Large-scale assessment of permafrost conditions using the Canadian Permafrost Electrical Resistivity Survey (CPERS) database

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ABSTRACT

Electrical resistivity tomography (ERT) is a geophysical technique that is commonly used to investigate permafrost conditions because the resistivity of earth materials tends to increase greatly when they are frozen, particularly if they are ice-rich. Despite the increasingly widespread use of ERT for permafrost applications over the last 20 years, data sharing in Canada and most other countries has been limited. We created the Canadian Permafrost Electrical Resistivity Survey (CPERS) database as a platform for standardized and accessible sharing of historical and current ERT datasets collected in permafrost environments. Individual researchers from several Canadian institutions have already contributed 280 ERT datasets and associated descriptive, standardized metadata. These datasets were collected between 2008 and 2022 from sites in British Columbia, Labrador, Northwest Territories, Québec, and Yukon, as well as Alaska. Here, we used the published datasets to examine relationships between permafrost resistivity, climate data, and site conditions, including landform type, disturbance, and near-surface substrate. The findings show an inverse relationship between mean annual air temperature and permafrost resistivity, with variability controlled by site conditions. These analyses demonstrate the utility of the CPERS database for examining large-scale trends in permafrost conditions across northern North America, a usefulness that will increase in the future as additional datasets are incorporated.

1 INTRODUCTION

Electrical resistivity tomography (ERT) is a geophysical method that images subsurface electrical resistivity in 2D or 3D. The resistivity of unfrozen earth materials depends on factors such as porosity, saturation, pore fluid salinity, and clay content (Archie 1942; Waxman and Smits 1968). ERT has become a common technique for studying permafrost because resistivity increases sharply at the freezing point for most earth materials and is especially high in ice-rich material (Scott et al. 1990). The technique has been used for a diverse range of permafrost applications including assessing permafrost extent and ice content (Lewkowicz et al. 2011; Scapozza et al. 2011; Hilbich et al. 2022), examining the impacts of climate change on permafrost (Mollaret et al. 2019; Etzelmüller et al. 2020; Buckel et al. 2022), evaluating how permafrost thaw affects infrastructure (Lautala et al. 2016; Rossi et al. 2022), and in many other ways. Over the last two decades, the number of academic publications using ERT to study permafrost has increased from 2–3 papers per year to more than 30 per year (Herring et al. 2023). The number of unpublished ERT surveys in permafrost environments is likely much higher.

Despite the widespread use of ERT for characterizing and monitoring in permafrost environments, data sharing has been limited. Consequently, it has been impossible to easily integrate the many existing datasets to make interpretations over large spatial or temporal scales. As part of PermafrostNet, a Canadian research network supported by the Natural Sciences and Engineering Research Council of Canada, we developed the Canadian Permafrost Electrical Resistivity Survey (CPERS) database with the goals of (1) archiving data in a standardized way, (2) establishing and implementing best practices for data processing, and (3) creating a platform for accessible data sharing. Here, we describe the CPERS database and use the first data contributions to examine large-scale trends in permafrost conditions across northern North America.

2 METHODOLOGY

2.1 The CPERS Database

2.1.1 Data contributions

Researchers from the University of Ottawa, Queen's University, and the University of Alberta responded to the initial call for data. These individuals provided data for 280 ERT surveys collected along 209 different profiles (i.e., 71 surveys were repeat surveys taken at the same location). The ERT surveys were collected between 2008 and 2022 in British Columbia, Labrador, Northwest Territories, Québec, and Yukon, as well as Alaska (Figures 1 and 2). Although Alaska is not part of Canada, we chose to include these data due to their proximity and relevance to the Canadian database.

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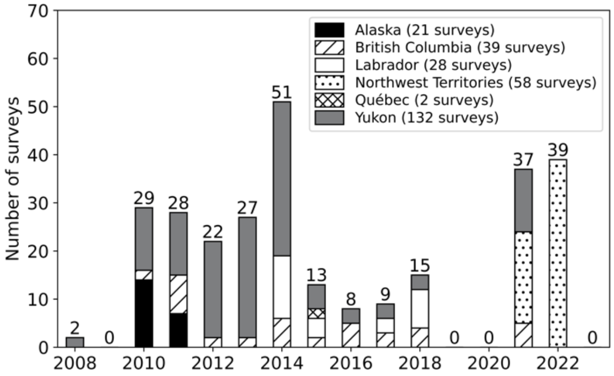


Figure 1. Survey regions and dates for the initial CPERS data publication.

