



Thermokarst domains of Canada

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Abstract. Thermokarst refers to landforms and processes resulting from the thaw of ice-rich permafrost. Thermokarst landforms vary with ground ice, substrate, and terrain conditions, which are products of geological and climatic history. Recognizing how thermokarst manifests across vast permafrost regions provides insights into the consequences of permafrost thaw, including sediment fluxes, carbon cycling, and ecosystem changes. Here, we present a conceptual model summarizing associations between thermokarst landforms and permafrost terrain conditions, based on a compilation and analysis of 19,549 landform observations from published literature. We recognize several broad thermokarst domains in Canada, based on permafrost and ground ice distribution and past climate, further modified by organic terrain conditions, which control landform types and their general distribution. These domains broadly group the distribution of thermokarst landforms observed today and suggest the range of thermokarst trajectories expected with future climate warming. The conceptual model supports the narrative expressed in the production of the Ground Ice Map of Canada and the permafrost landsystems framework, i.e., that geological and paleoenvironmental histories, including impacts of past thaw, influence the nature and variation in ground ice and thermokarst across permafrost regions.



1 Introduction

Thermokarst landforms result from the melting of ground ice as permafrost thaws, leading to terrain subsidence, slumping, and other indicative features (Kokelj and Jorgenson, 2013; O'Neill et al., 2023; Young et al., 2025). Thermokarst occurs across all permafrost zones, and climate change is increasing the frequency and distribution of thermokarst initiation (Fraser et al., 2018; Kokelj et al., 2017; Lewkowicz and Way, 2019; Rudy et al., 2017). An estimated 20% of northern permafrost landscapes could presently be affected by thermokarst (Olefelt et al., 2016). Thermokarst can impact aquatic and terrestrial ecosystems (Chin et al., 2016), damage infrastructure (Nelson et al., 2001), and influence carbon release from organic soils sequestered in permafrost terrain (Gibson et al., 2021; Littlefair and Tank, 2018).

The diverse terrain expression of ice-rich permafrost thaw varies with permafrost distribution, ground ice content, surficial materials, topography, and historical environmental conditions (Kokelj et al., 2026). For example, the deepening of ice wedge troughs (Farquharson et al., 2019; Burn et al., 2021) and thermo-erosional gullying of ice wedges (Fortier et al., 2007) is increasingly observed in cold, continuous permafrost Arctic uplands and wetlands, where wedge ice has accumulated over millennia near the base of the contemporary active layer (Fraser et al., 2018). Melting of relict (glacial) ice has triggered extensive thaw slumping on hillslopes in other areas of continuous permafrost near past glacial limits (Kokelj et al., 2017). Slumping of such ice-cored terrain has recently increased on hillslopes in the Canadian Arctic Archipelago (e.g., Lewkowicz and Way, 2019) and throughout the forest-tundra transition in the Beaufort Delta region (Kokelj et al., 2021). Near the southern limit of continuous permafrost, expansion and drainage of thermokarst lakes are observed in the Old Crow Flats, Yukon Territory (Lantz and Turner, 2015; MacDonald et al., 2021; Roy-Leveillee and Burn, 2017). In the discontinuous permafrost zone, collapse of polygonal peatlands, peat plateaus, palsas, and lithalsas is evident and associated with expanding thermokarst ponds and wetlands (Calmels et al., 2008; Carpino et al., 2018; Gibson et al., 2021; Kirkwood et al., 2021; Mamet et al., 2017; Sannel and Kuhry, 2011; Wang et al., 2024). Melting of segregated ground ice underlying peatlands in areas of sporadic permafrost has also increased the extent of ponds and wetlands (Payette et al., 2004). In areas with isolated patches of permafrost, treeless “internal lawns” have formed, where permafrost thaw resulting in ground surface settlement has caused wetland water tables to rise (Beilman and Robinson, 2003). Collectively, these examples illustrate the diversity of thermokarst processes and landforms reflecting variation in permafrost properties and thaw trajectories (Kokelj et al., 2026).

Three categories of thermokarst terrain types are recognized: 1) hillslope, 2) lake, and 3) wetland – the latter commonly associated with peatlands (e.g., Kokelj and Jorgenson, 2013; Olefeldt et al., 2016). Thermokarst



60 landforms within these terrain types are a product of variation in ground ice conditions, physiography, and
 ecosystem conditions, which are shaped by geologic and climatic legacies (Kokelj et al., 2026; O'Neill et al.,
 2019). Despite significant documentation of thermokarst landforms in permafrost regions, no comprehensive
 synthesis of their distribution and associations with terrain conditions exists in Canada, though initiatives to fill
 this gap are underway (e.g., Kokelj et al., 2023). This highlights the need for a robust review of thermokarst
 65 landform observations across these terrain types and permafrost zones to improve understanding of how
 landscapes may be modified by permafrost thaw and to identify areas lacking observations. As such, the
 objectives of this paper are 1) to compile observations of thermokarst landforms in Canada and analyze their
 associations with broad-scale terrain and ground ice conditions, 2) to advance a conceptual model that
 summarizes these associations and groups the distributions of landforms in Canada into “*thermokarst domains*”,
 70 distinguished by characteristic permafrost, terrain, and ground ice conditions, and 3) to synthesize the thermokarst
 landform assemblages and ground ice conditions that characterize each domain. This analysis builds on the
 concepts that periglacial and thermokarst landform assemblages combine to form *permafrost landsystems* that
 reflect variation in geological and climate legacy at regional scales (Kokelj et al., 2026).

75 2 Methods

2.1 Literature review and database compilation

Observations from 154 references were compiled to assess the type and distribution of thermokarst landforms
 across Canada. Publications spanned from 1961 to 2024 and included peer-reviewed journal articles, conference
 proceedings, and government reports. Search engines were used to identify authors, institutions, locations, and
 80 thermokarst landforms and processes, and references within articles were reviewed to create a comprehensive
 reference database for Canada. The database includes publications with field-documented thermokarst landforms
 and available inventories of point features produced from remote sensing analyses (e.g., Lewkowicz and Way,
 2019; Segal et al., 2016). The database is available as Geological Survey of Canada Open File 9296 (Wolfe et al.,
 2025). To this, we have added remote-sensing observations from Morse and Rudy (2022) that were omitted in the
 85 earlier database. The complete dataset is available in the supplementary spreadsheets.

Landforms that are well-defined in the literature as clear indicators of thermokarst were considered in this review
 (Fig. 1). These landforms represent a broad suite of thaw-driven terrain impacts that vary with substrate, ground
 ice, and ecological conditions and that reflect the diversity of geological and paleoclimate conditions across broad
 90 spatial scales (Canada) (Kokelj et al., 2026). The identification of thermokarst processes (e.g., peat plateau



collapse) and landforms (e.g., retrogressive thaw slumps) is prevalent in the literature (e.g., Lewkowicz et al., 2025). For consistency, we present observations as the associated landforms (Fig. 1). Although thaw subsidence is the fundamental thermokarst process, it was not included in the analysis on its own, as it is nearly ubiquitous across all permafrost zones with ground ice but is not a distinguishing landform (O'Neill et al., 2023; Streletskiy et al., 2025). It is also acknowledged that processes, such as peat plateau collapse, may be an umbrella term resulting in several landforms, including collapse ponds, collapse scars, and the transition of peat plateaus from permafrost bogs to fens. These landform observations were considered separately based on the reporting in the literature sources and their spatial distribution. This differentiation is useful, as collapse scars are commonly associated with peat plateaus (Lewkowicz et al., 2025), whereas collapse ponds occur in both mineralogic and organic terrain in association with degrading lithalsas (Wolfe et al., 2014), and peat plateaus or palsas (Payette et al., 2004). Wedge pseudomorphs, which represent former ice and sand wedges, are also included in the database (62 observations) but are not considered in this review.

