Characterizing Near-Surface Permafrost in Utqiaġvik, Alaska, using Electrical Resistivity Tomography and Ground Penetrating Radar

Valentina Ekimova[1, 2], MacKenzie A. Nelson[1], Taylor Sullivan[3], Thomas A. Douglas[3], Howard E. Epstein[1], Matthew G. Jull[4]

5 [1]Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904-4123, USA
[2]Environmental Institute, University of Virginia, Charlottesville, VA 22902, USA.
[3]U.S. Army Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Fort Wainwright, AK 99703-0170, USA
[4]Department of Architecture, University of Virginia, Charlottesville, VA 22903, USA

10 *Correspondence to*: Valentina Ekimova (sqa2tu@virginia.edu)

Abstract. Permafrost degradation in Arctic lowlands is a critical geomorphic process, increasingly driven by climate warming and infrastructure development. This study applies an integrated geophysical and surveying approach—Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR), and thaw probing—to characterize near-surface permafrost variability across four land use types in Utqiaġvik, Alaska: gravel road, snow fence, residential building and

15 undisturbed tundra. Results reveal pronounced heterogeneity in thaw depths (0.2 to >1 m) and ice content, shaped by both natural features such as ice wedges and frost heave and anthropogenic disturbances. Roads and snow fences altered surface drainage and snow accumulation, promoting differential thaw, deeper active layers, and localized ground deformation. Buildings in permafrost regions alter the local thermal regime through multiple interacting factors — for example, solar radiation, thermal leakage, snow cover dynamics, and surface disturbance — among others. ERT identified high-resistivity

20 zones (>1,000 $\Omega\cdot$m) interpreted as ice-rich permafrost and low-resistivity features (<5 $\Omega\cdot$m) likely associated with cryopegs or thaw zones. GPR delineated subsurface stratigraphy and supported interpretation of ice-rich layers and permafrost features. These findings underscore the strong spatial coupling between surface infrastructure and subsurface thermal and hydrological regimes in ice-rich permafrost. Geophysical methods revealed subsurface features and thaw depth variations across different land use types in Utqiaġvik, highlighting how infrastructure alters permafrost conditions. These findings

25 support localized assessment of ground stability in Arctic environments.

1 Introduction

Permafrost—frozen earth material such as soil, sediment, organic matter, or rock persisting below 0 °C for at least two consecutive years—provides the physical foundation of Arctic landscapes and infrastructure, but its long-term stability is tightly linked to surface thermal conditions that are now being disrupted by climate change and land use (Grosse et al., 2011;

30 Kudryavtsev, 1978; Popov, 1967).

These disruptions are particularly evident in the Arctic, which has warmed at more than twice the global average over the past century (~2.7 °C), with Alaskan permafrost warming by 1.5–2 °C in upper layers since the late 1980s and up to 3 °C in some areas (Moon et al., 2024; Romanovsky et al., 2010). Warming is also evident at depth, with rates of 0.4–0.6 °C per decade recorded at 15–20 m since the early 2000s, including a 0.05 °C rise at 16 m in Utqiaġvik between 2003 and 2023.

35 Infrastructure-induced changes in snow accumulation, surface hydrology, and thaw dynamics threaten to locally accelerate such permafrost warming (EPA, 2024; Spero et al., 2025).

For infrastructure planning and monitoring, it is important to recognize that permafrost does not respond uniformly to warming. Its behavior is strongly shaped by subsurface heterogeneity – including ice-rich zones (>20–30% ice), taliks (unfrozen nonsaline zones), and cryopegs (saline unfrozen layers) — which significantly contribute to the thermal regime

40 and structural stability of frozen sediments (Shumsky, 1959; Yershov, 2004). This heterogeneity means that the impacts of climate warming are expressed in multiple ways. Warming promotes thaw of frozen sediments and increases active layer thickness—the seasonally thawed layer above permafrost (Hinkel and Nelson, 2003; Jorgenson et al., 2001; Shiklomanov et al., 2010). It also triggers phase transitions of pore ice and pore water redistribution, which reduce the strength and bearing capacity of permafrost, increasing the risk of settlement, frost heave, structural failure, and generating significant financial

45 losses for Arctic communities and regional economies (Biskaborn et al., 2019; Chuvilin et al., 2022; Frolov, 2016; Hjort et al., 2022).

