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GEOLOGICAL SURVEY OF CANADA
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Canada

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Foreword

The Natural Hazards and Climate Change Geoscience Program (NHCCGP) provides an extensive evidence base for decision makers to ensure that Canada's built and natural environment is resilient to natural hazards in a changing climate. Within this strategic context, the program aims to develop a better understanding of the impacts of climate change in Canada by providing new data and information. This improves our understanding of how Canada's landmass is affected by climate change and provides support to land-use planning and informed decision-making.

Summary

This Open File provides a compilation of thermokarst and related landform observations from remote-sensing and field-based studies across Canada. Observations of 13 thermokarst landforms are compiled mainly from published literature. The database includes 15,999 thermokarst landform observations; 15,512 from remote-sensing studies and 487 from field-based studies. The data is provided in a comma-separated value (.csv) file. Observations are sub-divided into hillslope, wedge, lake, and wetland thermokarst landforms and their distribution across Canada is mapped.

Résumé

Ce dossier public fournit une compilation d'observations de thermokarst et de formes de relief connexes provenant d'études de télédétection et de terrain à travers le Canada. Les observations de 13 formes thermokarstiques sont compilées principalement à partir de la littérature publiée. La base de données comprend 15 999 observations de formes thermokarstiques; 15 512 provenant d'études de télédétection et 487 d'études sur le terrain. Les données sont fournies dans un fichier de valeur séparées par des virgules (CSV). Les observations sont subdivisées en formes thermokarstiques de versant, de coin de glace, de lac et de zone humide. Leur répartition à travers le Canada est cartographiée.

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Introduction

Thermokarst refers to processes and landforms that result from the thaw of ice-rich permafrost. Despite extensive documentation of active thermokarst processes and landforms in permafrost environments, no comprehensive study of their distribution or association with permafrost terrain conditions exists, though initiatives to fill this gap are underway (Kokelj et al., 2023). This gap limits the understanding of how permafrost thaw associated with climate change affects landscapes. This database is a compilation of point observations of thermokarst landforms in Canada based on an extensive literature review. It includes observations from field studies and those derived from remote sensing-based inventories. The database is further supplemented with additional remote sensing-based mapping of slumps in the high Arctic completed as part of this study.

Methods

Observations were compiled from published literature to assess the type and distribution of thermokarst landforms across Canada. Publication dates spanned from 1961 to 2024. The compiled observations are from peer-reviewed journal articles, conference proceedings, government reports, additional mapping by the authors, and unpublished data from the authors. Search functions were used on authors, institutions, locations and thermokarst processes and landforms in Google Scholar®, and references within articles were reviewed to populate a database of observations in Canada. The database includes publications describing field-documented landforms (e.g., Farquharson et al., 2019; Kokelj et al., 2013) and available inventories of point features produced from remote sensing analyses (e.g., Lewkowicz and Way, 2019; Segal et al., 2016e).

Landforms that were well-defined in the literature as clear indicators of thermokarst were considered in this review (Table 1). These represented a broad suite of observed terrain impacts and landforms associated with ice-rich permafrost thaw. Several additional processes and landform types were noted during the review but not included in this database. These included cryostratigraphic evidence of permafrost degradation, involuted ("brain-terrain") surface topography in permafrost terrain, sthermo-erosion of ground ice (other than wedge ice) resulting in cavities, and ground surface subsidence due to permafrost thaw and ground ice melt. Though thaw subsidence is the fundamental thermokarst process, it was not included in the analysis on its own because it is near-ubiquitous in all permafrost zones in ice-rich ground (O'Neill et al., 2023). Rather, specific landforms resulting from subsidence were included, such as collapse scars (Table 1). Exclusion of some processes and landforms was due to an insufficient number of observations, such as piping (Hyatt, 1992). Involuted terrain ("brain-terrain") was excluded because its origin is uncertain, though it may be associated with creep deformation and thaw of massive ice (Dallimore et al., 1996). Observations of low-centred or high-centred ice wedge polygons were not considered as distinct thermokarst landforms, but observations of deepened ice wedge troughs and expanding ice wedge melt ponds were included. The identification of both thermokarst processes (i.e., peat plateau collapse) and landforms (i.e., retrogressive-thaw slumps) is prevalent in the literature; for consistency, we formulate the naming of identified features or processes as landforms. It is also acknowledged that processes, such as peat plateau collapse, may be the umbrella process that results in several landforms, including collapse scars or ponds, bogs or fens, and internal lawns. Each of these thermokarst landform types are identified separately, based on the reporting in the literature sources. Wedge pseudomorphs, which represent either former remnants of ice wedges (Gao, 2005) or soil wedges (Fisher, 1996) developed in permafrost that have thawed completely, were also included in this database. Wedge pseudomorphs may be indicators of the past presence of permafrost, and can be useful in defining its former extent, although they are not representative of contemporary thermokarst. Terminology and definitions, wherever possible, are from the updated Glossary of Permafrost Science and Engineering (Lewkowicz et al., 2025).