For each survey, data contributors submitted several pieces of information. The first was a mandatory metadata form describing the site (e.g., location, project, related publications, borehole information if applicable), principal investigator information, profile characteristics (e.g., coordinates, landform, vegetation class, near-surface soil/sediment type), and survey characteristics (e.g., date of measurement, array type, topography). Some metadata fields were mandatory and some optional. The metadata form and database structure were developed in collaboration with the International Permafrost Association Action Group "Towards an International Database of Geoelectrical Surveys on Permafrost (IDGSP)" (Mollaret et al. 2022). Data contributors were encouraged to submit their raw ERT data. If submitted, the data contributor was given the option to publish the data immediately or after an embargo period of up to two years.

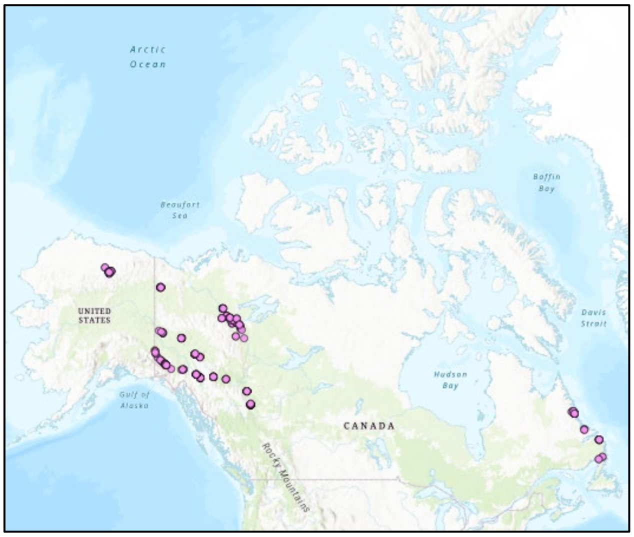
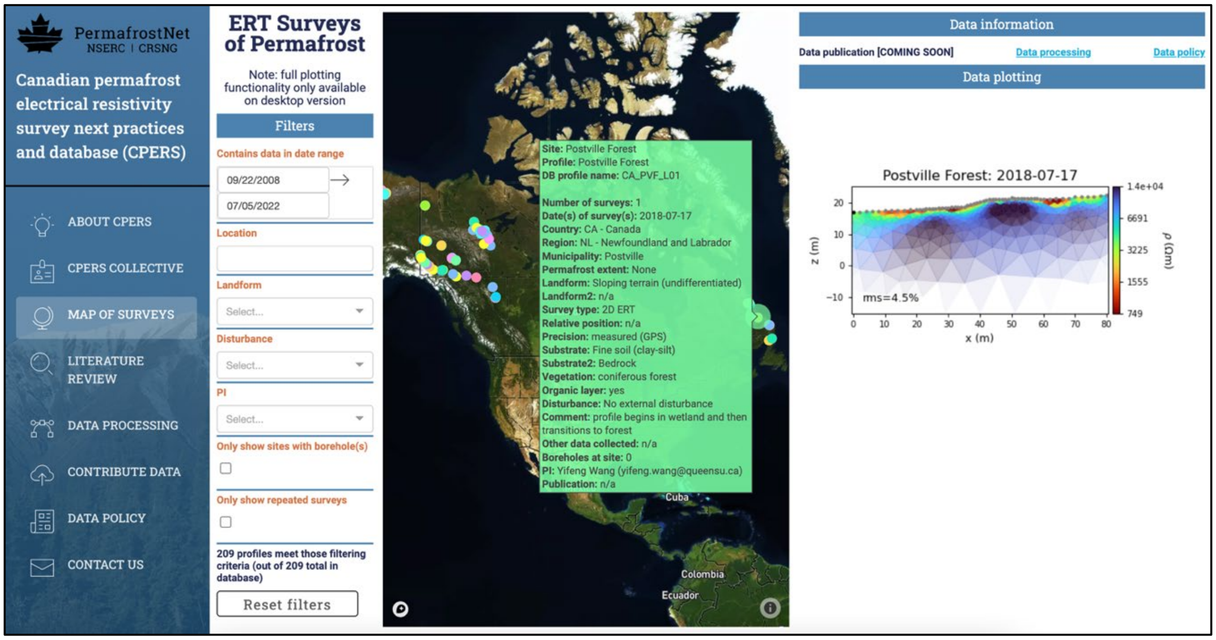


Figure 2. Map of ERT survey locations for the initial CPERS data publication.