As Hjort et al. (2022) showed, nearly 70% of Arctic infrastructure is at risk of permafrost thaw by 2050 for Utqiaġvik specifically. Moderate to high ground subsidence was projected under future climate scenarios (Streletskiy et al., 2023). These projections highlight Utqiaġvik as an area of concern where detailed, site-specific characterization of near-surface

50 permafrost is needed to understand how different infrastructure types affect permafrost conditions. To address this need, noninvasive geophysical techniques provide effective tools for investigating subsurface heterogeneity, offering insights that are critical both for assessing site conditions prior to construction and for monitoring infrastructure performance over time (Hauck and Kneisel, 2008).

A range of methods—including Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), seismic

55 surveys, Electromagnetic Induction (EMI), and Nuclear Magnetic Resonance (NMR)—enable larger-scale and dynamic monitoring (Kneisel et al., 2008; Tourei et al., 2024; Yoshikawa et al., 2006). In Alaska, geophysical surveys were first applied during WWII (Hopkins and Karlstrom, 1955) and have since become standard tools, with GPR and ERT particularly widespread (Kim et al., 2021).

GPR has been applied in Arctic permafrost research since the 1970s to image cryostructures (Annan et al., 1975). It detects

60 subsurface contrasts in dielectric permittivity, which is sensitive to water content, using electromagnetic pulses (Daniels, 2004). Typical GPR systems include a transmitter, receiver, and control unit (Jol, 2008). GPR is well-suited for identifying active layer thickness and structures such as ice lenses and wedges (Brandt et al., 2007; Edemsky et al., 2024; Hinkel et al., 2001; Moorman et al., 2007; Munroe et al., 2007). Frequencies range from ~12.5 MHz to >2 GHz; 200–400 MHz antennas provide shallow imaging (~10 m), and <100 MHz enables deeper, lower-resolution surveys (Daniels, 2004; Hauck and

65 Kneisel, 2008). Resolutions can reach 0.2 m in ideal settings (Gusmeroli et al., 2015; Westermann et al., 2010; Wollschläger et al., 2010). However, conductive or saline soils limit signal penetration (Dafflon et al., 2013; Daniels, 2004). Gravel pads and other coarse materials reduce permittivity contrast, underscoring the benefits of combining GPR with ERT (Annan et al., 1975; Moorman et al., 2003).

ERT, first used in Arctic permafrost studies in the 1970s (Hoekstra et al., 1975), was adapted for tomographic applications

70 by Kneisel et al. (2000). ERT measures resistance via electrodes in surface or borehole arrays to create 2D or 3D resistivity images (Kneisel et al., 2014; Loke et al., 2021). High ice-content soils typically exhibit 400–2000 Ωm, while unfrozen or saline zones are 10–20 Ωm (Herring et al., 2023; Tourei et al., 2024). Dry, coarse-grained materials and saline cryopegs obscure resistivity contrasts, complicating interpretation (Fortier et al., 2023; Kvon et al., 2019). Advances in systems and inversion algorithms now allow 15–30 m depth imaging with vertical resolution ~25% of electrode spacing (Kneisel et al.,

75 2014). Saturated active layers reduce penetration, and field deployment in Arctic terrain remains logistically demanding (Dafflon et al., 2013; Kneisel et al., 2008).

Coupled GPR–ERT interpretation enhances reliability in identifying subsurface features such as ice lenses, cryopegs, taliks, and wedge structures (Bobrov et al., 2018; Dafflon et al., 2013; Leger et al., 2017; Saintenoy et al., 2020). Numerous examples of independent GPR and ERT surveys in Utqiaġvik exist (Dafflon et al., 2020; Hinkel et al., 2001; Jafarov et al.,

80 2017). Combined use is less common; Leger et al., (2017) applied GPR (500 MHz) and ERT (0.5 m dipole–dipole) in polygonal tundra. Kim et al., (2025) employed GPR (250/500 MHz) and ERT (Wenner, 1 m spacing) to assess snow-fence impacts, showing snow-enhanced insulation deepens thaw and triggers subsidence. Other Arctic studies using this integration span Alaska (Yoshikawa et al., 2006), Canada (Kneisel et al., 2008; Moorman et al., 2003), Russia (Bobrov et al., 2018; Buddo et al., 2024; Olenchenko et al., 2017), Sweden (Sjöberg et al., 2015), Norway (Pace et al., 2024) and Greenland

85 (Ingeman-Nielsen et al., 2012).