Table 1. Thermokarst landform types, number of observations, and landform descriptions for observations compiled in the database.

Thermokarst landform type	Number of observations	Description of thermokarst landform (modified from Lewkowicz et al., 2025)	Example reference
Hillslope			
Retrogressive thaw slump (RTS)	12730	A slope failure in permafrost terrain that enlarges progressively due to ablation of exposed massive ice or ice-rich sediments.	Lacelle et al., 2015
Active-layer detachment failure (ALDF)	1715	A shallow translational slope failure formed by the rapid downslope movement of the thawed surface layer over frozen ground.	Lewkowicz and Harris, 2005a
Deep-seated permafrost landslide (DSPL)	163	Slope failure involving the translocation of permafrost terrain along a failure surface deeper than the active layer.	Young et al., 2022
Debris flow	3	The rapid downslope flow of a mixture of poorly-sorted sediment and water.	Huscroft et al., 2003
Wedge			
Thermo-erosional gully	8	A steep-sided channel, often several metres deep, that is cut into ice-rich permafrost terrain by thermal erosion.	Fortier et al., 2007
Ice-wedge melt pond (IWMP)	169	An elongated body of water developed within an ice wedge polygon trough that indicates thaw settlement of the overlying and adjacent sediments.	Fraser et al., 2018
Deepened ice-wedge trough	9	Deepened and widened ice-wedge trough caused by ice-wedge melt.	Farquharson et al., 2019
Wedge pseudomorph	59	Sediment or ice filling the space formerly occupied by an ice wedge or soil/sand wedge.	Rémillard et al., 2015
Lake			
Thermokarst lake (TL)	1018	A body of water occupying a depression that formed, at least in part, by thermokarst processes, including ground settlement or expansion due to the thaw of ice-rich permafrost.	Bandara et al., 2020
Wetland			
Collapse scar	60	A portion of a permafrost peatland where part or all of a perennial frost mound or peat plateau has thawed and collapsed towards the level of the surrounding peatland	Mamet et al., 2017
Collapse pond (palsa, peat plateau, lithalsa)	28	Pond that has formed from permafrost degradation in palsas, peat plateaus, or lithalsas.	Breton et al., 2009

Thermokarst landform type	Number of observations	Description of thermokarst landform (modified from Lewkowicz et al., 2025)	Example reference
Bog or fen	28	Wetland formed due to subsidence from permafrost thaw	Carpino et al., 2018
Internal lawn	9	Recently thawed, treeless, sedge-covered area of former densely forested area with permafrost frost mounds.	Beilman and Robinson, 2003

Database Structure

The database includes 15,999 thermokarst landforms and related observations from 155 articles, proceedings, and reports. Point observations from specific field studies were extracted from 142 articles, and points derived from remote sensing-based inventories from 13 publications. The database is supplemented with additional remote sensing-based mapping of retrogressive thaw slumps in the high Arctic completed as part of this study. The data is provided as a .csv file (of_9296_Thermokarst.csv) and a complete reference list can be found in Appendix A. The description of the attribute field names in the .csv are listed below:

DBID	Database unique identification number
Latitude	Latitude in decimal degrees; WKID 4326
Longitude	Longitude in decimal degrees; WKID 4326
TKFeature	Thermokarst landform type as defined in Table 1
Reference	Thermokarst landform literature source (refers to Appendix A reference list)
DOI	Data source Digital Object Identifier (if applicable)
Compile	Person who compiled the observation (if applicable)

The observations compiled from remote sensing studies using airborne or satellite-based imagery are primarily of retrogressive thaw slumps (RTS), active-layer detachment failures (ALDF), deep-seated permafrost landslides (DSPL), ice wedge melt ponds (IWMP) and thermokarst lakes (TL). The years of image acquisition range from 1970 for aerial photographs to 2020 for Landsat satellite imagery. Image resolution, and thus minimum feature resolution, varies from 0.5 m for WorldView-2 satellite and aerial photograph ortho-mosaic images, to 30 m for Landsat satellite images and older aerial photographs (Table 2). A total of 15,512 observations are from remote sensing studies, and include 12,608 retrogressive thaw slumps, 1,683 active layer detachment failures, 156 deep-seated permafrost landslides, 917 thermokarst lakes, and 169 ice wedge melt ponds.