2.1.2 Database access

The CPERS database currently consists of: (1) a relational PostgreSQL database hosted by NSERC PermafrostNet and supported by the Digital Research Alliance of Canada, (2) a web interface to enable easy access to data and quick visualization tools (https://data.permafrostnet.ca/cpers/; Figure 3), and (3) a data publication with the repository Nordicana D, hosted by the Centre d'études nordiques (CPERS Collective 2023) so that data are permanently archived in an established repository.



Canadian permafrost electrical resistivity survey next practices and database (CPERS)

ERT Surveys of Permafrost

Note: full plotting functionality only available on desktop version

Contains data in date range
09/22/2008 →
07/05/2022

Location

Landform

Disturbance

PI

Only show sites with borehole(s) ☐

Only show repeated surveys ☐

209 profiles meet those filtering criteria (out of 209 total in database)

Site: Postville Forest
Profile: Postville Forest
DB profile name: CA_PVF_L01

Number of surveys: 1
Date(s) of survey(s): 2018-07-17
Country: CA - Canada
Region: NL - Newfoundland and Labrador
Municipality: Postville
Permafrost extent: None
Landform: Sloping terrain (undifferentiated)
Landform2: n/a
Survey type: 2D ERT
Relative position: n/a
Precision: measured (GPS)
Substrate: Fine soil (clay-silt)
Substrate2: Bedrock
Vegetation: coniferous forest
Organic layer: yes
Disturbance: No external disturbance
Comment: profile begins in wetland and then transitions to forest
Other data collected: n/a
Boreholes at site: 0
PI: Yifeng Wang (yifeng.wang@queensu.ca)
Publication: n/a

Data publication [COMING SOON]

Figure 3. CPERS web interface showing (from left to right): additional resources, querying parameters, profile locations on an interactive map, and standardized data processing output for the selected survey.

The first data release was completed in 2023, and additional datasets will be added in annual database updates.

2.2 Data Analysis

2.2.1 *Standardized data processing*

Since data contributors provided raw, unprocessed ERT measurements, we were able to develop and apply a standardized data filtering and inversion routine to all datasets. The standardized routine for data processing was informed by a literature review (Herring et al. 2023) and iteratively tested and modified to produce reasonable results for all datasets. Data were inverted using PyGIMLi, an open-source geophysical inversion and modelling library (Rücker et al. 2017). The data processing steps are described by Herring et al. (2023) and the open-source data processing code is linked on the CPERS website (https://data.permafrostnet.ca/cpers/processing.html). The outputs of this data processing workflow are shown on the map of surveys on the CPERS website.

2.2.2 *Data visualization*

To better understand large-scale trends in permafrost resistivity, we plotted average resistivity as a function of mean annual air temperature (MAAT). MAAT was chosen because these data are easily available and closely related at a continental scale to the ground thermal regime (Smith and Riseborough 2002). A single average resistivity value was calculated for each ERT survey by averaging the resistivity of all model cells where the coverage value (calculated by PyGIMLi during inversion based on the normalized model sensitivity) was above 0.3. Defining this zone of sensitivity ensured that model cells with low sensitivity were not included in the calculation. The MAAT was calculated for each site by averaging Daymet air temperatures over the 10 years preceding the survey date (Thornton et al. 2022). For this analysis, only publicly available (i.e., non-embargoed) ERT datasets are used. Additionally, only data collected between June and October are presented in order to reduce the influence of seasonal variation on the results. Consequently, this analysis includes a total of 231 data points collected between 2008-2022 in British Columbia, Labrador, Northwest Territories, Québec, and Yukon, and Alaska.

3 RESULTS

The plots of average resistivity vs. MAAT showed a trend of increasing resistivity with colder air temperatures, with significant scatter (about two orders of magnitude) around the line of best fit (Figure 4). Previous work has observed scatter in the relationship between MAAT and mean annual ground temperature at sites across Canada, with local variability attributed to lithology, snow conditions, vegetation, and water/ice content (Throop et al. 2012). Although resistivities were lower at higher MAATs, there was no sharp discontinuity in the distribution at 0 °C. This is likely because sites included in the database are biased to include sites where permafrost has been able to persist at MAATs that exceed 0 °C.

As electrical resistivity is also expected to vary with local parameters, we used the information contained in the submitted metadata to examine how different site conditions affected subsurface resistivity.

