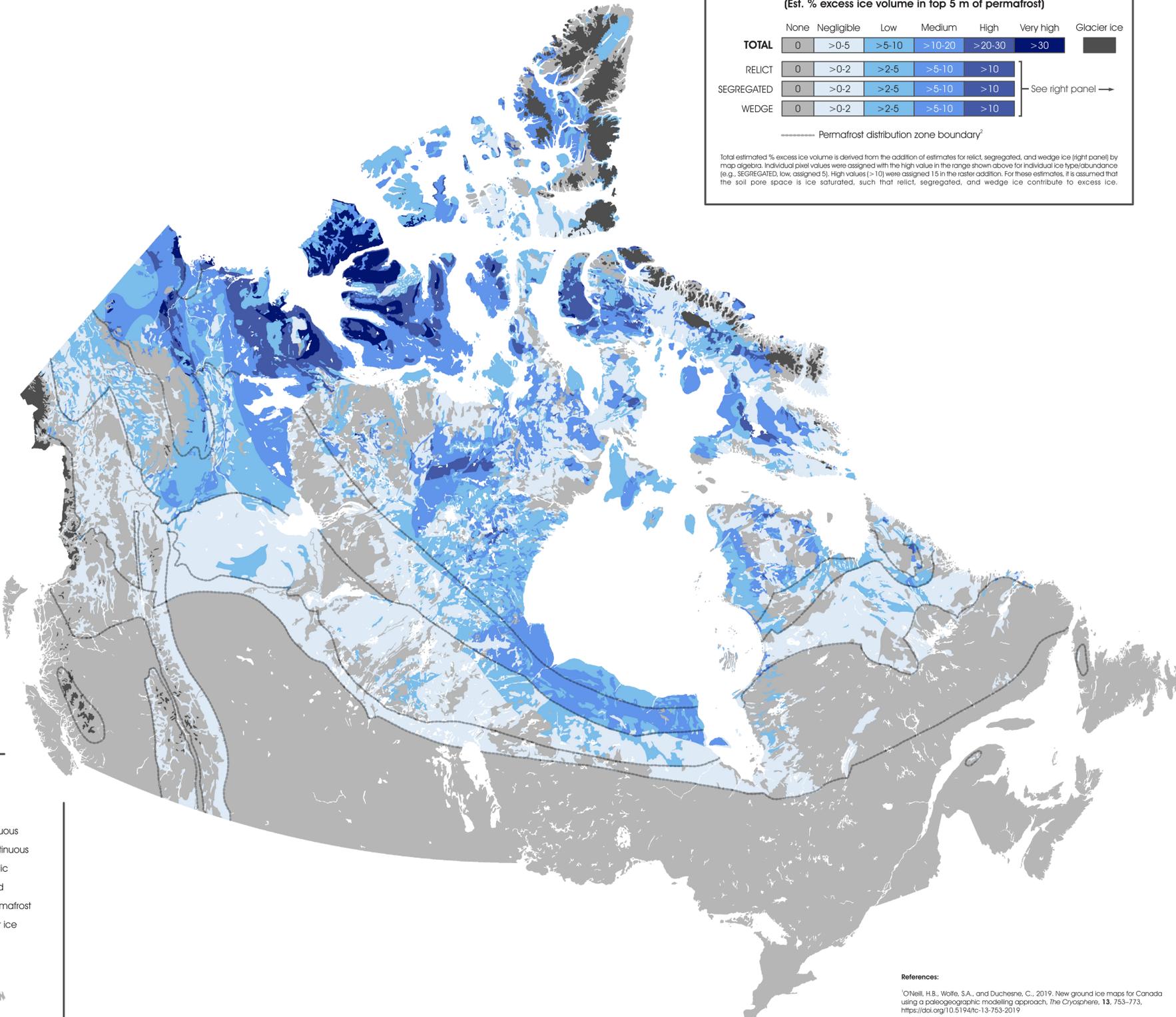
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PERMAFROST DISTRIBUTION²