Previously unpublished observations of retrogressive thaw slumps derived from remote sensing sources are also included in this study within a limited area in the high Arctic to fill data gaps where features are known but not well recorded. RTS locations were mapped systematically as point features from Google Earth® in the Fosheim Peninsula region of Ellesmere Island using 2014 Worldview-2 satellite data with a spatial resolution of 0.5 m. RTS were identified from observable headwalls and debris lobes, with substantially darker tones than the surrounding terrain. Historical satellite imagery provided confirmation of slump identification based on headwall retreat. A total of 136 RTS were identified in this region, which supplement observations made in field studies and past mapping (Ward Jones et al., 2019; Rudy et al., 2016).

An additional 148 ice wedge melt ponds (IWMP), developed within high-centred polygon networks, were extracted from the unpublished dataset of Steedman et al., (2017), identified using aerial photographs from 1972 and 2004. From the original dataset, terrain with contemporary melt ponds in 2004 or 1972 were used in this review. The extracted data is included within the remote sensing dataset (Table 2).

Table 2. Data sources for retrogressive thaw slump (RTS), active layer detachment (ALDF), deep-seated permafrost landslides (DSPL), thermokarst lakes (TL) and ice wedge melt ponds (IWMP) from remote sensing studies.

Location	Data Source	Image Source	Year(s)	Feature	Number
Banks Island, NT	Unpublished data from Rudy et al., 2017a	SPOT 4/5 Worldview-2	2008 2009 2015	RTS	**555**
Sabine Pen. Melville Is, NU	Unpublished data from Rudy et al., 2017b	Worldview-2	2011	ALDF	**762**
Fosheim Pen. Ellesmere Is, NU	Unpublished data from Rudy et al., 2016	Worldview-2	2013	RTS	**70**
Fosheim Pen. Ellesmere Is, NU	This Study	Worldview-2	2013	RTS	**136**
Cape Bounty Melville Is, NU	Unpublished data from Rudy et al., 2017b	Worldview-2	2011	ALDF	**147**
Inuvik to Tulita, NT	Couture and Riopel, 2008	Mackenzie Valley Orthomosaic	2004	RTS	**596**
				ALDF	**456**
Eastern Banks Island, NT	Segal et al, 2016b	Quickbird SPOT 4/5	2004 2006 2009 2010	RTS	**831**
Bluenose Moraine, NU	Segal et al., 2016d	SPOT 4/5	2006	RTS	**82**
Tuktoyaktuk Coastlands, NT	Segal et al., 2016c	Mackenzie Valley Orthomosaic	2004	RTS	**2069**
Peel Plateau, NT	Segal et al., 2016a	SPOT 5/4 Quickbird	2006 2007 2008	RTS	**206**
Dempster HWY & Inuvik-Tuk HWY, NT	Sladen et al., 2022	Worldview-2	2004-2011	RTS	**389**
				ALDF	**155**
				TL	**917**
Central Mackenzie Valley, NT	Young et al., 2022	Landsat 4/5/7/8 SPOT 5 Sentinel 2A/2B	1984-2020	RTS	**120**

Location	Data Source	Image Source	Year(s)	Feature	Number
				DSPL	**156**
Yukon Coast, YT	Wolfe et al., 2001	Field obs. (1999) Air Photos: 1:23000 (1970) 1:31000 (1985)	1970 1985 1999	RTS	**151**
				ALDF	**163**
Banks (Bks), Victoria (Vic), Bluenose (Blu), Paulatuk (Pau), Richardson Mts. /Peel Plateau (R/PP)	Lewkowicz, 2024	Landsat	1984-2018	RTS	Bks: **4604** Vic: **1403** Blu: **438** Pau: **326** R/PP: **632**
Tuktoyakuk Coastlands, NT	Unpublished data from Steedman et al., 2017	1:12000 (1972) 1:30000 (2004)		IWMP	**148**

Results

Figures 1 to 5 present the distribution of thermokarst landforms and related observations compiled in the database. Figure 1 shows the distribution of all 15,999 thermokarst landforms. Many of these observations are concentrated in the western Arctic, which reflects both the concentrations of studies – particularly remote sensing studies conducted within the Northwest Territories on retrogressive thaw slumps and active layer detachment failures – and because this region of Canada includes significant ground ice (O’Neill et al., 2022).