To extend these geophysical approaches to a local context, we conducted GPR and ERT surveys during peak seasonal thaw in 2021–2023 in Utqiaġvik, Alaska. Our focus on residential buildings, raised gravel roads, and snow fences reflects the most widespread infrastructure types in the Arctic, with undisturbed tundra included as a natural reference. Together, these settings allow evaluation of how both natural conditions and human disturbance shape near-surface permafrost. Geophysical

90 profiles were interpreted alongside 3 m resolution satellite imagery (ESRI/QGIS) to provide site-specific insight into permafrost–infrastructure interactions.

2 Site Description and Survey Locations

Utqiaġvik (formerly Barrow), Alaska (71.290558, -156.788605) lies within the zone of continuous permafrost at the northernmost tip of the state. The region experiences a mean annual air temperature of ~–12 °C, with ground temperatures

95 around -9 to -9.5 °C at 20–30 m depth (Jorgenson et al., 2008; Liu, 2020). Permafrost extends 200–400 m deep and underpins sensitive ecosystems and infrastructure (Bunnell et al., 1975; Hinkel et al., 2001; Osterkamp and Payne, 1981).

The area is underlain by Quaternary nearshore marine, alluvial, and eolian sediments forming the Gubik Formation, divided into the Barrow Unit (organic-rich sands, silts, and gravels) and the Skull Cliff Unit (marine, clay-to-cobble materials) (Black, 1964; Sellmann and Brown, 1973). Ice-rich permafrost is common, with segregated ice reaching 40–80% by volume

100   and massive ice wedges several meters deep (Jorgenson et al., 2008; Kanevskiy et al., 2017; Munroe et al., 2007; Zhang et al., 1999). Cryopegs occur at ~10–30 m depth (Brown, 1969; Iwahana et al., 2021).

Thermokarst features and ground subsidence are widespread due to ice content and thaw sensitivity (Farquharson et al., 2016; Hinkel and Hurd, 2006; Hinkel and Nelson, 2003; McCarthy, 1994). Active layer thickness generally ranges from ~0.3 to 1.0 m, influenced by vegetation, soil, and climate variability (Hinkel and Nelson, 2003; Shiklomanov et al., 2010), with

105   deepening trends observed in recent decades (Nyland et al., 2021; Victor, 2022).

Surveys were conducted at four sites (Fig. 1): (1) a Taġiuġmiullu Nunamiullu Housing Authority (TNHA) residential area with localized thermokarst; (2) the old section of Cakeeater Road that crosses an ice-wedge polygonal landscape; (3) a snow fence with delayed melt and frost heave (Hinkel and Hurd, 2006); and (4) the Barrow Environmental Observatory (BEO), representing undisturbed tundra (Hinkel and Nelson, 2003). These sites represent a range of infrastructure and land use

110   conditions relevant to permafrost degradation and geophysical monitoring.

Figure 1: Location of geophysical survey (ERT - blue dots, GPR - green dots) sites in Utqiaġvik, Alaska, shown on ESRI satellite imagery in QGIS. Sites include (a) the Taġiuġmiullu Nunamiullu Housing Authority (TNHA) residential facility, (b) the old section
115 **of Cakeeater Road, (c) a snow fence location near Cakeeater Road, and (d) the Barrow Environmental Observatory (BEO).**

