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GROUND ICE DEGRADATION AND THERMOKARST TERRAIN FORMATION IN CANADA IN THE PAST 16 000 YEARS

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Overview

We compiled a geodatabase of thermokarst processes and features from across Canada identified in a literature review (Figure 1), and then assessed their distribution in the context of a suite of biophysical and geological variables relevant to permafrost. These included permafrost distribution[1], present-day biome[2], general thermokarst terrain type[3], surficial materials[4], and associated ground ice type and abundance[4]. Outputs from the Ground ice map of Canada[5] were used to infer qualitative levels of ground ice degradation in the past 16k years (Figure 2). Summaries of preliminary associations between these variables and the mapped processes/features are shown in Table 1. The database currently includes 440 entries of 13 processes/features gathered from 140 references.

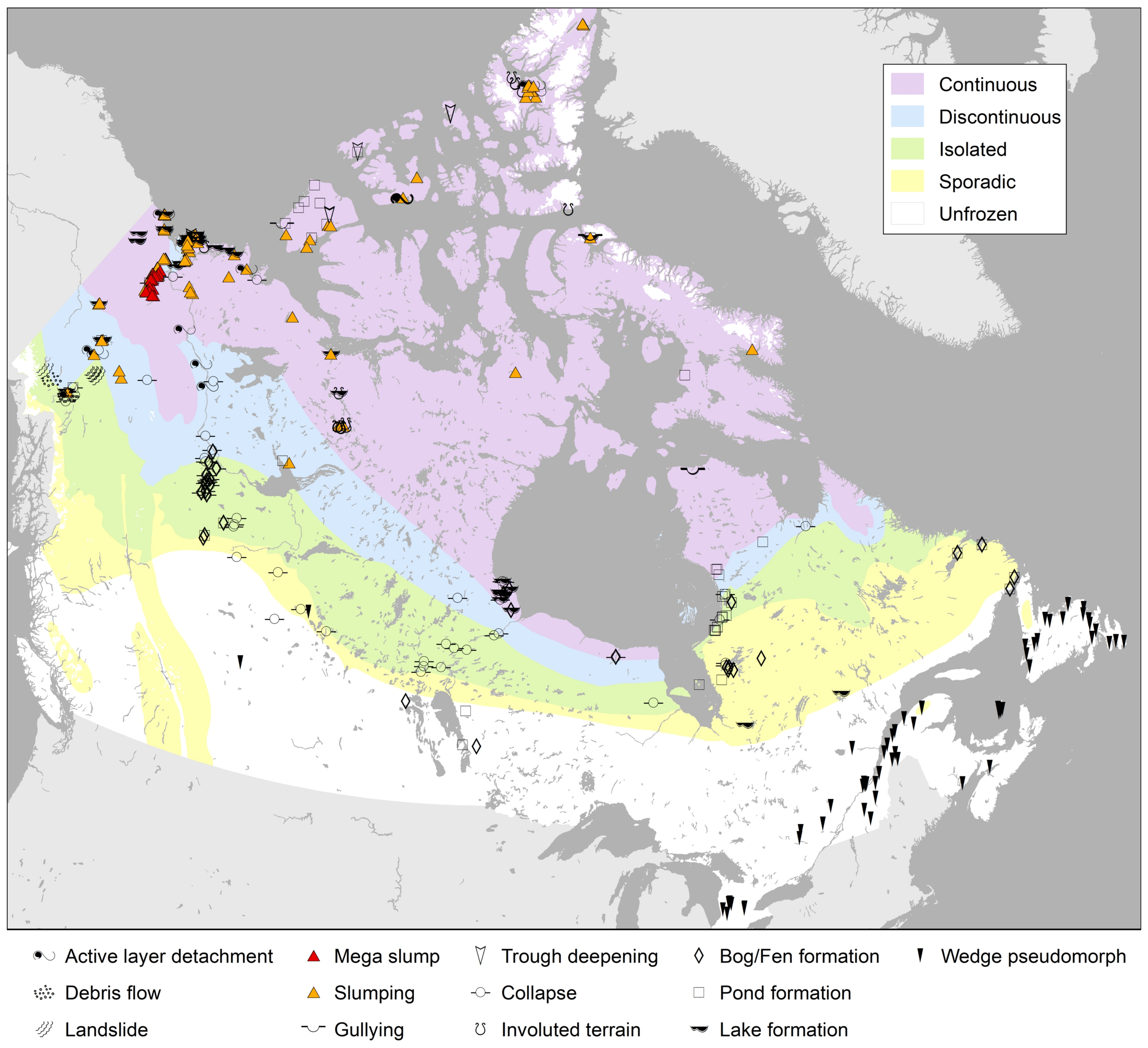


Figure 1. Thermokarst processes and features identified in literature review. Permafrost zones from Hegginbottom et al. 1995.