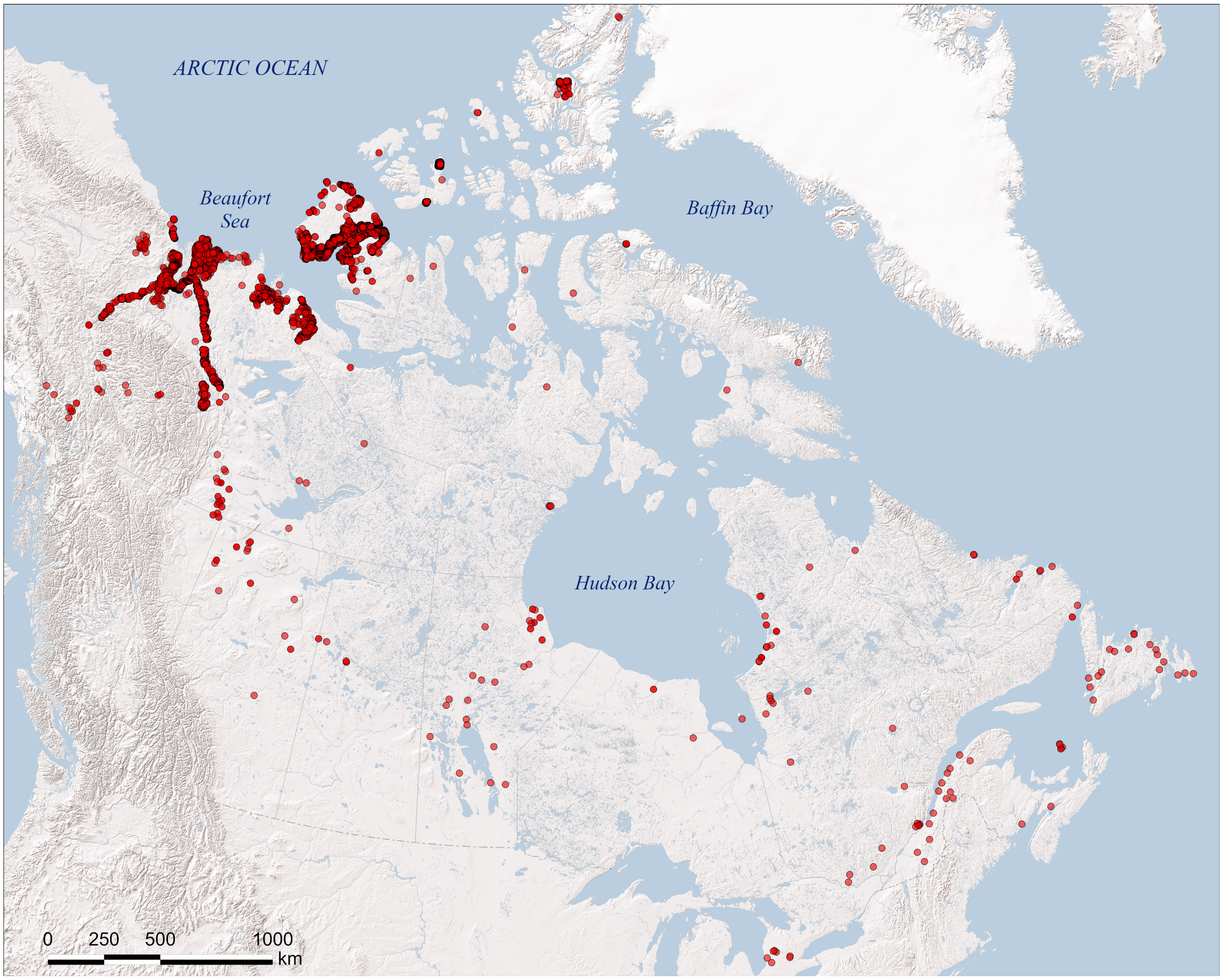

Figure 1. Distribution of all compiled thermokarst and related landforms from remote sensing and field-based studies in the database.

Figure 2 depicts the 14,611 hillslope thermokarst landform observations, including 12,730 retrogressive thaw slumps, 1,715 active layer detachment failures, 163 deep-seated permafrost landslides, and 3 debris flows. Many of these observations were mapped using remote sensing and are concentrated in the western Arctic.

