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MODELLING GROUND ICE IN PERMAFROST USING A PALEOGEOGRAPHIC APPROACH

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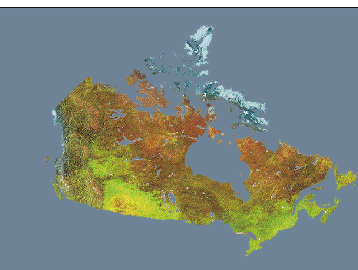

INTRODUCTION

Ground ice melt caused by permafrost degradation may trigger significant ecological change, damage infrastructure, and alter biogeochemical cycles. The fundamental ground ice mapping for Canada is now >20 years old, and does not include insights gained from recent field and remote sensing based studies. New modelling incorporating paleogeography is presented here to depict the distribution of three ground ice types (relict ice, segregated ice, and wedge ice) in northern Canada. The outputs are compared to the previous ground ice mapping.

DATA and METHODS

Ground ice abundance is modelled using a GIS. The expert-system approach is built on principles informed by empirical studies that relate environmental conditions to ground ice formation and preservation. Present-day ground ice abundance for each ice type (relict, segregated, wedge) is calculated using map algebra, accounting for broad-scale Holocene environmental changes over time including deglaciation, glacial lake and marine inundation, and paleovegetation shifts.

A national surficial materials dataset forms the basis of the models (Fig. 1). A time series of deglacial and paleovegetation maps is used to iteratively modify ground ice abundance through 14 time steps from 14 ka BP (17 cal ka BP) to 1 ka BP (Fig. 2). Then, the contemporary permafrost distribution (Fig. 3) is used to modify ice abundance based on the likelihood of permafrost in different surficial material units.

SURFICIAL MATERIALS

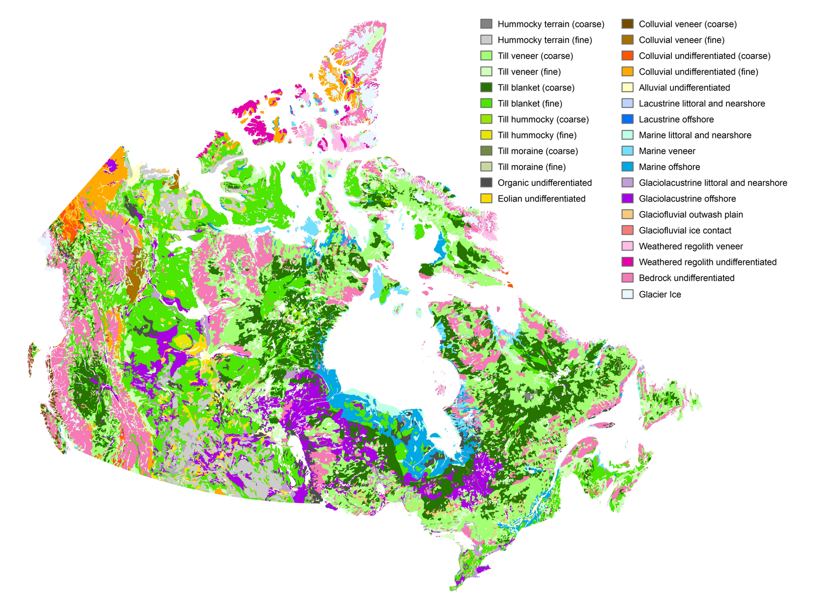

Fig. 1. The surficial materials dataset includes the 1:5,000,000 scale ***Surficial geology of Canada***[1], modified with additional information from the ***Glacial map of Canada***[2] and the bedrock ***Geological map of Canada***[3] to better reflect physical conditions pertinent to ground ice formation.

Relict ice model
The relict ice model represents large bodies of buried glacial or intrasedimental ice preserved in thick till and outwash deposits. Values are modified through the 14 time steps based on changes in biome distributions and marine and glacial lake inundation, representing melt due to large-scale environmental changes. Ice is considered to melt in the modern discontinuous permafrost zone, where recurrent forest fires cause significant increases in active-layer thickness.

Segregated ice model
An initial value is assigned to each surficial material, representing frost susceptibility. The segregated ice values may decline following biome transitions from tundra to boreal forest, reflecting the partial melt of ice during warmer periods.