Summary of database & relations

Table 1. Summary of database entries presenting relations between thermokarst processes / features, permafrost, terrain, excess ground ice conditions, and inferred degree of Holocene ground ice degradation. **Bold face** indicates dominant relations, and *italics* indicate secondary relations.

Thermokarst process/ feature	**Permafrost zone(s)** (Heginbottom et al. 1995)	**Modern Biome(s)** (Dyke et al. 2003)	**Thermokarst terrain type(s)** (Olefeldt et al. 2016)	**Surficial material(s)** (O'Neill et al. 2019)	**Ice type association(s)** (O'Neill et al. 2019 & Fig. 2)	**Holocene ground ice degradation estimate(s)** (Fig. 2)
1 - Trough deepening (n=7)	**Continuous**	**Herb tundra** *Shrub tundra*	**Hillslope** *Lake-Wetland-Hillslope*	**Hummocky till (f)** **Till blanket (f)** **Weathered regolith veneer**	**Segregated-Wedge** *Relict-Wedge-Segregated*	**Mostly undegraded**
2 - Gullying (n=11)	**Continuous**	**Herb tundra** *Shrub tundra*	**Lake-Wetland-Hillslope** *Hillslope-Wetland*	**Till blanket (f)** **Bedrock**	**Relict-Segregated-Wedge**	**Mostly undegraded**
3 - Involuted terrain (n=14)	**Continuous**	**Shrub tundra** *Herb tundra*	**Hillslope** *Wetland-Hillslope*	**Till veneer (f)** *Glaciofluvial outwash pln*	**Segregated-Wedge** *Relict-Wedge*	**Mostly undegraded** *Partially degraded*
4 - Mega slumping (n=15)	**Continuous**	**Shrub tundra**	**Hillslope-Wetland** *Hillslope*	**Hummocky till (f)** *Till blanket (f)*	***Relict-Segregated-Wedge***	**Partially degraded** *Mostly undegraded*
5 - Slump (n=99)	**Continuous** *Discontinuous*	**Shrub tundra** *Boreal forest* *Herb tundra*	**Hillslope** *Lake-Wetland-Hillslope* *Hillslope-Wetland* *Hillslope-Lake-Wetland*	**Hummocky till (f)** **Till blanket (f)** *Till veneer (f)* *Glaciolacustrine offshore* *Marine offshore* *Glaciofluvial*	**Relict-Segregated-Wedge** **Segregated-Wedge** *Relict-Wedge-Segregated* *Wedge-Relict-Segregated*	**Mostly undegraded** *Partially degraded*
6 - Active-layer detachment (n=28)	**Continuous** *Discontinuous*	**Herb tundra** *Boreal forest* *Shrub tundra*	**Hillslope**	**Weathered regolith undiff** ***Colluvial undiff*** ***Glaciolacustrine offshore***	**Segregated-Wedge**	**Mostly undegraded**
7 - Lake formation (n=67)	**Continuous** *Discontinuous*	**Shrub tundra** *Boreal forest* *Forest tundra*	**Lake-Wetland-Hillslope** *Wetland-Lake* *Lake-Hillslope-Wetland*	**Hummocky till** *Marine offshore* *Glaciolacustrine offshore* *Alluvial undiff*	**Relict-Segregated-Wedge** *Segregated-Wedge* *Relict-Wedge-Segregated* *Relict-Wedge* *Wedge-Relict-Segregated*	**Mostly undegraded** **Partially degraded** *Mostly degraded*
8 - Pond formation (n=46)	**Sporadic** *Continuous*	**Forest tundra** *Shrub tundra* *Herb tundra*	**Wetland** *Lake-Hillslope-Wetland*	**Bedrock undiff** *Marine nearshore* *Till blanket (f)* *Till blanket (c)* *Marine offshore* *Weathered regolith undiff*	**Segregated-Wedge** *Relict-Segregated-Wedge* *Segregated* *Segregated-Relict-Wedge* *Relict-Wedge-Segregated*	**Mostly undegraded** **Partially degraded** *Mostly degraded*
9 - Collapse (Palsa-peatland and Lithalsa) (n=51)	**Sporadic** *Discontinuous* *Continuous* *Isolated*	**Boreal forest** *Forest tundra* *Shrub tundra*	**Wetland** *Wetland-Lake*	**Till blanket (f)** *Glaciolacustrine offshore* *Marine offshore* *Bedrock undiff*	**Segregated-Wedge** *Segregated* *Relict-Segregated-Wedge*	**Mostly degraded** **Partially degraded** *Mostly undegraded*
10 - Bog/Fen formation (n=32)	**Sporadic** *Isolated* *Continuous*	**Boreal forest** *Forest tundra*	**Wetland-Lake** *Wetland*	**Till blanket (f)** *Bedrock undiff* *Marine offshore*	**Segregated-Wedge** *Relict-Segregated-Wedge* *Segregated* *Segregated-Relict-Wedge* *Wedge-Relict-Segregated*	**Mostly degraded** *Completely degraded*
11 - Permafrost landslide (n=4)	**Sporadic**	**Boreal forest**	-------	**Till blanket (f)** **Till veneer (f)** **Till veneer (c)**	**Segregated-Wedge** *Relict-Segregated-Wedge*	*Mostly degraded* *Partially degraded* *Completely degraded*
12 - Frozen debris flow (n=4)	**Sporadic** *Discontinuous*	**Boreal forest**	--------	**Till veneer (f)** *Till blanket (f)* *Till blanket (c)*	**Segregated-Wedge** *Relict-Segregated-Wedge*	*Mostly degraded* *Partially degraded*
13 - Wedge pseudomorph (n=62)	**Unfrozen** *Mountain*	**Mixed forest** **Boreal forest**	**Not applicable**	**Till veneer (f)** *Till veneer (c)* *Marine offshore* *Till blanket (f)* *Glaciolacustrine offshore*	**Segregated-Wedge** *Segregated* *Relict-Segregated-Wedge* *Segregated-Relict-Wedge* *Relict-Wedge*	**Completely degraded**