2.2 Thermokarst and terrain associations

Thermokarst observations (n = 19,549) were compiled in a geodatabase, and the landform type, latitude, and longitude, as well as publication references, were recorded for each point (Wolfe et al., 2025). Observations include 15,999 from the database of Wolfe et al. (2025), supplemented by an additional 3,550 observations of collapse ponds (i.e., degraded lithalsas with collapse ponds) and thermokarst lakes from Morse and Rudy (2022). Terrain and ground ice conditions were extracted at each point from ancillary geospatial datasets using a geographic information system (ArcGIS Pro version 3.6) for all observations. Ancillary data sources included permafrost distribution (Heginbottom et al., 1995), surficial materials (Fulton, 1995), bedrock geology (Wheeler et al., 1996), biomes (Dyke et al., 2004), and peat cover (Tarnocai et al., 2011), as these factors control the type and abundance of ground ice present (O'Neill et al., 2019) and the resulting nature of thermokarst landforms. The geospatial dataset of Olefeldt et al. (2016) was used to associate thermokarst landforms with areas modelled to indicate potential for hillslope, lake, and wetland thermokarst terrain. Broad-scale modelled ground ice type and relative abundance (O'Neill et al., 2022) were extracted for each thermokarst point location, and a derived estimate of Holocene ground ice loss was determined as a product of the model. Thermokarst landforms relate both to the present-day abundance of ground ice and the extent and type of ground ice that has been accumulated or lost in the past. The qualitative Holocene ground ice loss variable was derived based on outputs from the Ground Ice map of Canada models (O'Neill et al., 2022). The models predict ground ice accumulation and melt through time at approximately 1000-year intervals based on mapped biome shifts (O'Neill et al., 2019). Interpreted maximum Holocene ground ice abundance of each ice type was obtained from intermediate model steps and compared to the modern abundance to obtain a relative indicator of ground ice loss or gain (Table A1).

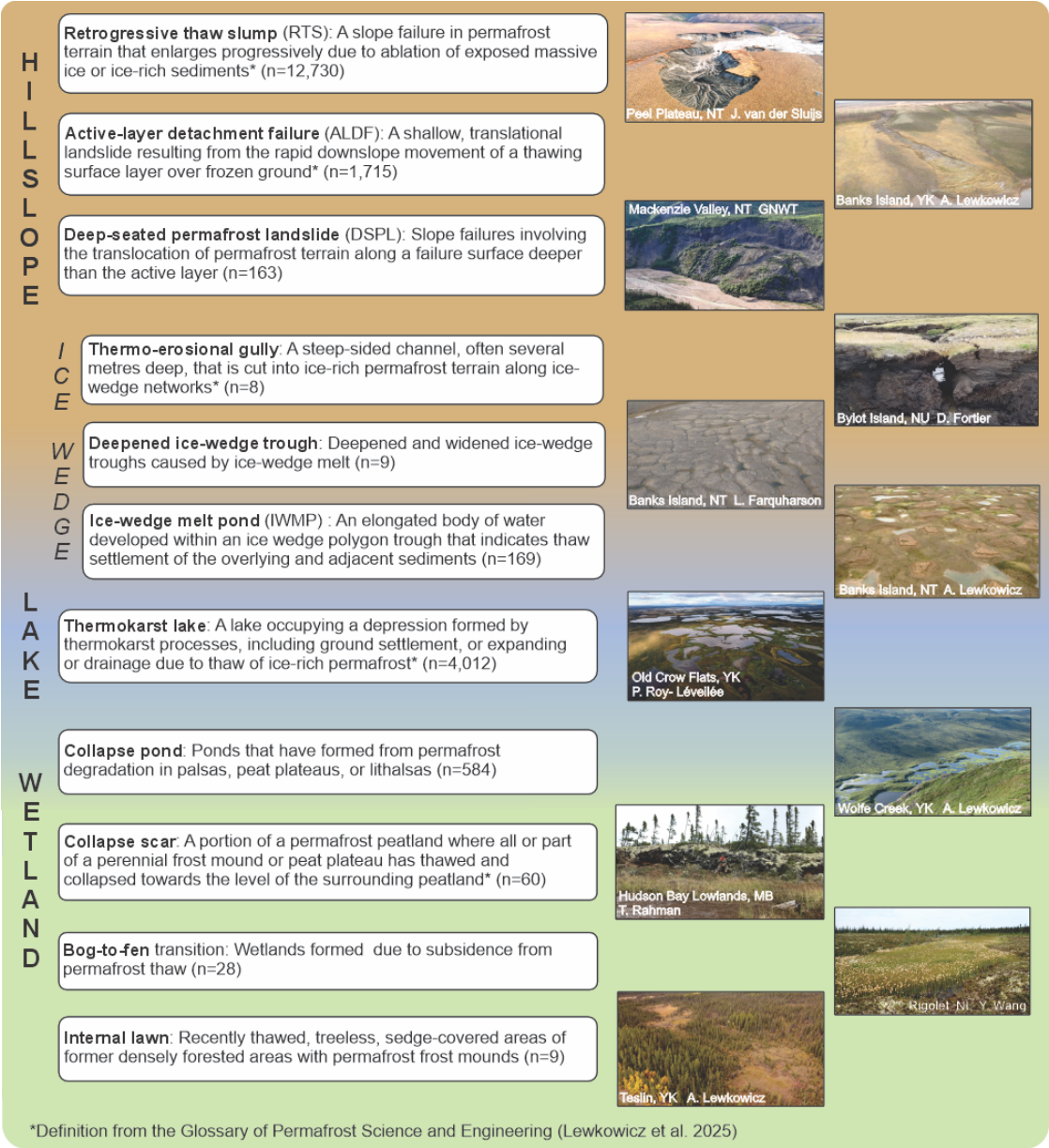


Percent peat cover (Tarnocai et al., 2011) was also extracted for each point, as many wetland thermokarst
landforms are controlled by the occurrence of peatlands. For each terrain and ground ice variable, frequency
tables were produced for the thermokarst landform types. This allowed the identification of dominant and
secondary associations between landforms and environmental controls and formed the basis of the summary
thermokarst domain conceptual model (Tables A1-2). The small-scale datasets used in the analysis may not fully
capture site-scale conditions, such as surficial geology and ground ice, that control thermokarst landform
development at each observed point, due to the inherent generalization of these layers (Kokelj et al., 2023;
O'Neill et al., 2024; Wang et al., 2023). The frequency tables are available in the Supplement.

The 11 identified thermokarst landforms were grouped into the three main thermokarst terrain categories of
hillslope, lake, and wetland (Fig. 1). Ice wedge thermokarst landforms were grouped as a distinct subcategory.
Observations of ice wedge landforms were dominantly associated with hillslope thermokarst landscapes, but ice
wedge thermokarst landforms occur across hillslope, lake, and wetland landscapes (Table A1).

3 Results and Interpretation

Thermokarst landforms vary in range and extent across Canada in the reported literature (Fig. 2). These spatial
datasets summarize where point observations have been made to date, which is a function of the prevalence of
thermokarst across Canada, but also of research bias driven in part by accessibility and motivation of sampling
initiatives. Historical discrepancies in research effort create an observational bias toward the western Arctic, due
partly to the considerable infrastructure and past work associated with oil and gas development in the region
(Couture and Riopel, 2008; Sladen et al., 2022) and widespread terrain features of interest in remote-sensing-
based studies (Fraser et al., 2023; Lewkowicz and Way, 2019; Morse and Rudy, 2022). To this end, spatial and
topical gaps and biases are recognized and can be reduced through more regionally based mapping initiatives,
such as the Thermokarst Mapping Collective (Kokelj et al., 2023). Nevertheless, landform distribution patterns
exist and may be related to permafrost terrain conditions, including physiography, type, distribution, and
abundance of excess ground ice, or the degree of ground ice loss over the Holocene.



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Figure 1. The 11 thermokarst landforms identified in the literature review, categorized by the three broad thermokarst terrain categories (hillslope, lake, wetland) and a subcategory of ice wedge-related landforms (Wolfe et al., 2025). Photos courtesy of J. van der Sluis, A. Lewkowicz, Government of the Northwest Territories, D. Fortier, L. Farquharson, P. Roy-Leveillé, T. Rahman, Y. Wang.