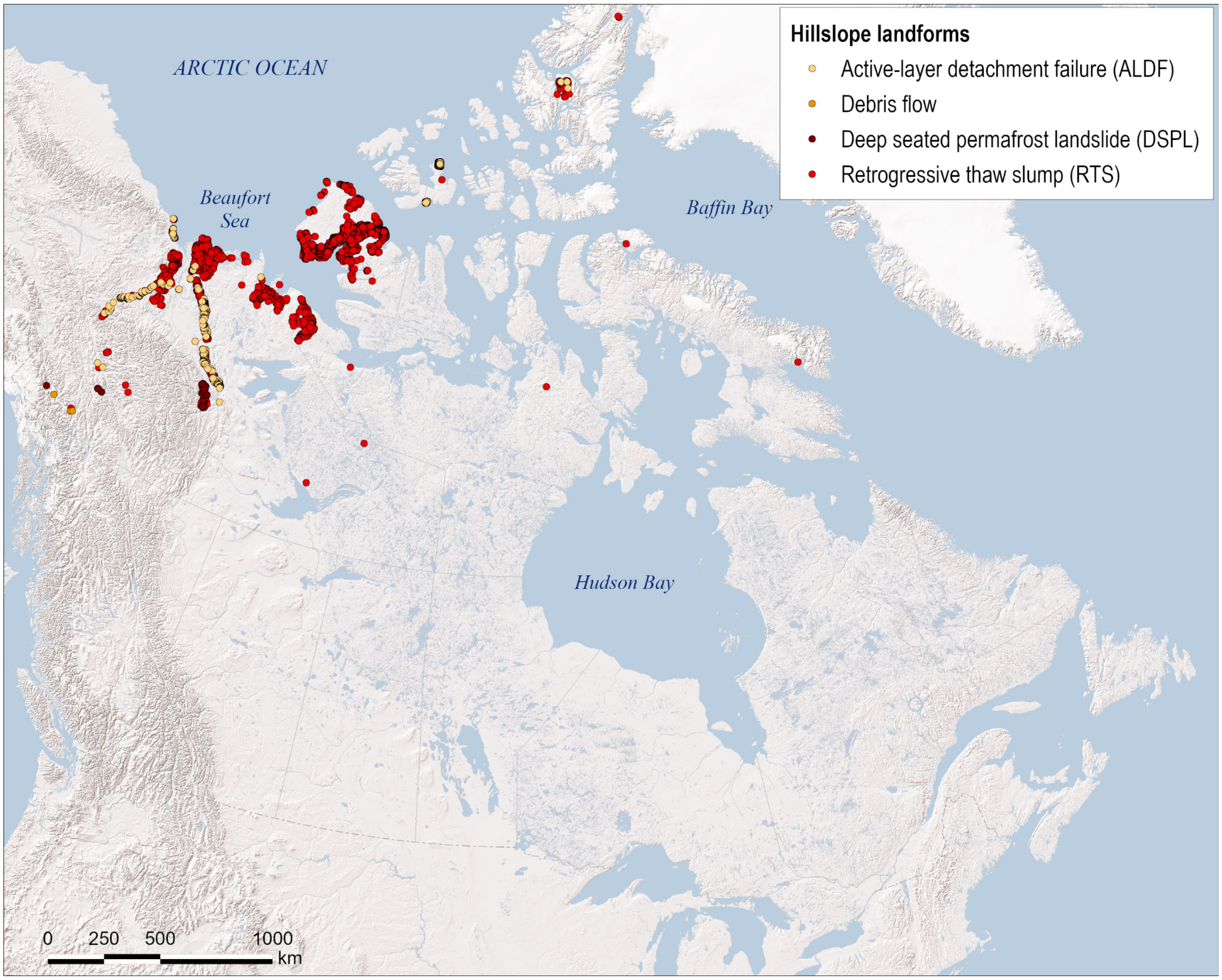

Figure 2. Distribution of all compiled hillslope thermokarst landforms from remote sensing and field-based datasets.

Figure 3 depicts the 245 wedge thermokarst and related observations including 9 deepened ice wedge troughs, 169 ice wedge melt ponds, 8 thermo-erosional gullies, and 59 wedge pseudomorphs. Figure 3 also shows degraded ice-wedge terrain interpreted by Fraser et al. (2023) from analysis of remote sensing data. The results show that degrading ice wedge terrain and field-based observations of ice wedge melt ponds are widespread in the Canadian Arctic Archipelago.