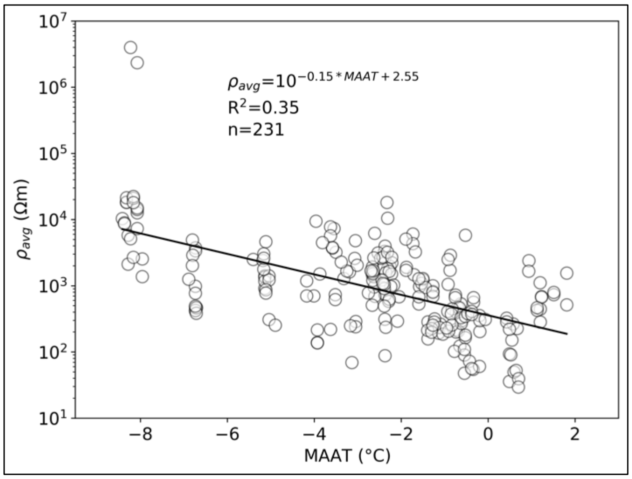


Figure 4. Average inverted resistivity in the zone of sensitivity (see text for further description) as a function of MAAT averaged over the 10 years preceding the survey date, including the line of best fit. Note the logarithmic y-axis.

We found that some of the variability in average resistivity could be attributed to landform type. Many landforms had only a few data points, making it difficult to make reliable interpretations. However, data points associated with some landforms showed clear deviation from the trendline (Figure 5a). Higher resistivities were observed in permafrost landforms that are likely to be ice-rich, like lithalsas and palsas. In contrast, thermokarst mounds tended to exhibit lower resistivities, likely due to warmer, wetter conditions (Kokelj and Jorgenson 2013).

Some variability in resistivity appeared to be correlated with near-surface conditions. We found that profiles with no organic layer tended to have lower resistivity than those where an organic layer was present (Figure 5b), potentially indicating lower ground temperatures, higher ice content, or both. Previous works have noted an organic layer of moss and/or peat serves to protect permafrost from warming climates (Yi et al. 2007; Shur and Jorgenson 2008). The observed large-scale resistivity trends suggest a link between organic layer cover and permafrost preservation.

Additionally, there was a pronounced relationship between anthropogenic surface disturbance and average subsurface resistivity, where sites with no anthropogenic disturbance had much higher average subsurface resistivities than sites where surface disturbance covered more than 50% of the profile (Figure 5c). This is likely due to local ground warming, and consequently lower resistivities at disturbed sites. Sites classified as having surface disturbance include revegetating agricultural land, school fields, cleared areas, gravel pads, a golf course, a