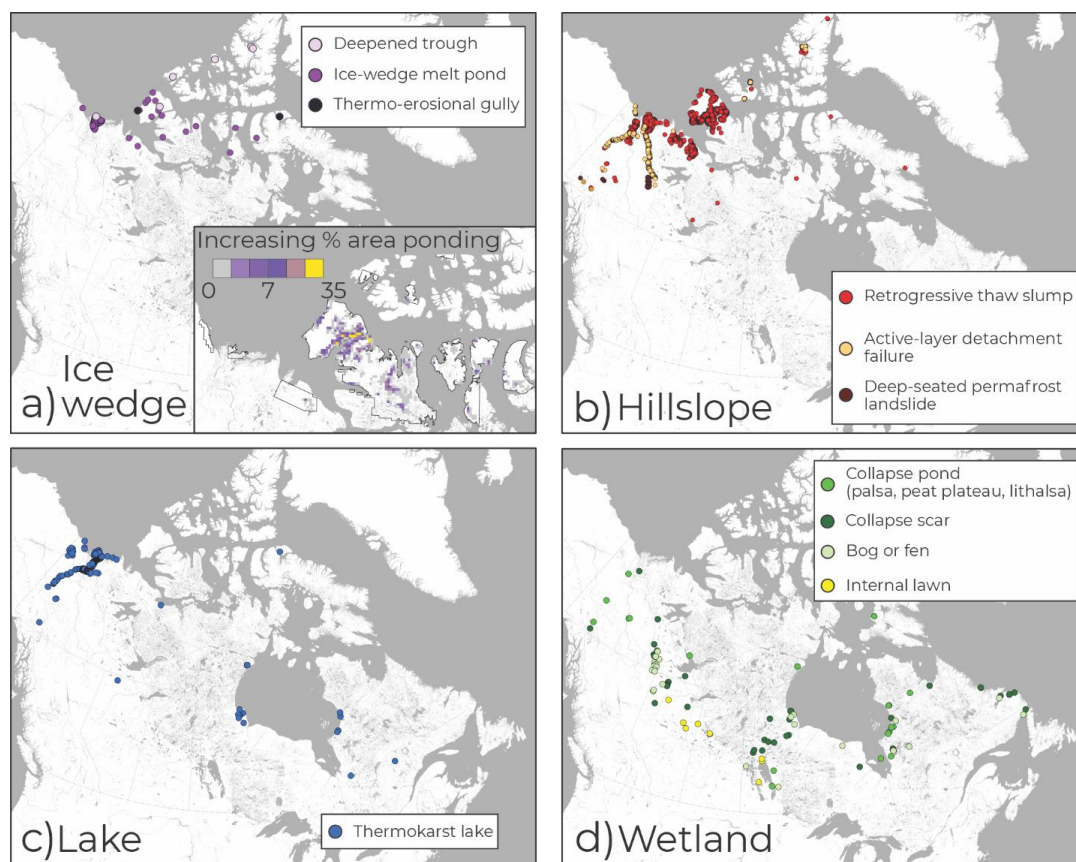


Figure 2. The distributions of mapped a) ice wedge, b) hillslope, c) lake, and d) wetland thermokarst landforms in Canada (data available in the supplementary spreadsheets). The inset in a) shows mapping, based on remote sensing analyses, of historically increased ice wedge ponding (modified from Fraser et al., 2023).

The landform observations occur in five *thermokarst domains* (I-V, Fig. 3) that parallel the permafrost zones of Canada. Subdomains reflect variation in landscape history that give rise to terrain conditions with high peatland cover (IIp, IIIp, IVp and Vp), where landforms are controlled by properties of the organic material. Each domain includes a unique set of permafrost, terrain, and ground ice conditions that combine to form unique thermokarst landform assemblages.

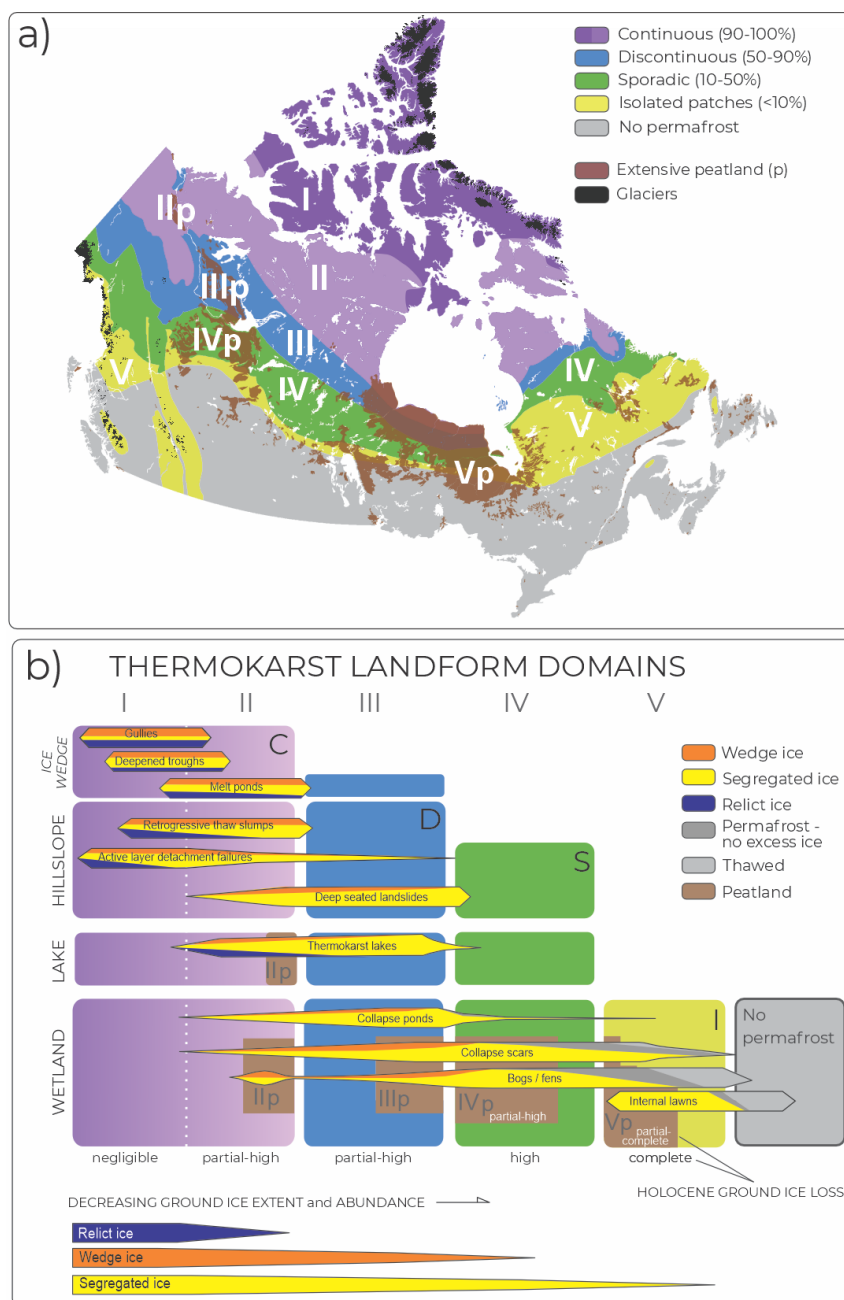


Figure 3. a) Thermokarst landform domains in Canada. Extensive peatlands (where % peatland cover is >40%) are based on mapping by Tarnocai et al. (2011). Permafrost zones are from Heginbottom et al. (1995), with the darker purple indicating the coldest regions of the continuous permafrost zone where ground ice has been mostly preserved or aggraded during the Holocene.



The conceptual model in b) is based on the relations between 19,549 observations and permafrost terrain conditions, including permafrost extent, modelled ground ice conditions, biomes, percent peat cover, and modelled Holocene ground ice loss (Tables A2 and A3). The domains represent the broad permafrost terrain conditions associated with characteristic thermokarst landforms. The varying taper of the lozenges represents the proportion of the landform occurrence in each domain (and not relative to other landforms; Table A4). The lozenge fill colours represent the modelled abundance of different ground ice types associated with the thermokarst landform observations (Tables A2 and A3). C, D, S, and I represent continuous, discontinuous, sporadic and isolated patches permafrost zones, respectively.

Domain I represents thermokarst terrain where cold, continuous permafrost has been maintained throughout the Holocene in an herb tundra biome. This domain, covering 1,200,000 km², includes most of the Middle Arctic Tundra and all the High Arctic and polar desert regions of northern Canada. These areas are characterized by high latitudes, cold climates, arid ecosystems, and minimal vegetation (Walker et al., 2005). In this domain, ground ice has been predominantly “permafrost-preserved”, owing to cold-climate conditions throughout the Holocene (Dyke et al., 2004; Kokelj et al., 2017). Consequently, throughout the Holocene, there has been a negligible loss of relict glacial ice relative to other domains, and, in the case of wedge ice, significant accumulation over time (Fig. 3b; Coulombe et al., 2022; O’Neill et al., 2019). Permafrost occurs near the ground surface, and organic cover is thin or absent. Landforms include thermo-erosional gullies, deepened ice wedge troughs, and ice wedge melt ponds (Fig. 3b), which occur as bellwether features of permafrost thaw as wedge ice melts and troughs or gullies develop on slopes and as patterned ponds develop across upland terrain (Abolt et al., 2024; Burn et al., 2021; Fortier et al., 2007; Fraser et al., 2018). Other abundant thermokarst landforms include retrogressive thaw slumps (RTS), their formation commonly predicated on relict (buried glacial) ice near the contemporary permafrost table (Kokelj et al., 2017; Nesterova et al., 2024) and active-layer detachment failures (ALDF), associated with the presence of segregated and wedge ice susceptible to melting during years with deep thaw. These observations highlight the dominance of hillslope and ice wedge thermokarst, whereas lake and wetland thermokarst prevalence is comparatively low, with lake expansion most commonly associated with RTS development on shorelines (Lewkowicz and Way, 2019; Table A2, A3).