VEGETATION AND DEGLACIATION

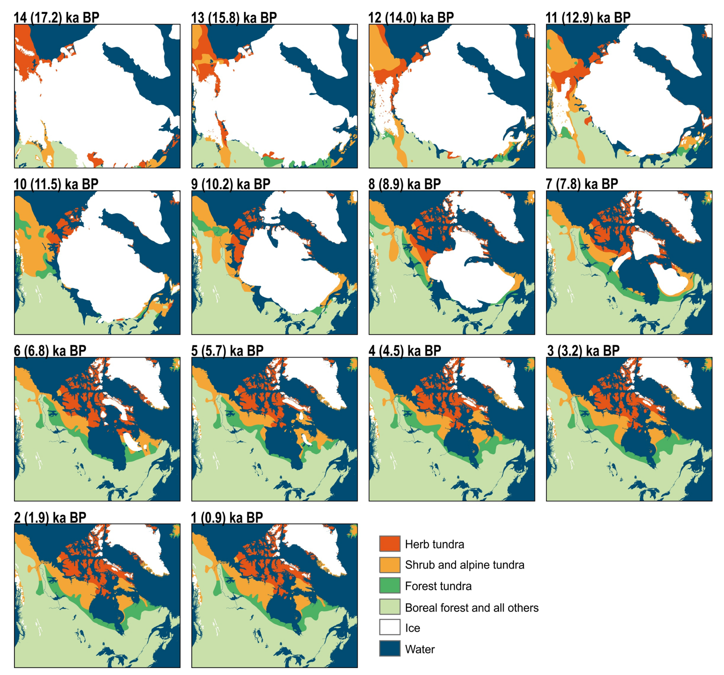

Fig. 2. The simplified ***Paleovegetation maps of northern North America***[4] dataset used to modify ground ice abundance over time. The biome, ice, and lake/marine configurations control, for example, the melt of relict and segregated ice over time, and the timing and rate of wedge ice accumulation. Calibrated ^{14}C ages are in brackets.

PERMAFROST DISTRIBUTION

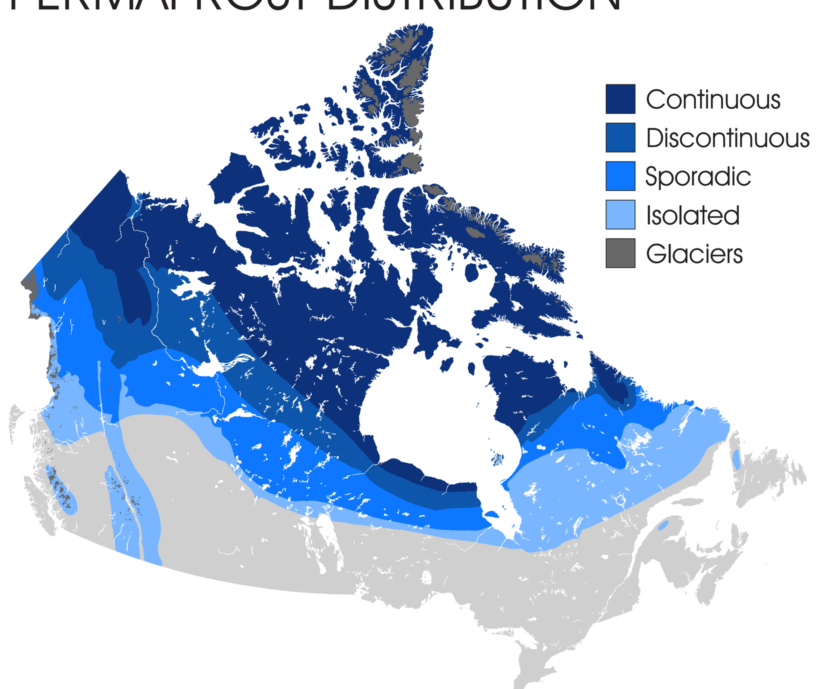

Fig. 2. The contemporary distribution of permafrost from the ***Permafrost map of Canada***[5].

Segregated ice model (cont.)
The values also decrease in discontinuous permafrost zones, representing the decrease in areal extent of permafrost and preferential thaw in coarse-grained material.