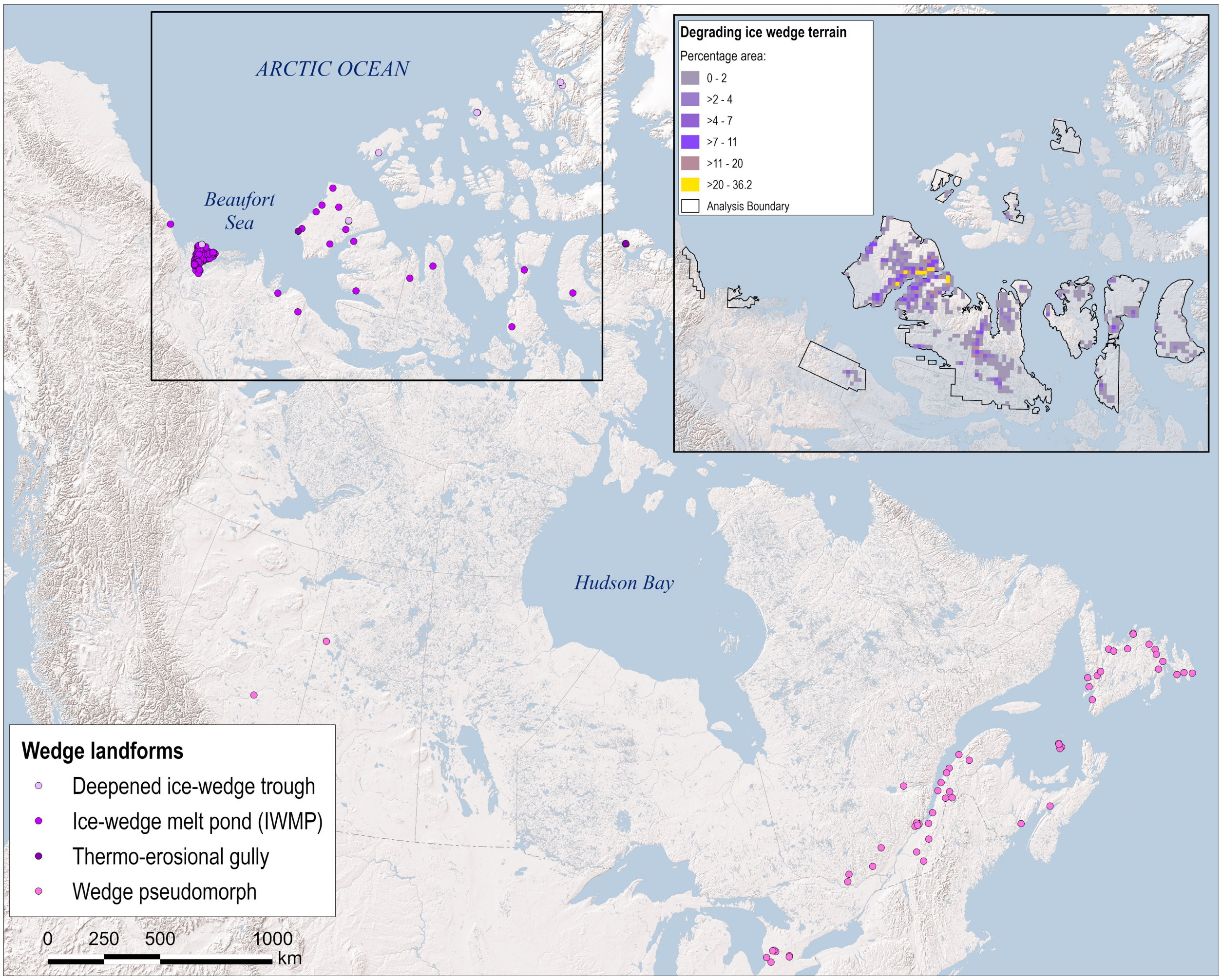

Figure 3. Distribution of all compiled wedge thermokarst and related landforms from remote sensing and field-based datasets. Inset shows percent area of degrading ice wedge terrain in areas mapped by Fraser et al. (2023).

Figure 4 depicts the 1,018 thermokarst lake observations, including 917 remote-sensing observations and 101 field-based observations. Many thermokarst lake observations are concentrated in the western Arctic, presumably due to the focus of remote sensing-based studies in that area. Although under-represented as an observed thermokarst landform, thermokarst lakes are probably widely distributed in fine-grained, unconsolidated sediments in northern Canada.