Domain II represents terrain within the continuous permafrost zone with partial loss of ground ice during the Holocene due to spatially broad permafrost thaw associated with climatic shifts, Holocene treeline advance, and wildfire (Burn et al., 1986; Dyke et al., 2004; French, 1999). The partial loss of relict glacial ice is important as a control on thermokarst processes in this domain, as erosion or thaw must occur through a thicker transition zone above the permafrost table than in Domain I before activating slope failures (Shur et al., 2005). Nevertheless, fluvial incision and preconditioning of slopes through past disturbance can initiate rapid thermokarst change in areas with relict ice (Kokelj et al., 2021). Domain II includes shrub tundra, forest tundra, and boreal forest biomes. Encompassing ~1,900,000 km², it is the largest thermokarst domain and includes the greatest range of thermokarst



landforms due to its ecotonal nature (Kokelj et al., 2026). Ice wedge melt ponds, deepened troughs, ALDF, and
 205 RTS are common in hillslope-dominated terrain. Thermokarst lakes are abundant within this domain and are
 widely associated with the loss of segregated and wedge ice, whereas existing observations of wetland
 thermokarst landforms such as collapse ponds and scars occur in relatively low abundance (Fig. 3b). Bog-to-fen
 transitions in this domain are associated only with thicker peat covers in the boreal forest biome, as are some
 thermokarst lakes and collapse scars (Domain IIp, covering ~90,000 km²). These occur predominantly within
 210 interpreted wetland thermokarst landscapes (Olefeldt et al., 2016; Table A2 and A3).

Domain III is characterized by discontinuous permafrost in contemporary shrub tundra, forest tundra, and boreal
 forest biomes. This domain covers ~800,000 km² of the discontinuous permafrost zone (Fig. 3a). Observations of
 relict glacial ice are mostly lacking in Domain III, as it is interpreted to have melted out during Holocene tundra-
 215 to-forest transitions (O'Neill et al., 2019). Segregated ice and wedge ice occur, although wedges are likely
 inactive where there is forest cover (Kokelj et al., 2014; Mackay, 2000). Deep-seated permafrost landslides
 (DSPL), more recently termed permafrost detachment slides (Young et al., 2026), are a prominent hillslope
 thermokarst landform, where near-surface ice-rich permafrost detaches from underlying unfrozen soils (Young et
 al., 2022). ALDF occur in lower abundance than in Domains I and II. The prevalence of RTS is very low, owing
 220 to the absence of relict ice, and they occur primarily in areas interpreted as wetland thermokarst landscapes (Table
 A3). Thermokarst lakes are common and are associated with wetland landforms, including collapse ponds and
 collapse scars, which are prevalent due to the melt of segregated and wedge ice. Bog-to-fen transitional landforms
 occur in high abundance where higher peatland cover intersects with discontinuous permafrost (Domain IIIp,
 covering ~195,000 km²), with low abundances outside of these zones (Fig. 3b).

Domain IV occurs in the sporadic permafrost zone, encompassing ~990,000 km² within forest tundra and boreal
 forest biomes. This domain has undergone high Holocene ground ice loss in areas that still host permafrost (Fig.
 3b) and partial-to-high loss in peatland subdomains (Domain IVp, covering ~289,000 km²), where the thermal
 properties of organic terrain preferentially maintain permafrost. This warm permafrost includes segregated ice.
 230 Wedge ice is typically absent, as its growth has been limited by the short time during the Holocene when climatic
 conditions would have favoured thermal contraction cracking, and otherwise its melt has been ensured by past
 Holocene thaw of upper permafrost. Wetland thermokarst landforms are pervasive, with collapse scars and bog-
 to-fen transitional landforms in peatland subdomains (Domain IVp) and collapse ponds within mineral soils
 (Domain IV). In contrast, hillslope thermokarst landforms are rare (Table A3).



Domain V (~909,000 km²) includes isolated patches of permafrost (<10% of land area) in boreal forest biomes with relatively low ground ice abundance. This domain is characterized by wetland thermokarst landscapes (Table A2 and A3), with landforms including residual collapse scars in mineral soils (Domain V) and collapse ponds and bog-to-fen transitional landforms in the peatland subdomain (Domain Vp, covering ~182,000 km²; Fig. 3b). Most of the residual permafrost and thermokarst landforms in this domain are found within the peatland subdomain, due to the association between permafrost presence and organic terrain near the southern limit of permafrost (Beilman et al., 2001). A unique component of this domain is internal lawns, which form when permafrost thaws in forested areas, leaving residual sedge-covered wetlands (Fig. 1; Fig. 3b). However, much of the terrain in Domain V, including sedge-covered wetlands, has probably never hosted permafrost during the Holocene.

4 Discussion and conclusions

Several efforts to document and map thermokarst across the circumpolar north have been undertaken (Liu et al., 2025; Olefeldt et al., 2016; Webb et al., 2026). Most mapping studies have examined the distribution of specific thermokarst landforms at local to regional scales, including thermokarst lakes, ice wedge melt ponds, ALDF, and RTS (Fraser et al., 2023; Lewkowicz, 2024; Lewkowicz and Way, 2019; Olthof et al., 2015). Other regional studies have examined multiple thermokarst landform types and assessed the extent of permafrost degradation (Jorgenson et al., 2008) and the distribution of landforms in relation to variables including surficial geology, topographic drainage, and ground ice conditions (Farquharson et al., 2019; Webb et al., 2026). Several of these studies recognize that limited excess ice may remain today because extensive thermokarst and ground ice melt have already occurred during the Holocene in some regions, which has influenced the types of thermokarst landforms expressed and the rates at which they develop (Farquharson et al., 2019). More recent studies have mapped a diversity of features to identify regional associations and assemblages of permafrost and thermokarst landforms that reflect ground ice and material properties, influenced by geological and climate legacy (Kokelj et al., 2023, 2026). These reveal that different types of landforms are associated with specific thermokarst “fingerprints” in mid-Arctic, southern Arctic, and taiga regions (Kokelj et al., 2023), and with landform assemblages occurring within permafrost landsystems (Kokelj et al., 2026). Within this nested framework, our current study draws upon an extensive compilation of empirically based mapping and field observations to contribute a broad, conceptual framework of thermokarst landform distribution within the permafrost zones of Canada. The conceptual model provides a basis for describing broad thermokarst domains, complementing other recent work highlighting that thermokarst and periglacial landforms group into specific assemblages. Several of the key observations related to landform assemblages and associated permafrost conditions across thermokarst domains are summarized below.



Domain I is dominated by thermokarst landforms associated with hillslope processes. These include RTS and
 270 ALDF, in addition to thermo-erosional gullies and deepened ice wedge troughs, which occur in cold, Middle and
 High Arctic regions of the continuous permafrost zone. These landforms dominate where ground ice content is
 high near the permafrost table due to relict buried glacial ice, segregated ice that has enriched the upper
 permafrost (Cheng, 1983; Mackay, 1983), and the accumulation of wedge ice throughout the Holocene. In these
 northern regions, surface organic cover and active layers are typically thin, measuring <20 cm and <70 cm,
 275 respectively (Handley et al., 2026; Lafrenière et al., 2013), so conditions respond readily to rising air temperatures
 and/or extreme precipitation events (Farquerson et al., 2019; Shur and Jorgenson, 2007), which may trigger
 regional top-down thawing of permafrost (Lewkowicz and Way, 2019) or thermal erosion (Fortier et al., 2007).
 Many hydrological catchments are small, and rivers are short, so impacts of hillslope thermokarst, often
 associated with fine-grained, ice-rich tills, readily propagate through hydrological networks, transporting
 280 sediments and solutes to the ocean (Godin et al., 2014; Kokelj et al., 2021; Rudy et al., 2017).

Domain II contains the highest diversity of thermokarst landforms, with hillslope, lake, and wetland thermokarst
 processes all present. This domain occupies the central and southern regions of the continuous permafrost zone
 (Domain II) and associated organic terrain (Domain IIp). It is transitional between permafrost-preserved
 landsystems (Domain I) and those where partial-to-complete melt of excess ice has occurred in the past (Domains
 285 III, IV, V). As with Domain I, top-down thaw dominates; however, much of Domain II has experienced some loss
 of ground ice during regional episodes of deeper thaw (e.g., Burn, 1997). Therefore, a key characteristic of
 Domain II is the presence of a transition zone with lower ice content than the terrain in Domain I (Shur et al.,
 2005), where relict ice and large ice wedges occur at or near the contemporary permafrost table. Water and
 associated latent heat play a significant role, where thermokarst lakes are the most abundant landform in lowlands
 290 (Kokelj and Jorgenson, 2013) and where bog-to-fen transitions are initiated within peatlands. Contemporaneously,
 the loss of ground ice on hillslopes initiates ALDF and RTS, degrades wedge ice, and further facilitates lake
 expansion in adjacent areas (Burn et al., 2021; Kokelj et al., 2009).