Wedge ice model
Wedge ice accumulates over the 14 time steps, beginning when terrain becomes subaerially exposed. The rate of wedge ice growth depends on climatic severity inferred by paleobiome distributions, and surficial material.

RESULTS

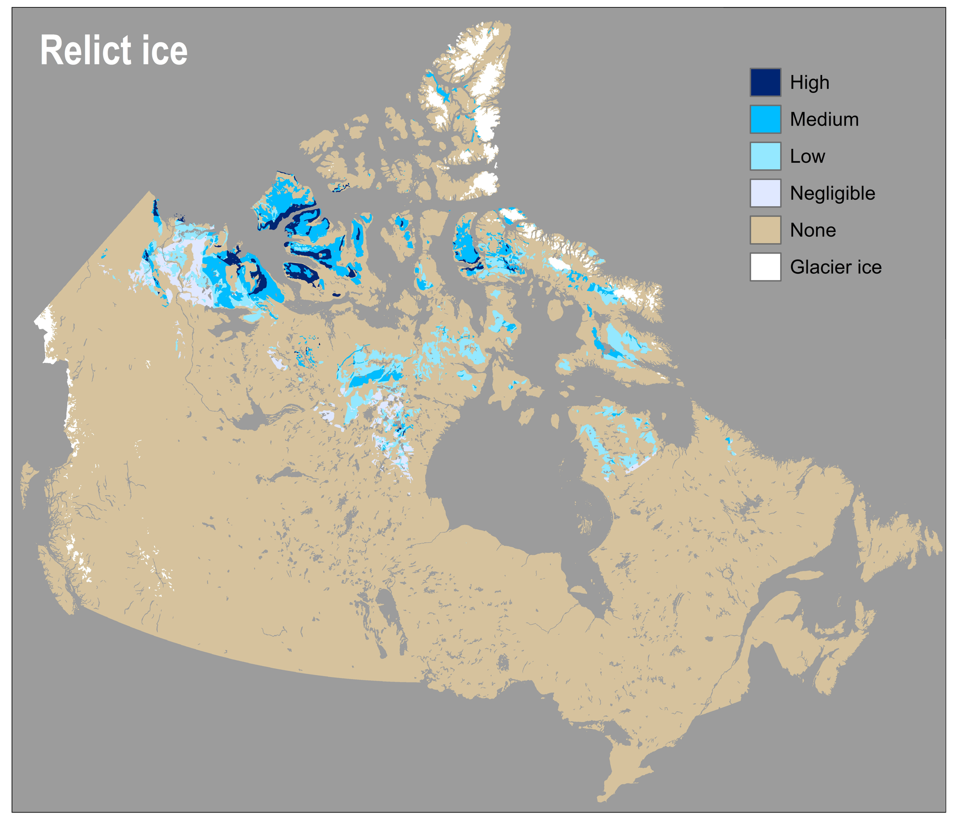

Fig. 4 (left). Modelled relict ice abundance.

RELICT ICE

Modelled relict ice abundance reflects the distribution of thick glacigenic sediments in regions that have remained in herb and shrub tundra since deglaciation, and occur in the modern continuous permafrost zone (Fig. 4). Areas of high abundance constitute about 2% of the continuous permafrost zone in Canada and areas of medium abundance about 9%.