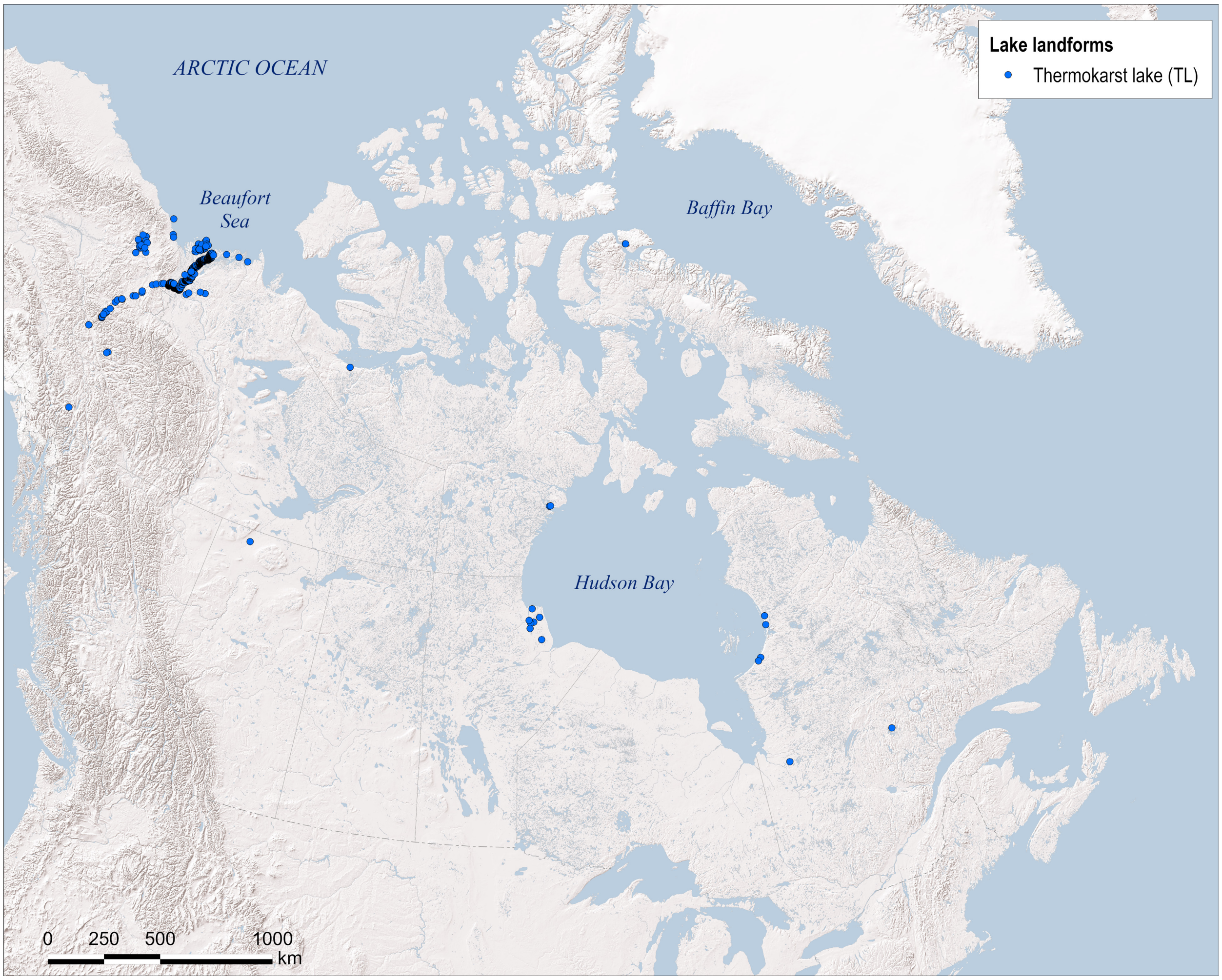

Figure 4. Distribution of all compiled thermokarst lake landforms from remote-sensing and field-based datasets.

Figure 5 depicts the 125 wetland thermokarst landforms including 28 bogs or fens formed following recent permafrost thaw, 28 collapse ponds, 60 collapse scars and 9 internal lawns. All of these observations were from field-based studies.