Domain III is transitional, with a high diversity of thermokarst landforms across hillslope, lake, and wetland
 landscapes, but lacking landforms associated with the melt of relict and wedge ice (Fig. 3). Rather, thermokarst
 295 landforms are associated primarily with the loss of segregated ice in different terrain settings. DSPLs are
 associated with hillslopes (Young et al., 2022), while thermokarst lakes and collapse ponds occur within lowlands
 (Morse and Rudy, 2022). Collapse scars and bog-to-fen transitions are also associated with thawing of permafrost
 in peatland terrain (Olefelt et al., 2016). Thermokarst development may be enhanced by changes in temperature
 and precipitation regimes and the occurrence of wildfires, promoting the loss of segregated ice (Holloway and
 300 Lewkowicz, 2020; Young et al., 2022).



The more southerly Domains IV and V are characterized by lower thermokarst landform richness (Fig. 3) (Kokelj et al., 2026) and are dominated by wetland features within peatlands, which are associated with permafrost presence near the southern limit of its distribution (Beilman et al., 2001; Quinton and Baltzer, 2013; Wang et al., 2023). Peat cover plays an increasing role in the type and abundance of thermokarst landforms, including collapse scars and bog-to-fen transitions. These thermokarst landforms, as with DSPL and collapse ponds, are attributed primarily to the melt of segregated ice, as relict ice is absent and ice wedges are sparse, small, and inactive. Within the sporadic and isolated permafrost zones, thermokarst, as with permafrost, becomes predominantly confined to terrain with high organic cover (Domains IVp and Vp). In contrast with Domains I and II, thermokarst initiation in these domains is strongly influenced by lateral permafrost thaw and the development of suprapermfrost taliks, and thaw can be enhanced by disturbances such as wildfire (Devoie et al., 2019; Shur and Jorgenson, 2007).

This review has identified sets of permafrost conditions associated with the distribution of thermokarst landforms in Canada. The significance of ground ice type and abundance and ground ice loss from past permafrost thaw is reflected in the conceptual model of thermokarst domains of Canada (Fig. 3). As the circumpolar climate continues to warm, permafrost will thaw further, causing an inevitable northward shift in permafrost zones (Kwong and Gan, 1994). Short-term and long-term impacts on the distribution and abundance of thermokarst landforms are anticipated. Short-term effects include an increased prevalence of the inventoried thermokarst landforms within the established domains. Such increases have already been observed, including increased development of deepened ice wedge troughs (Burn et al., 2021; Farquharson et al., 2019), ice wedge melt ponds (Fraser et al., 2018), and RTS in the Middle and High Arctic regions of Domain I (Lewkowicz and Way, 2019; Rudy et al., 2017) and in the northern parts of Domain II (Lantz and Kokelj, 2008) as melting of near-surface wedge and relict ice progresses. In other domains, the short-term effects of permafrost thaw include increased expansion and development of new thermokarst lakes in Domain II (Olthof et al., 2015). DSPL initiation will likely further increase in Domains II & III (Kokelj et al., 2021; Young et al., 2022), where thaw-driven processes occur at or near the base of permafrost (Young et al., 2025), in contrast to slope processes in Domains I and II, where top-down thaw dominates. Increased collapse pond formation from degradation of mineralogical mounds (lithalsas) in Domains II and III may also occur (Vallée and Payette, 2007), mainly driven by the loss of segregated ice in these domains (Wolfe et al., 2016). In peatland sub-domains (IIp – Vp), increased bog-to-fen transition, collapse scar formation, and the establishment of internal lawns are associated with segregated ice melt (Gibson et al., 2021; Olefeldt et al., 2021; Quinton et al., 2011). Greater wildfire activity, like the record fire year in 2023, will further serve to accelerate thermokarst initiation in Domains III-V in the short term (Baltzer et al., 2025; Young et al., 2022).



335 Longer-term effects include a northward shift in permafrost zones. The prevalence of some landforms will
 increase in Domain I, such as thermokarst lakes, due to the extensive ice wedge networks and large areas of
 preserved ice. Arctic greening (Frost et al., 2025) may also contribute to the expansion of wetland thermokarst
 landscapes as conditions become favourable for shrub expansion and peat accumulation in Domain I. Rapid
 expansion of some high Arctic peatlands within Domain I has already been observed in response to recent
 340 warming (Handley et al., 2026). In Domain II, a northward expansion of discontinuous permafrost commensurate
 with treeline advance may result in the thickening of the active layer, permafrost thaw, and the reduction of
 ground ice with repeated, increasingly frequent cycles of wildfire (Zhang et al., 2015). In Domains III, IV, and V,
 longer-term effects include continued permafrost thaw and associated loss of carbon stocks within thermokarst-
 affected peatlands (Harris et al., 2023). With a northward retreat of permafrost in the discontinuous permafrost
 345 zone (Bielman et al., 2001; Thibault and Payette, 2009) and warming of the ground in the continuous zone (Smith
 et al., 2022), it may not be appropriate to strictly assume that all thermokarst processes and landforms in a
 southern zone will transfer northward, owing to differences in geological legacies that give rise to existing
 permafrost extents and thickness, surficial sediments, organic accumulations, and ground ice conditions. Specific
 conditions of cold, continuous permafrost and ground ice distributions today in Domain I may never have existed
 350 within warmer permafrost zones, and thus warming within these colder Domains may bring about novel
 alterations to permafrost landscapes.

This study is the first to compile and summarize existing observations of thermokarst landforms in Canada. It has
 integrated 19,549 field-based and remote-sensing observations from 155 literature sources derived over 60
 decades. It has identified 11 key thermokarst landforms linked to thermokarst terrain processes (i.e., hillslope,
 355 lake, and wetland). These thermokarst landforms are shown to combine to form landform assemblages that can be
 grouped within thermokarst domains, which are tied to permafrost extent and geological legacies affecting
 surficial geology, organic terrain, and ground ice conditions (Kokelj et al., 2026). Despite the comprehensive
 review of existing literature, gaps in data distribution still affect the extent of knowledge and interpretation of
 results. Existing data are clustered where landforms are known and readily measurable in the field or by remote
 sensing. Whereas some landforms, such as RTS and ALDF, may be well-represented by the current datasets,
 360 others, such as ice wedge thermokarst landforms and thermokarst lakes, likely remain underrepresented in
 proportion to their distribution across Canada. Interpretations of thermokarst distributions and assemblages may
 change with additional data, but the presented conceptual model provides a foundation for understanding the
 distribution of thermokarst landforms and future changes in Canada.