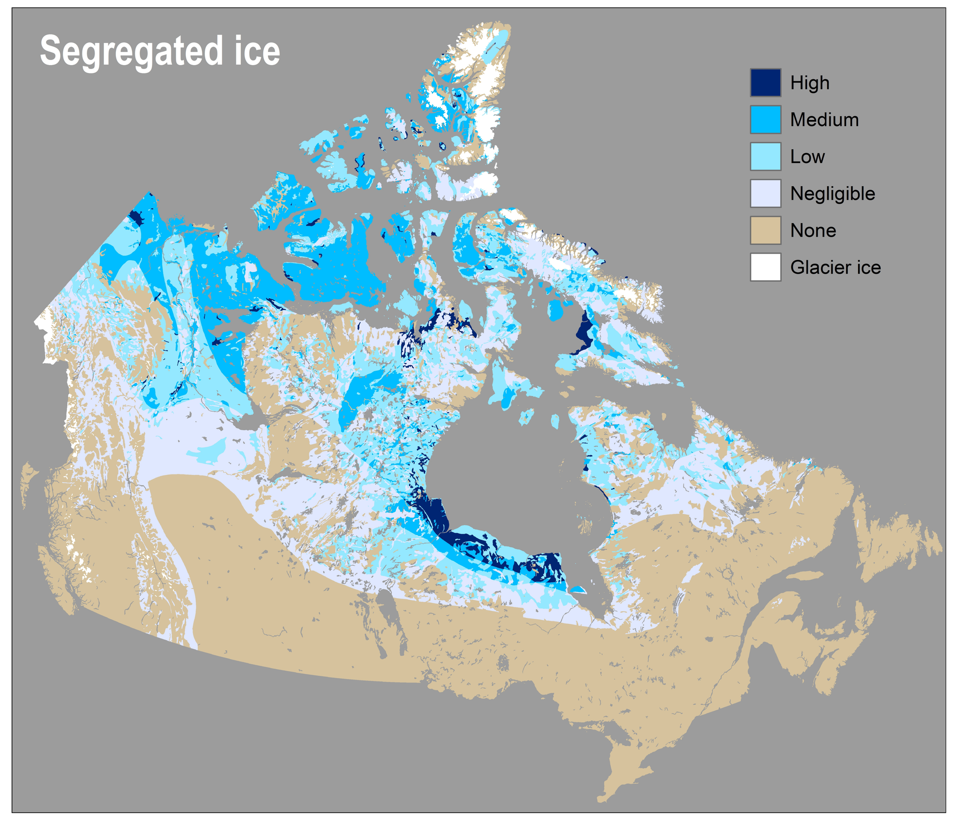

Fig. 5 (left). Modelled segregated ice abundance.

SEGREGATED ICE

Modelled segregated ice is widely distributed due to the ubiquity of frost-susceptible surficial materials. High abundance occurs in areas covered by marine or lacustrine sediments in tundra of the continuous permafrost zone. Areas of high abundance occupy about 3% of the continuous and 4% of the extensive discontinuous permafrost zones. Widespread areas of medium abundance largely reflect the distribution of finer-grained till derived from sedimentary bedrock in northwestern Canada.

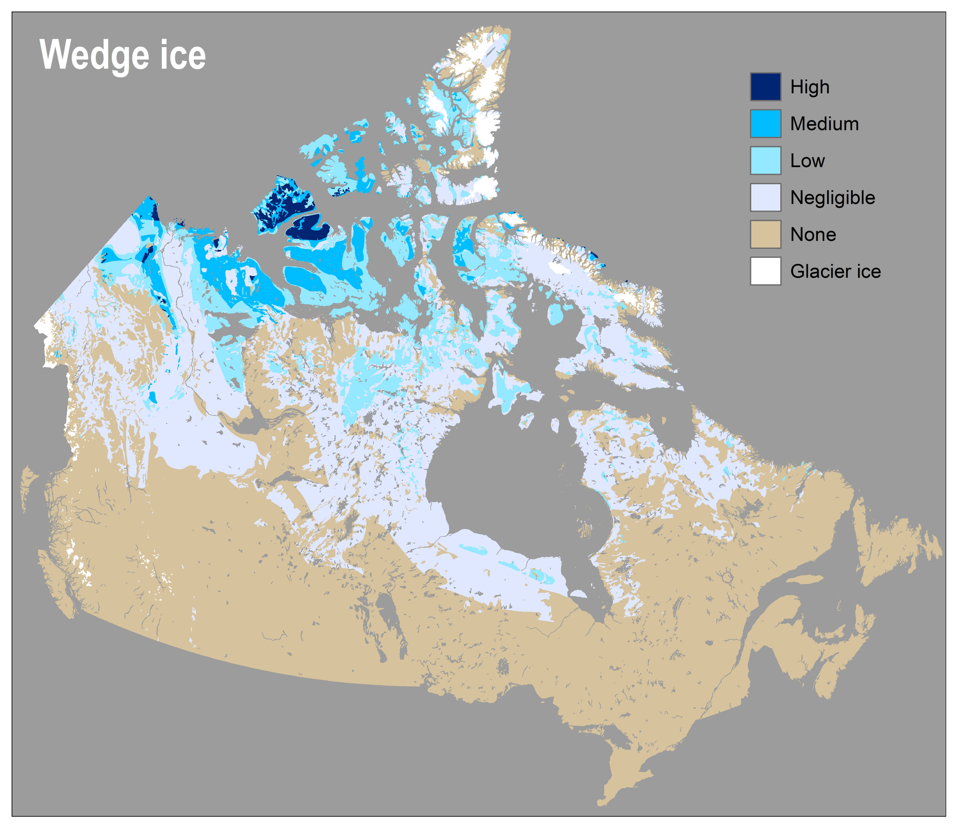

Fig. 6 (left). Modelled wedge ice abundance.