Holocene ground ice degradation

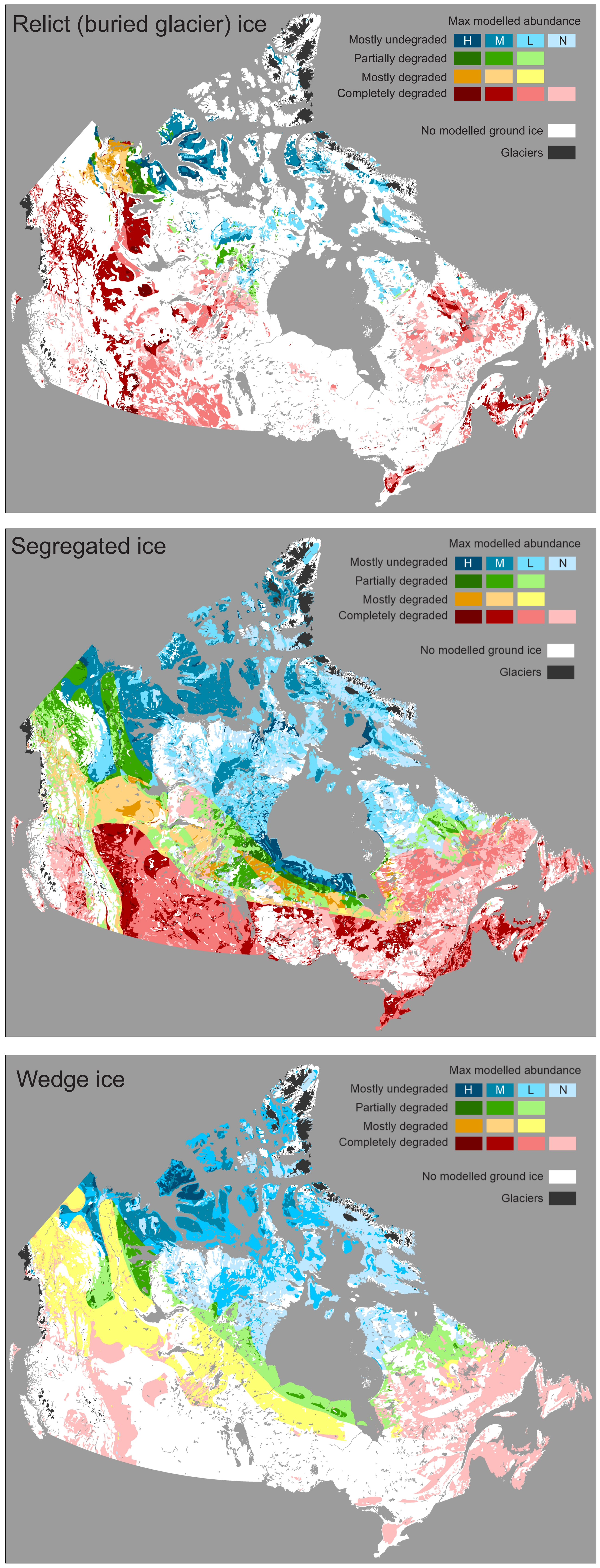
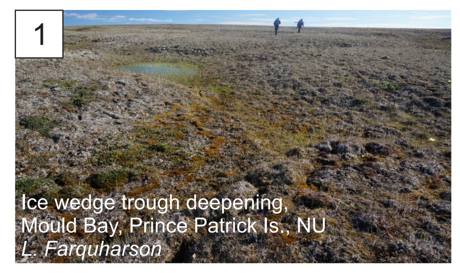
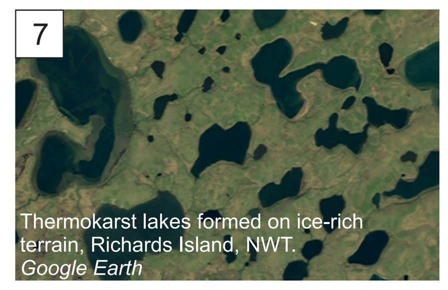
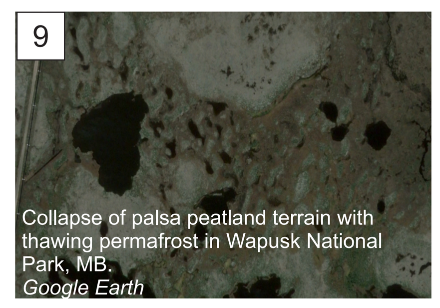