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References

- Abolt, C.J., Atchley, A.L., Harp, D.R., Jorgenson, M.T., Witharana, C., Bolton, W.R., Schwenk, J., Rettelbach, T., Grosse, G., Boike, J., Nitze, I., Liljedahl, A.K., Rumpca, C.T., Wilson, C.J., Bennett, K.E.: Topography Controls Variability in Circumpolar Permafrost Thaw Pond Expansion, *J. Geophys. Res. Earth Surf.*, 129, e2024JF007675, <https://doi.org/10.1029/2024JF007675>, 2024.
- 375 Baltzer, J.L., Haché, S., Hodson, J., Ahmed, M.R., Carrière, S., Coyle, M., McIntire, E.J.B., McLaren, A., Riordan-Short, E., Turetsky, M.R., Van Der Sluijs, J., Wilson, J., Woodworth, B.K.: Impacts of novel wildfire disturbance on landcover and wildlife in boreal North America, *Front. Environ. Sci.* 13, 1504568, <https://doi.org/10.3389/fenvs.2025.1504568>, 2025.
- 380 Beilman, D.W., Robinson, S.D.: Peatland permafrost thaw and landform type along a climatic gradient, in: Proceedings of the 8th International Conference on Permafrost, Zurich: University of Zurich-Irchel. Balkema, Lisse, NL, pp. 61–65, 2003.
- Beilman, D.W., Vitt, D.H., Halsey, L.A.: Localized Permafrost Peatlands in Western Canada: Definition, Distributions, and Degradation, *Arct. Antarct. Alp. Res.*, 33, 70–77, <https://doi.org/10.1080/15230430.2001.12003406>, 2001.
- 385 Burn, C.R.: Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic coast, Canada, *Can. J. Earth Sci.*, 34, 912–925, <https://doi.org/10.1139/e17-076>, 1997.
- Burn, C.R., Lewkowicz, A.G., Wilson, M.A.: Long-term field measurements of climate-induced thaw subsidence above ice wedges on hillslopes, western Arctic Canada, *Permafr. Periglac. Process.*, 32, 261–276, <https://doi.org/10.1002/ppp.2113>, 2021.
- 390 Burn, C.R., Michel, F.A., Smith, M.W. Stratigraphic, isotopic, and mineralogical evidence for an early Holocene thaw unconformity at Mayo, Yukon Territory, *Can. J. Earth Sci.*, 23, 794–803, <https://doi.org/10.1139/e86-081>, 1986.
- Calmels, F., Delisle, G., Allard, M.: Internal structure and the thermal and hydrological regime of a typical lithalsa: significance for permafrost growth and decay, *Can. J. Earth Sci.*, 45, 31–43, <https://doi.org/10.1139/e07-068>, 2008.
- 395 Carpino, O.A., Berg, A.A., Quinton, W.L., Adams, J.R.: Climate change and permafrost thaw-induced boreal forest loss in northwestern Canada, *Environ. Res. Lett.*, 13, 084018, <https://doi.org/10.1088/1748-9326/aad74e>, 2018.
- 400 Cheng, G.: The mechanism of repeated-segregation for the formation of thick layered ground ice, *Cold Reg. Sci. Technol.*, 8, 57–66, 1983.
- Chin, K.S., Lento, J., Culp, J.M., Lacelle, D., Kokelj, S.V.: Permafrost thaw and intense thermokarst activity decreases abundance of stream benthic macroinvertebrates, *Glob. Change Biol.*, 22, 2715–2728, <https://doi.org/10.1111/gcb.13225>, 2016.
- 405 Coulombe, S., Fortier, D., Bouchard, F., Paquette, M., Charbonneau, S., Lacelle, D., Laurion, I., Pienitz, R.: Contrasted geomorphological and limnological properties of thermokarst lakes formed in buried glacier ice and ice-wedge polygon terrain, *The Cryosphere*, 16, 2837–2857, <https://doi.org/10.5194/tc-16-2837-2022>, 2022.
- Couture, R., Riopel, S.: Landslide Inventory along a Proposed Gas Pipeline between Inuvik and Tulita, Mackenzie Valley, Northwest Territories (Geological Survey of Canada, Open File No. 5740), Natural Resources Canada, <https://doi.org/10.4095/226200>, 2008.
- 410



- Devoie, É.G., Craig, J.R., Connon, R.F., Quinton, W.L.: Taliks: A Tipping Point in Discontinuous Permafrost Degradation in Peatlands, *Water Resour. Res.*, 55, 9838–9857, <https://doi.org/10.1029/2018WR024488>, 2019.
- 415 Dyke, A.S., Giroux, D., Robertson, L.: Paleovegetation maps of northern North America, 18 000 to 1000 BP (Open File 4682), Geological Survey of Canada, Ottawa, ON, Canada, 2004.
- Farquharson, L.M., Romanovsky, V.E., Cable, W.L., Walker, D.A., Kokelj, S.V., Nicolsky, D.: Climate Change Drives Widespread and Rapid Thermokarst Development in Very Cold Permafrost in the Canadian High Arctic. *Geophys. Res. Lett.*, 46, 6681–6689, <https://doi.org/10.1029/2019GL082187>, 2019.
- 420 Fortier, D., Allard, M., Shur, Y.: Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago, *Permafr. Periglac. Process.*, 18, 229–243, <https://doi.org/10.1002/ppp.595>, 2007.
- Fraser, R.H., Kokelj, S.V., Lantz, T.C., McFarlane-Winchester, M., Olthof, I., Lacelle, D.: Climate Sensitivity of High Arctic Permafrost Terrain Demonstrated by Widespread Ice-Wedge Thermokarst on Banks Island, *Remote Sens.*, 10, 954, <https://doi.org/10.3390/rs10060954>, 2018.
- 425 Fraser, R.H., McFarlane-Winchester, M., Kokelj, S.V.: Recent ponding of upland ice-wedge polygon networks detected across the Canadian Arctic Archipelago using satellite remote sensing (Open File No. 69), Geomatics Canada, Ottawa, ON, Canada, <https://doi.org/10.4095/329618>, 2023.
- French, H.M.: Past and present permafrost as an indicator of climate change, *Polar Res.*, 18, 269–274, <https://doi.org/10.3402/polar.v18i2.6584>, 1999.
- 430 Frost, G.V., Bhatt, U.S., Macander, M.J., Berner, L.T., Walker, D.A., Raynolds, M.K., Magnússon, R.Í., Bartsch, A., Bjerke, J.W., Epstein, H.E., Forbes, B.C., Goetz, S.J., Hoy, E.E., Karlsen, S.R., Kumpula, T., Lantz, T.C., Lara, M.J., López-Blanco, E., Montesano, P.M., Neigh, C.S.R., Nitze, I., Orndahl, K.M., Park, T., Phoenix, G.K., Rocha, A.V., Rogers, B.M., Schaepman-Strub, G., Tømmervik, H., Verdonen, M., Veremeeva, A., Virkkala, A.-M., Waigl, C.F.: The changing face of the Arctic: four decades of greening and implications for tundra ecosystems, *Front. Environ. Sci.*, 13, 1525574, <https://doi.org/10.3389/fenvs.2025.1525574>, 2025.
- 435 Fulton, R.J.: Surficial materials of Canada, “A” Series Map 1880A, <https://doi.org/10.4095/205040>, 1995.
- Gibson, C., Cottenie, K., Gingras-Hill, T., Kokelj, S.V., Baltzer, J.L., Chasmer, L., Turetsky, M.R.: Mapping and understanding the vulnerability of northern peatlands to permafrost thaw at scales relevant to community adaptation planning, *Environ. Res. Lett.*, 16, 055022, <https://doi.org/10.1088/1748-9326/abe74b>, 2021.
- 440 Godin, E., Fortier, D., Coulombe, S.: Effects of thermo-erosion gully on hydrologic flow networks, discharge and soil loss, *Environ. Res. Lett.*, 9, 105010, <https://doi.org/10.1088/1748-9326/9/10/105010>, 2014.
- Handley, J., Fewster, R.E., Sim, T.G., Hodson, S., Parker, B., Crichton, K., Charman, D., Anderson, K., Gameau, M., Välranta, M., Beilman, D.W., Swindles, G.T., Aquino-López, M., Blaauw, M., Comas, X., Levesque, E., Maire, V., Addis, H., Amesbury, M., Fortier, D., Mleczko, M., Gallego-Sala, A.: Pan-Arctic Peatlands Have Expanded During Recent Warming, *Glob. Change Biol.*, 32, e70684, <https://doi.org/10.1111/gcb.70684>, 2026.
- 445 Harris, L.I., Olefeldt, D., Pelletier, N., Blodau, C., Knorr, K., Talbot, J., Heffernan, L., Turetsky, M.: Permafrost thaw causes large carbon loss in boreal peatlands while changes to peat quality are limited, *Glob. Change Biol.*, 29, 5720–5735, <https://doi.org/10.1111/gcb.16894>, 2023.
- 450 Heginbottom, J.A., Dubreuil, M.-A., Harker, P.: Permafrost - Canada, National Atlas of Canada MCR 4177, <https://doi.org/10.4095/294672>, 1995.
- Holloway, J.E., Lewkowicz, A.G.: Half a century of discontinuous permafrost persistence and degradation in western Canada, *Permafr. Periglac. Process.*, 31, 85–96, <https://doi.org/10.1002/ppp.2017>, 2020.
- 455 Jorgenson, M.T., Yoshikawa, K., Kanevskiy, M., Shur, Y., Romanovsky, V.E., Marchenko, S., Grosse, G., Brown, J., Jones, B.: Permafrost Characteristics of Alaska + Map, in: *Proceedings of the 9th International Conference on Permafrost*, Fairbanks, AK, Institute of Northern Engineering, University of Alaska, Fairbanks, AK, pp. 1–3, https://doi.org/https://www.researchgate.net/publication/334524021_Permafrost_Characteristics_of_Alaska_Map, 2008.
- 460