WEDGE ICE

Modelled wedge ice abundance reflects exposure time of sediments to cold climatic conditions. The pattern of deglaciation and Holocene environmental history thus strongly control the distribution. Areas of high and medium wedge ice abundance comprise about 2% and 10% of the modern continuous permafrost zone, respectively.

COMPARISON with PREVIOUS MAPPING

Modelled ground ice abundance is in broad agreement with empirical evidence[6]. Here we present a comparison between the ***Permafrost map of Canada***[5] (PMC) (Figs. 7a-c) and the model outputs. The legends were standardized and raster difference maps were produced to identify areas of differing relative ice abundance (Figs. 7d-f). "Massive ice" on the PMC is analogous to our "relict ice", and the latter term is used for both in the comparison.

RELICT ICE

The model output better reflects current knowledge of relict ice than the PMC. The PMC indicates high abundance over much of the Canadian Arctic Archipelago (CAA), whereas the model indicates none in areas that are covered by regolith or colluvium, and were partially or fully inundated during deglaciation (Fig. 7d). In the northern Mackenzie Valley region, the abundance is higher on the PMC than the model output, where it is reduced following Holocene tree line advance. In the Peel Plateau region, modelled abundance is high and medium where widespread relict ice exposures occur[7], whereas the PMC indicates that ice is absent or sparse.

SEGREGATED ICE

Segregated ice distribution is broadly similar on the PMC and model output, with relatively high abundance in the western Arctic mainland and islands. However, key differences are evident (Fig. 7e). Ice content is low-medium in Hudson Bay Lowlands on the PMC, but the model indicates high abundance in the region, which includes many peat plateaus and palsas[8]. The PMC indicates a higher abundance of segregated ice than the model on many eastern and high Arctic islands in areas covered by weathered regolith and bedrock, which likely contain little or no excess ice.

WEDGE ICE

Broad patterns are similar on the model output and PMC, with areas of high abundance mainly in the western Arctic. However, the PMC indicates more wedge ice on many islands of the central and northern CAA (Fig. 7f). The modelled abundance is generally low because the substrate is dominantly weathered bedrock, which does not favour large ice wedge development. In the northern Mackenzie Valley and Mackenzie Delta regions, modelled wedge ice abundance is lower than indicated on the PMC due to the modelled decrease across the tundra-forest transition (Fig. 6). This pattern reproduces field observations from the region[9].

[1]Geological Survey of Canada. 2014. Canadian Geoscience Map 195, https://doi.org/10.4095/295462
[2]Prest et al. 1968. "A" Series Map 1253A, https://doi.org/10.4095/108979
[3]Wheeler et al. 1996. "A" Series Map 1860A, https://doi.org/10.4095/208175
[4]Dyke et al. 2004. Open File 4682, https://doi.org/10.4095/215634
[5]Heginbottom et al. 1995. National Atlas of Canada MCR 4177, https://doi.org/10.4095/205314
[6]O'Neill et al. 2018. The Cryosphere, https://www.the-cryosphere.net/13/753/2019/
[7]Lacelle et al. 2015. Geomorphology, 235, https://doi.org/10.1016/j.geomorph.2015.01.024
[8]Payette, S. 2004. Geophys. Res. Lett., 31(18), https://doi.org/10.1029/2004GL020358. 2004.
[9]Kokelj et al. 2014. J. Geophys. Res. Earth Surf., 119(9), https://doi.org/10.1002/2014JF003085