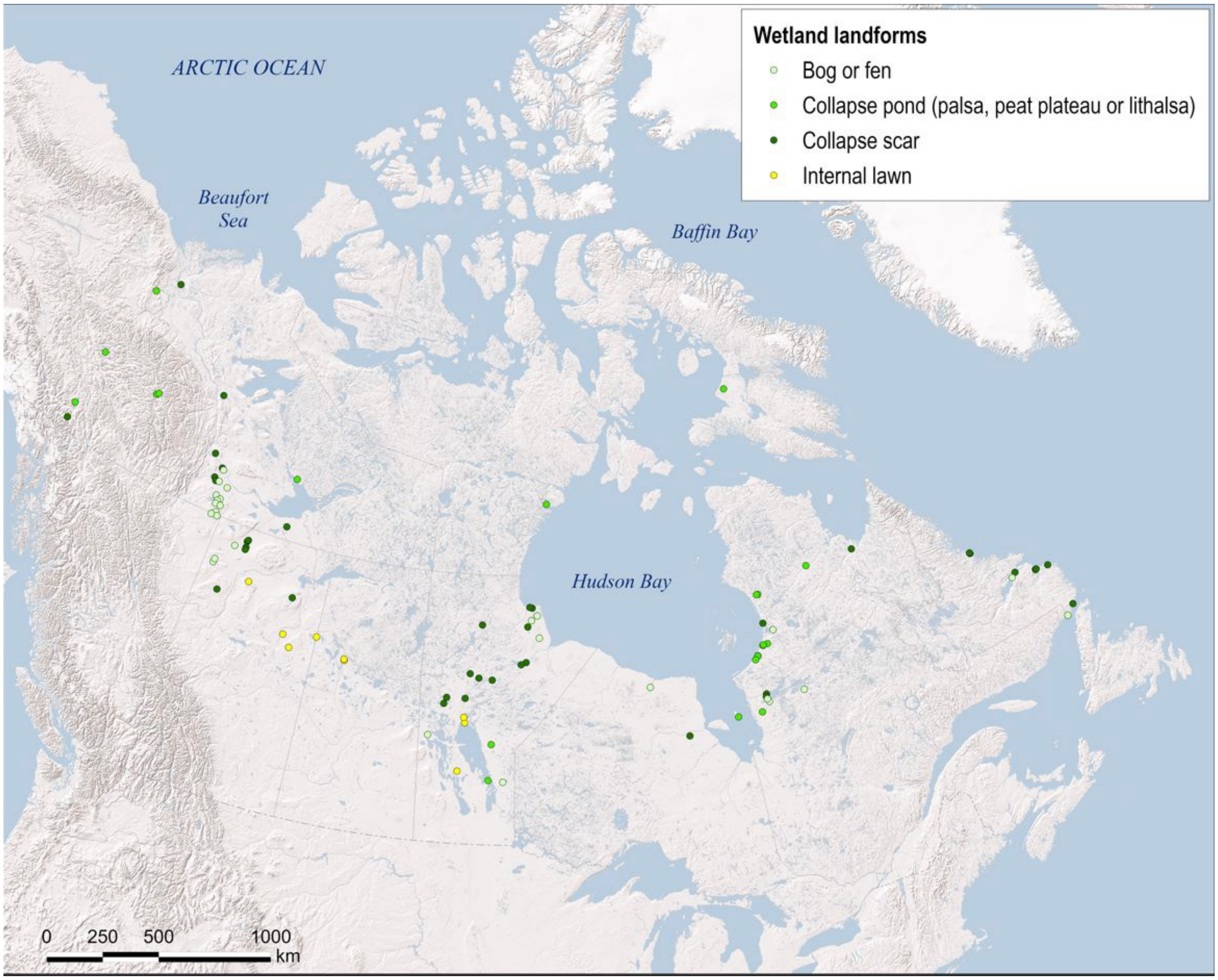

Figure 5. Distribution of all compiled wetland thermokarst landforms from field-based datasets.

Conclusion

In summary, the database likely represents the most complete literature synthesis on research covering observations of thermokarst landforms in Canada to date. The information can be used in future analyses and complements recent grid-based mapping of thermokarst processes and landforms (Kokelj et al., 2023; Fraser et al., 2023).

Note on Citations

All references in the database are provided in Appendix A. Additional references that include pertinent information on thermokarst are included in Appendix B. However, references in Appendix B did not include observations that contributed to the database, either because the observations are represented in another reference, or because observations were of landforms other than the 13 types included in this review. They are provided to serve as a resource for those who wish to learn more about thermokarst.

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Appendix B – Additional thermokarst-related references

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