- Kirkwood, J.A.H., Roy-Léveillé, P., Mykytczuk, N., Packalen, M., McLaughlin, J., Laframboise, A., Basiliko, N.: Soil Microbial Community Response to Permafrost Degradation in Palsa Fields of the Hudson Bay Lowlands: Implications for Greenhouse Gas Production in a Warming Climate, *Glob. Biogeochem. Cycles*, 35, e2021GB006954, <https://doi.org/10.1029/2021GB006954>, 2021.
- 465 Kokelj, S.V., Gingras-Hill, T., Daly, S.V., Morse, P.D., Wolfe, S.A., Rudy, A.C.A., van der Sluijs, J., Weiss, N., O'Neill, H.B., Baltzer, J.L., Lantz, T.C., Gibson, C., Cazon, D., Fraser, R.H., Froese, D.G., Giff, G., Klengenberg, C., Lamoureux, S.F., Quinton, W.L., Turetsky, M.R., Chiasson, A., Ferguson, C., Newton, M., Pope, M., Paul, J.A., Wilson, M.A., Young, J.M.: The Northwest Territories Thermokarst Mapping Collective: A northern-driven mapping collaborative toward understanding the effects of permafrost thaw, *Arct. Sci.*, 1–33, <https://doi.org/10.1139/AS-2023-0009>, 2023.
- 470 Kokelj, S.V., Jorgenson, M.T.: Advances in thermokarst research, *Permafr. Periglac. Process.*, 24, 108–119, <https://doi.org/10.1002/ppp.1779>, 2013.
- Kokelj, S.V., Kokoszka, J., van der Sluijs, J., Rudy, A.C.A., Tunnicliffe, J., Shakil, S., Tank, S.E., Zolkos, S.: Thaw-driven mass wasting couples slopes with downstream systems, and effects propagate through Arctic drainage networks, *The Cryosphere*, 15, 3059–3081, <https://doi.org/10.5194/tc-15-3059-2021>, 2021.
- 475 Kokelj, S.V., Lantz, T.C., Kanigan, J., Smith, S.L., Coutts, R.: Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada, *Permafr. Periglac. Process*, 20, 173–184, <https://doi.org/10.1002/ppp.642>, 2009.
- 480 Kokelj, S.V., Lantz, T.C., Tunnicliffe, J., Segal, R., Lacelle, D.: Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada, *Geology*, 45, 371–374, <https://doi.org/10.1130/G38626.1>, 2017.
- Kokelj, S.V., Lantz, T.C., Wolfe, S.A., Kanigan, J.C., Morse, P.D., Coutts, R., Molina-Giraldo, N., Burn, C.R.: Distribution and activity of ice wedges across the forest-tundra transition, western Arctic Canada, *J. Geophys. Res. Earth Surf.*, 119, 2014JF003085, <https://doi.org/10.1002/2014JF003085>, 2014.
- 485 Kokelj, S.V., Wolfe, S.A., Weiss, N., Froese, D., Baltzer, J.L., Lantz, T.C., O'Neill, H.B., Morse, P.D., Sniderhan, A., Speetjens, N.J., Van Der Sluijs, J., Alvarez, A., Tank, S.E., Gruber, S.: Permafrost landsystems define regional variability in climate change effects on northern environments, *Nat. Commun.*, 17, 4799, <https://doi.org/10.1038/s41467-026-71216-2>, 2026.
- Kwong, Y.T.J., Gan, T.Y.: Northward migration of permafrost along the Mackenzie Highway and climatic warming, *Clim. Change*, 26, 399–419, <https://doi.org/10.1007/BF01094404>, 1994.
- 490 Lafrenière, M.J., Laurin, E., Lamoureux, S.F.: The Impact of Snow Accumulation on the Active Layer Thermal Regime in High Arctic Soils, *Vadose Zone J.*, 12, 1–13, <https://doi.org/10.2136/vzj2012.0058>, 2013.
- Lantz, T.C., Kokelj, S.V.: Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. *Geophys. Res. Lett.* 35. <https://doi.org/10.1029/2007GL032433>, 2008.
- 495 Lantz, T.C., Turner, K.W.: Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. *J. Geophys. Res. Biogeosciences*, 120, 513–524, <https://doi.org/10.1002/2014JG002744>, 2015.
- Lewkowicz, A.G.: Retrogressive thaw slump activity and related lake colour change in five areas of the western Canadian Arctic, v. 1.0 (1984–2018), *Nordicana D1*, <https://doi.org/10.5885/45888XD-C644C19F4F414D58>, 2024.
- 500 Lewkowicz, A.G., O'Neill, H.B., Wolfe, S.A., Roy-Leveille, P., Roujanski, V., Hoeve, E., Gruber, S., Brooks, H., Rudy, A.C.A., Koenig, C.E.M., Brown, N., Bonnaventure, P.P.: Glossary of Permafrost Science and Engineering, 1st ed, Canadian Permafrost Association, 2025.
- Lewkowicz, A.G., Way, R.G.: Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment, *Nat. Commun.*, 10, 1329, <https://doi.org/10.1038/s41467-019-09314-7>, 2019.
- 505 Littlefair, C.A., Tank, S.E.: Biodegradability of Thermokarst Carbon in a Till-Associated, Glacial Margin Landscape: The Case of the Peel Plateau, NWT, Canada, *J. Geophys. Res., Biogeosciences*, 123, 3293–3307, <https://doi.org/10.1029/2018JG004461>, 2018.
- Liu, Y., Qiu, H., Wang, N., Yang, D., Zhao, K., Yang, G., Huangfu, W., Luo, W.: Thermokarst disturbance responses to climate change across the circumpolar permafrost regions from 1990 to 2023, *Geosci. Front.*, 16, 102147, <https://doi.org/10.1016/j.gsf.2025.102147>, 2025.
- 510



- MacDonald, L.A., Turner, K.W., McDonald, I., Kay, M.L., Hall, R.I., Wolfe, B.B.: Isotopic evidence of increasing water abundance and lake hydrological change in Old Crow Flats, Yukon, Canada, *Environ. Res. Lett.*, 16, 124024, <https://doi.org/10.1088/1748-9326/ac3533>, 2021.
- 515 Mackay, J.R.: Thermally induced movements in ice-wedge polygons, western arctic coast: a long-term study, *Géographie Phys. Quat.*, 54, 41–68, <https://doi.org/10.7202/004846ar>, 2000.
- Mackay, J.R.: Downward water movement into frozen ground, western Arctic coast, Canada, *Can. J. Earth Sci.*, 20, 120–134, <https://doi.org/10.1139/e83-012>, 1983.
- 520 Mamet, S.D., Chun, K.P., Kershaw, G.G.L., Loranty, M.M., Peter Kershaw, G.: Recent Increases in Permafrost Thaw Rates and Areal Loss of Palsas in the Western Northwest Territories, Canada, *Permafr. Periglac. Process.*, 28, 619–633, <https://doi.org/10.1002/ppp.1951>, 2017.
- Morse, P.D., Rudy, A.C.A.: Distributions of degraded and intact lithalsas, North Slave region, Northwest Territories (Open File No. 8869), Geological Survey of Canada, Ottawa, ON, Canada, <https://doi.org/10.4095/329643>, 2022.
- 525 Nelson, F.E., Anisimov, O.A., Shiklomanov, N.I.: Subsidence risk from thawing permafrost, *Nature*, 410, 889–890, <https://doi.org/10.1038/35073746>, 2001.
- Nesterova, N., Leibman, M., Kizyakov, A., Lantuit, H., Tarasevich, I., Nitze, I., Veremeeva, A., Grosse, G.: Review article: Retrogressive thaw slump characteristics and terminology, *The Cryosphere*, 18, 4787–4810, <https://doi.org/10.5194/tc-18-4787-2024>, 2024.
- 530 Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., McGuire, A.D., Romanovsky, V.E., Sannel, A.B.K., Schuur, E.A.G., Turetsky, M.R.: Circumpolar distribution and carbon storage of thermokarst landscapes, *Nat. Commun.*, 7, 13043, <https://doi.org/10.1038/ncomms13043>, 2016.
- Olefeldt, D., Heffernan, L., Jones, M.C., Sannel, A.B.K., Treat, C.C., Turetsky, M.R.: Permafrost Thaw in Northern Peatlands: Rapid Changes in Ecosystem and Landscape Functions, in: Canadell, J.G., Jackson, R.B. (Eds.), *Ecosystem Collapse and Climate Change*, Ecological Studies, Springer International Publishing, Cham, pp. 27–67, https://doi.org/10.1007/978-3-030-71330-0_3, 2021.
- 535 Olthof, I., Fraser, R.H., Schmitt, C.: Landsat-based mapping of thermokarst lake dynamics on the Tuktoyaktuk Coastal Plain, Northwest Territories, Canada since 1985, *Remote Sens. Environ.*, 168, 194–204, <https://doi.org/10.1016/j.rse.2015.07.001>, 2015.
- 540 O’Neill, H.B., Smith, S.L., Burn, C.R., Duchesne, C., Zhang, Y.: Widespread permafrost degradation and thaw subsidence in northwest Canada, *J. Geophys. Res. Earth Surf.*, 128, 1–16, <https://doi.org/10.1029/2023JF007262>, 2023.
- O’Neill, H.B., Wolfe, S.A., Duchesne, C. Ground ice map of Canada (version 1.1) (Open File No. 8713), Geological Survey of Canada, Ottawa, ON, Canada, <https://doi.org/10.4095/326885>, 2022.
- 545 O’Neill, H.B., Wolfe, S.A., Duchesne, C. 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>, 2019.
- O’Neill, H.B., Wolfe, S.A., Duchesne, C., Parker, R.J.H.: Effect of surficial geology mapping scale on modelled ground ice in Canadian Shield terrain, *The Cryosphere*, 18, 2979–2990, <https://doi.org/https://doi.org/10.5194/tc-18-2979-2024>, 2024.
- 550 Payette, S., Delwaide, A., Caccianiga, M., Beauchemin, M.: Accelerated thawing of subarctic peatland permafrost over the last 50 years, *Geophys. Res. Lett.*, 31, L18208, <https://doi.org/10.1029/2004GL020358>, 2004.
- Quinton, W.L., Baltzer, J.L.: The active-layer hydrology of a peat plateau with thawing permafrost (Scotty Creek, Canada), *Hydrogeol. J.*, 21, 201–220, <https://doi.org/10.1007/s10040-012-0935-2>, 2013.
- 555 Quinton, W.L., Hayashi, M., Chasmer, L.E.: Permafrost-thaw-induced land-cover change in the Canadian subarctic: implications for water resources, *Hydrol. Process.*, 25, 152–158, <https://doi.org/10.1002/hyp.7894>, 2011.
- Roy-Leveille, P., Burn, C.R.: Near-shore talik development beneath shallow water in expanding thermokarst lakes, Old Crow Flats, Yukon, *J. Geophys. Res. Earth Surf.*, 122, 1070–1089, <https://doi.org/10.1002/2016JF004022>, 2017.
- 560 Rudy, A.C.A., Lamoureux, S.F., Kokelj, S.V., Smith, I.R., England, J.H.: Accelerating Thermokarst Transforms Ice-Cored Terrain Triggering a Downstream Cascade to the Ocean, *Geophys. Res. Lett.*, 44, 11,080–11,087, <https://doi.org/10.1002/2017GL074912>, 2017.