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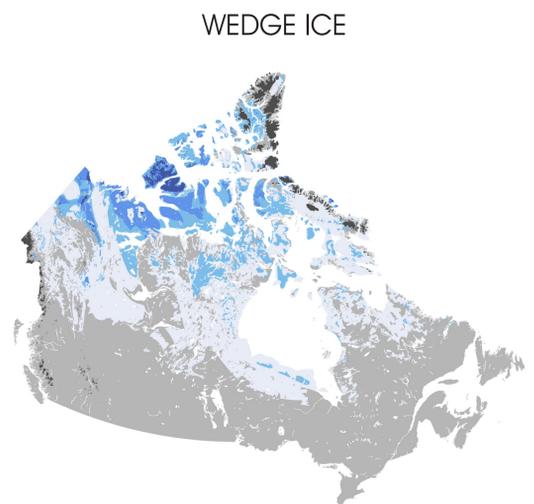
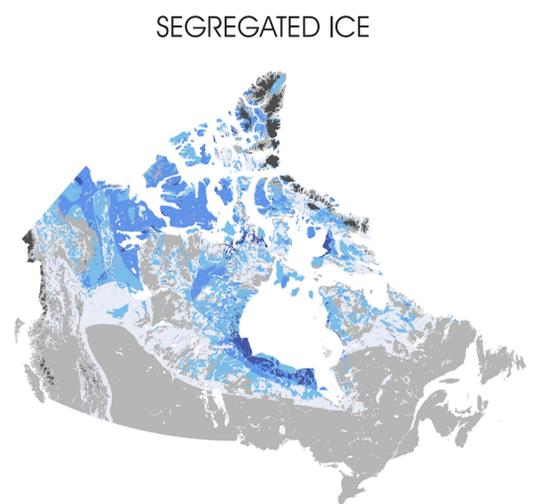
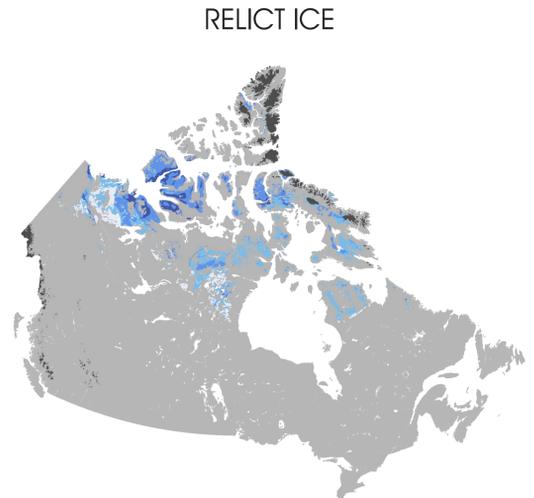


Ground ice abundance
(Est. % excess ice volume in top 5 m of permafrost)

	None	Negligible	Low	Medium	High	Very high	Glacier ice
TOTAL	0	>0-5	>5-10	>10-20	>20-30	>30	
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		

----- Permafrost distribution zone boundary²

Total estimated % excess ice volume is derived from the addition of estimates for relict, segregated, and wedge ice (right panel) by map algebra. Individual pixel values were assigned with the high value in the range shown above for individual ice type/abundance (e.g., SEGREGATED, low, assigned 5). High values (>10) were assigned 15 in the raster addition. For these estimates, it is assumed that the soil pore space is ice saturated, such that relict, segregated, and wedge ice contribute to excess ice.



References:
O'Neill, H.B., Wolfe, S.A., and Duchesne, C., 2019. New ground ice maps for Canada using a paleogeographic modelling approach. *The Cryosphere*, **13**, 753-773. <https://doi.org/10.5194/TC-13-753-2019>

²Hegnbjorn, J.A., Dubreuil, M.-A., and Harker, P., 1995. Permafrost - Canada. National Atlas of Canada MCR 4177. Scale 1:7,500,000. Department of Energy, Mines and Resources Canada. <https://doi.org/10.4095/294672>

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