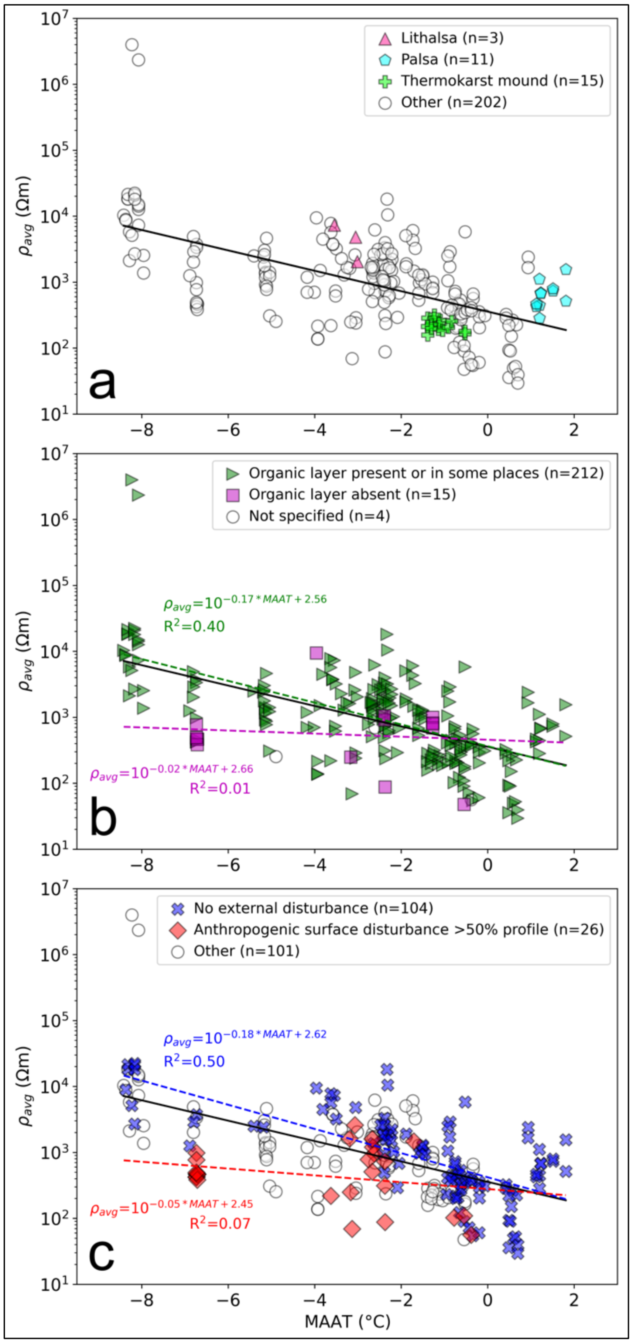


Figure 5. Average inverted resistivity in the zone of sensitivity as a function of MAAT, where the trend line for the entire dataset is shown in black and trend lines and statistics for subsets are shown in their respective colours. Some site characteristics were associated with deviations from the overall trend, including a) landform type, b) the presence or absence of a near-surface organic layer, and c) anthropogenic surface disturbance.

sewage lagoon, a firebreak, airports, roads, and trails. In several other studies, anthropogenic surface disturbances have been shown to cause permafrost thaw, subsidence, slumping, erosion, and ponding in permafrost environments (Brown and Grave 1979; Slaughter et al. 1990; Smith and Riseborough 2010; Williams et al. 2013). It is therefore not surprising that sites with surface disturbance show lower average resistivity values, representing degraded permafrost conditions.

4 DISCUSSION

The results presented here do not represent an exhaustive analysis of every parameter that could affect permafrost resistivity, but these findings confirm the expected trend of increasing resistivity in colder regions and indicate that some of the variability is likely attributable to the landform type, near-surface conditions, and disturbance. This represents an important step towards large-scale interpretations of permafrost landscapes across Canada.

The analyses to date are limited by the number of data points in the CPERS database. The total of 231 ERT surveys included in this analysis represents an enormous collective effort of several different researchers, northern communities, and institutions. Even so, it is difficult to make conclusive interpretations of some trends. For example, sixteen different landform types are represented in the database, but there are fewer than five ERT surveys for ten of these landforms. Furthermore, the CPERS database has data gaps in the northern parts of central and eastern Canada. Some permafrost landforms and regions are therefore underrepresented in this analysis. With the contribution of additional ERT surveys to the database, we should be able to examine a larger number of relationships and identify trends and variability with greater certainty.

In this work, we used average resistivity within the zone of sensitivity as a first-pass analysis tool. This does not account for differences in survey length or depth of investigation. In other studies, researchers have averaged modelled resistivities in a manually-defined zone of interest to better represent permafrost conditions (Kneisel et al. 2014; Etzelmüller et al. 2020; Hilbich et al. 2022). Future work could involve defining a site-specific zone of interest for each ERT profile or examining resistivity as a function of depth to differentiate resistivity trends for near-surface and deeper permafrost.

Furthermore, there is some uncertainty in the resistivity and temperature values used here. Uncertainty in modelled resistivities exists due to the limited data coverage and smoothness constraints applied during the inversion. Consequently, ERT inversion does not exactly recover true subsurface resistivities, especially in permafrost environments where large resistivity contrasts and sharp boundaries are common (Supper et al. 2014; Herring and Lewkowicz 2022). There is also uncertainty in the MAAT data. The values presented were interpolated from ground-based observations, but climate stations in Canada's North tend to be sparse (Vincent et al. 2009). The MAAT values presented here therefore represent an initial estimate.

5 CONCLUSIONS

Our analysis of 231 ERT surveys collected across Canada showed a distinct overall trend of increasing average subsurface resistivity at colder sites, with a large spread about the line of best fit. This spread can be attributed to several different factors. Here, we showed that landform type and near-surface conditions, including the presence of an organic layer and degree of anthropogenic surface disturbance, correlated with deviations from the overall trend. Additional datasets and analysis techniques are expected to enable more robust interpretations of Canada-wide permafrost conditions and relationships to climatic and environmental factors. To this end, we invite researchers and practitioners to contribute their ERT datasets to the CPERS database during planned annual updates.

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