- Sannel, A.B.K., Kuhry, P.: Warming-induced destabilization of peat plateau/thermokarst lake complexes, *J. Geophys. Res.*, 116, G03035, <https://doi.org/10.1029/2010JG001635>, 2011.
- 565 Segal, R.A., Lantz, T.C., Kokelj, S.V.: Acceleration of thaw slump activity in glaciated landscapes of the Western Canadian Arctic, *Environ. Res. Lett.*, 11, 034025, <https://doi.org/10.1088/1748-9326/11/3/034025>, 2016.
- Shur, Y., Hinkel, K.M., Nelson, F.E.: The transient layer: implications for geocryology and climate-change science, *Permafr. Periglac. Process.*, 16, 5–17, <https://doi.org/10.1002/ppp.518>, 2005.
- Shur, Y.L., Jorgenson, M.T.: Patterns of permafrost formation and degradation in relation to climate and ecosystems, *Permafr. Periglac. Process.*, 18, 7–19, <https://doi.org/10.1002/ppp.582>, 2007.
- 570 Sladen, W.E., Parker, R.J.H., Morse, P.D., Kokelj, S.V., Smith, S.L.: Geomorphic feature inventory along the Dempster and Inuvik to Tuktoyaktuk highway corridor, Yukon and Northwest Territories (Geological Survey of Canada, Open File No. 8885), Natural Resources Canada, Ottawa, ON, Canada, <https://doi.org/10.4095/329969>, 2022.
- 575 Streletskiy, D.A., Maslakov, A., Grosse, G., Shiklomanov, N.I., Farquharson, L., Zwieback, S., Iwahana, G., Bartsch, A., Liu, L., Strozzi, T., Lee, H., Debolskiy, M.V.: Thawing permafrost is subsiding in the Northern Hemisphere—review and perspectives, *Environ. Res. Lett.*, 20, 013006, <https://doi.org/10.1088/1748-9326/ada2ff>, 2025.
- Tarnocai, C., Kettles, I.M., Lacelle, B.: Peatlands of Canada, (Open File No. 6561, Geological Survey of Canada, <https://doi.org/10.4095/288786>, 2011.
- 580 Vallée, S., Payette, S.: Collapse of permafrost mounds along a subarctic river over the last 100 years (northern Québec), *Geomorphology*, 90, 162–170, <https://doi.org/10.1016/j.geomorph.2007.01.019>, 2007.
- Walker, D.A., Raynolds, M.K., Daniëls, F.J.A., Einarsson, E., Elvebakk, A., Gould, W.A., Katenin, A.E., Kholod, S.S., Markon, C.J., Melnikov, E.S., Moskalenko, N.G., Talbot, S.S., Yurtsev, B.A.(†), The Other
- 585 Members Of The Cavm Team: The Circumpolar Arctic vegetation map, *J. Veg. Sci.*, 16, 267–282, <https://doi.org/10.1111/j.1654-1103.2005.tb02365.x>, 2005.
- Wang, Y., Way, R.G., Beer, J.: Multi-decadal degradation and fragmentation of palsas and peat plateaus in coastal Labrador, northeastern Canada, *Environ. Res. Lett.*, 19, 014009, <https://doi.org/10.1088/1748-9326/ad0138>, 2024.
- 590 Wang, Y., Way, R.G., Beer, J., Forget, A., Tutton, R., Purcell, M.C.: Significant underestimation of peatland permafrost along the Labrador Sea coastline in northern Canada, *The Cryosphere*, 17, 63–78, <https://doi.org/10.5194/tc-17-63-2023>, 2023.
- Webb, H., Pierce, E., Abbott, B.W., Bowden, W.B., Chen, Yaping, Chen, Yating, Douglas, T.A., Eklof, J.F., Euskirchen, E.S., Langer, M., Myers-Smith, I.H., Overeem, I., Strauss, J., Walter Anthony, K., Wang, K.,
- 595 Whitley, M.A., Turetsky, M.R.: A comprehensive database of thawing permafrost locations across Alaska: version 2.0.0, *Earth Syst. Sci. Data* 18, 3147–3164. <https://doi.org/10.5194/essd-18-3147-2026>, 2026.
- Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., Roest, W.R.: Geological map of Canada, “A” Series Map 1860A, <https://doi.org/10.4095/208175>, 1996.
- 600 Wolfe, S.A., Duchesne, C., O’Neill, H.B., Parker, R.J.H., Young, J.M., Rudy, A.C.A., Steedman, A.E., Lantz, T.C., Kokelj, S.V.: A database of thermokarst and related landform observations in Canada (1961 to 2024) (Open File No. 9296e), Geological Survey of Canada, Ottawa, ON, Canada, <https://doi.org/10.4095/pxqr7ad0un>, 2025.
- Wolfe, S.A., Stevens, C.W., Gaanderse, A.J., Oldenborger, G.A.: Lithalsa distribution, morphology and landscape associations in the Great Slave Lowland, Northwest Territories, Canada, *Geomorphology*, 204, 302–313, <https://doi.org/10.1016/j.geomorph.2013.08.014>, 2014.
- 605 Young, J., Van Der Sluijs, J., Kokelj, S.V., Gruber, S., Herring, T., Rudy, A., Alvarez, A., Froese, D.: Permafrost detachment slides: A novel high magnitude permafrost mass wasting process, <https://doi.org/10.22541/essoar.15002869/v1>, 2026.
- 610 Young, J.M., Alvarez, A., Van Der Sluijs, J., Kokelj, S.V., Rudy, A., McPhee, A., Stoker, B.J., Margold, M., Froese, D.: Recent Intensification (2004–2020) of Permafrost Mass-Wasting in the Central Mackenzie Valley Foothills Is a Legacy of Past Forest Fire Disturbances, *Geophys. Res. Lett.*, 49, e2022GL100559, <https://doi.org/10.1029/2022GL100559>, 2022.



615 Young, J.M., Farquharson, L., Luo, J., Nesterova, N., Van Der Sluijs, J., Kokelj, S.V.: Permafrost Mass Wasting
in Ice-Rich Landscapes: Recent Advances (2013 to 2024) on Mechanisms, Dynamics and Impacts,
Permafr. Periglac. Process., p. 70015, <https://doi.org/10.1002/ppp.70015>, 2025.

Zhang, Y., Wolfe, S.A., Morse, P.D., Olthof, I., Fraser, R.H.: Spatiotemporal impacts of wildfire and climate
warming on permafrost across a subarctic region, Canada, J. Geophys. Res. Earth Surf., 120, 2338–2356,
<https://doi.org/10.1002/2015JF003679>, 2015.

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