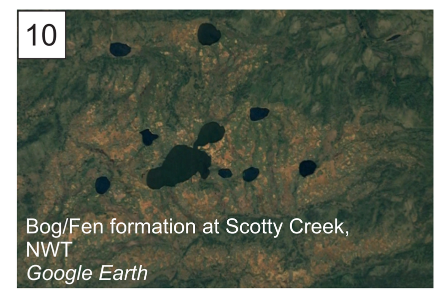
Figure 2. Broad-scale assessment of the degree of Holocene ground ice degradation inferred by examining modelled[4] excess ground ice conditions over the past 16k years for buried, segregated and wedge ice types (methodology not explained here). Degradation represents difference between modelled maximum and contemporary abundance at any one location. Blue hues indicate areas that have remained in cold climate conditions since deglaciation, where there has likely been little ground ice loss due to climate-biome changes. Red areas indicate where permafrost and ground ice may have existed under past climatic conditions, but where no ground ice is modelled to exist today. Green and orange hues indicate where some degree of degradation is interpreted due to climatic-biome changes. Legend entries H, M, L, and N indicate high, medium, low, and negligible maximum interpreted ground ice abundance in the last 16k years.

Examples of thermokarst processes / features









Discussion and next steps

Distinctive thermokarst processes / landforms result due to specific permafrost, surficial geological, ground ice, and environmental conditions. The relative degree of ground ice loss during the Holocene also influences thermokarst processes. Though not exhaustive in nature, the database associations highlight, for example, how ice wedge trough deepening, trough gullying, and mega slumping are associated with tundra of the continuous permafrost zone where ground ice has formed and/or been largely preserved in relatively high abundance during the Holocene. The potential for past thermal contraction cracking and ice wedge development is predicted in southern Canada (Fig. 2), and numerous observations of ground wedge pseudomorphs occur in these regions (Fig 1). Further population of the database and statistical analyses of relations will assist in understanding the suite of present-day processes and in predicting future thermokarst landscape evolution with a changing climate.

References
[1]Heginbottom et al. 1995. https://doi.org/10.4095/294672
[2]Dyke et al. 2003. https://doi.org/10.4095/215634
[3]Olefeldt et al. 2016. 10.1038/ncomms13043
[4]O'Neill et al. 2019. doi.org/10.5194/tc-13-753-2019
[5]O'Neill et al. 2020. https://doi.org/10.4095/326885

Geological Survey of Canada (no image)

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