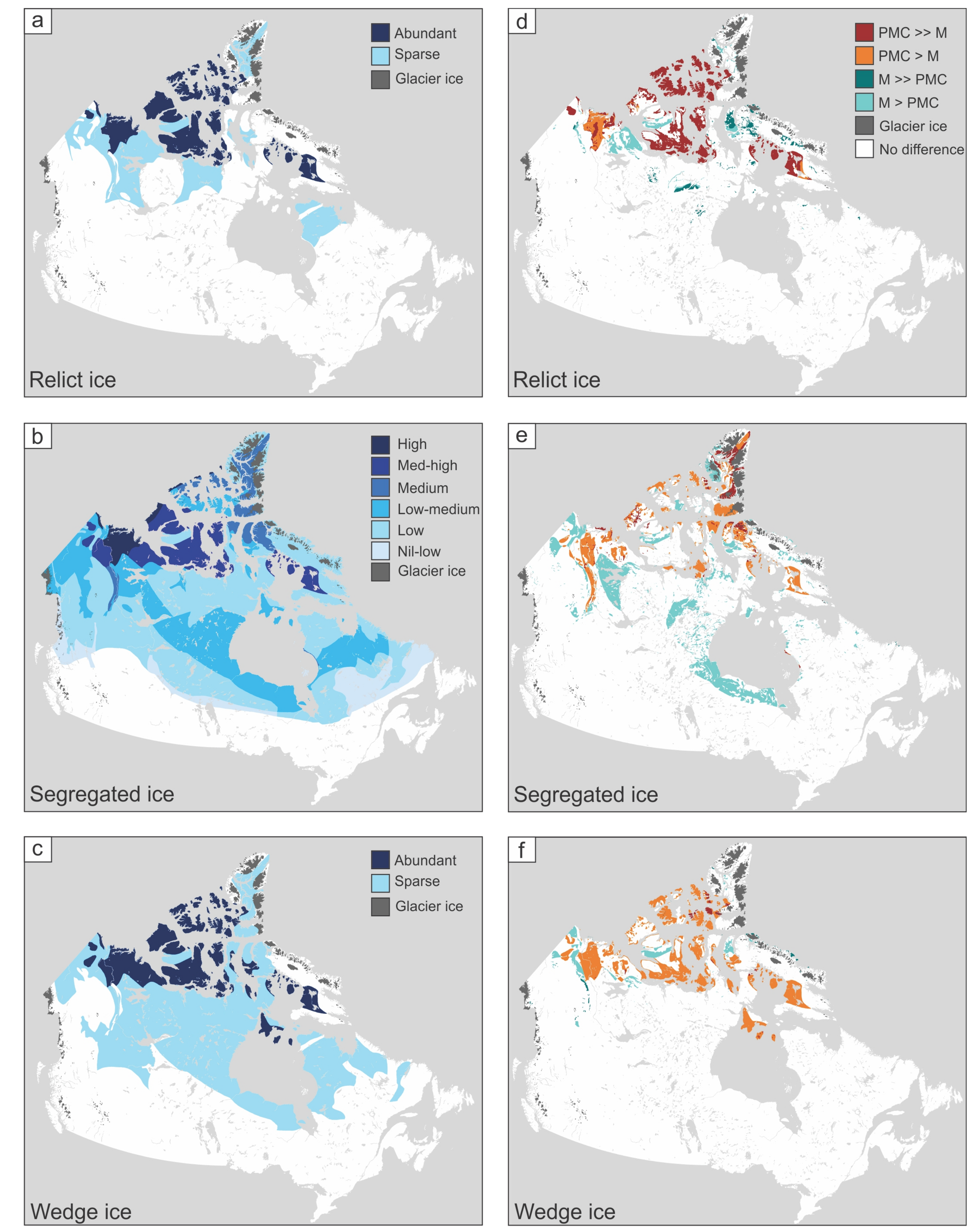

Fig. 7. The ***Permafrost map of Canada***[5] (PMC) depictions of (a) massive (relict) ice, (b) segregated and intrusive ice, and (c) wedge ice; and comparisons (d-f) between the PMC and the models (M). PMC >> M indicates, for example, that the reclassified relative ground ice abundance on the PMC is 'high' and the modelled abundance is 'none'. M > PMC indicates the reclassified ground ice abundance is 'high' on the model output and 'low' on the PMC.

IMPLICATIONS

The results improve ground ice mapping for Canada. The modelling is of practical relevance given recent circumpolar landscape changes that have been observed due to ground ice melt. The model outputs offer better spatial detail and accuracy in many areas compared to the previous depiction, and this has implications for models that have used the ground ice information as input parameters.

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