3 Geophysical and Ground Truth Methods

Field data were collected near peak thaw conditions in late summer (late August - early September) in 2021, 2022, and 2023. ERT data were collected using a SuperSting R8 system (AGI, Inc.) with 84 stainless steel electrodes. Electrode spacing ranged from 1 to 5 meters depending on the survey design, targeting both near-surface and deeper permafrost features. All
120 measurements were conducted in a dipole–dipole array configuration, which provides high resolution of lateral resistivity contrasts and is commonly used in permafrost investigations (Douglas et al., 2016; 2025). The SuperSting R8 has a nominal measurement range of 0.01–105 Ω·m, though measurement precision can be reduced at the extreme ends of this range. Raw apparent resistivity data were reviewed and filtered to remove values with noise levels exceeding 3% or with poor reciprocal error statistics. Inversion was performed using ResIPy (Blanchy et al., 2020), a Python-based interface for the R2 resistivity
125 modeling engine, which allows flexible constraint testing and model optimization. Regularization parameters were adjusted iteratively based on data misfit and model smoothness. Topographic data were incorporated into the inversion. The resulting 2D resistivity cross-sections were interpreted in the context of known permafrost resistivity ranges to infer thaw depth, cryopegs, and ice-rich zones.

GPR data were collected using a GSSI system with 200 and 400 MHz shielded antennas and processed using GPRPy
130 (Plattner, 2020), an open-source Python-based package designed for reproducible radargram analysis. Processing steps included high-pass filtering of the low-frequency drift, mean subtraction, time-zero correction, and manual gain control. Horizontal scaling was performed using GPS-referenced distances. Data were further processed with background removal and bandpass filtering to enhance reflection continuity. Two-way travel time was converted to depth as $z=vt/2$. We used a constant v=0.050 m·ns^{-1}, obtained by aligning the permafrost-table reflector with active-layer thickness at co-located thaw-
135 probe points. This value is consistent with published velocities for thawed, fine-grained (silt-dominated) active-layer sediments. Within 0–1 m, the absolute difference between GPR-derived depths and probe measurements was ≤ 0.08 m. Interpretation of thaw depth and ice-rich features was based on reflection strength, geometry (e.g., hyperbolas), and signal attenuation, following best practices established in Arctic GPR surveys (Munroe et al., 2007; Shein et al., 2022).

Thaw probing served as the primary ground validation technique, involving the insertion of a metal probe into the ground
140 until reaching the point of refusal, which corresponds to the depth of the permafrost table. This method is highly effective for identifying the depth to permafrost but is less reliable in rocky terrain due to probe obstruction (Boike et al., 2022).

Following field data acquisition, transect locations were mapped in QGIS using high-resolution ESRI World Imagery (ESRI, 2024; QGIS Development Team, 2024). Satellite-based interpretation of surface features—such as ice-wedge polygons, thaw ponds, and infrastructure effects—supported the analysis of ERT and GPR results. Many surface observations corresponded
145 with geophysical anomalies, underscoring the complementary role of remote imagery in subsurface interpretation.

4 Results and Discussion: Integrated Geophysical Investigation of Permafrost Degradation in Utqiaġvik

Our sites include infrastructure-affected areas (TNHA, Cakeeater Road, Snow Fence) and relatively undisturbed tundra (BEO), selected to capture variability in permafrost conditions across different land use types. Most profiles yielded interpretable data; some were excluded due to signal loss or environmental noise. While time-series comparisons were
150   limited, representative datasets were selected for analysis.

Each site is discussed individually, focusing on thaw depth variability, distribution of subsurface ice, and infrastructure-related effects. For large-scale ERT profiles, interpretation relied on approximate resistivity ranges commonly used in Arctic permafrost studies, including Tourei et al. (2024). These include: A) very low resistivity (0.5–10 Ω·m), typically associated with cryopegs; B) low resistivity (10–100 Ω·m), characteristic of the active layer; C) moderate to high resistivity (400–
155   1,000 Ω·m), representing transition zones between frozen and unfrozen ground; D) high resistivity (>1,000 Ω·m), indicating ice-rich permafrost; and E) very high resistivity (~10,000 Ω·m or greater), suggesting excess ice features such as ice lenses and ice wedges. These ranges are used as interpretive guides rather than fixed thresholds. A cross-site synthesis follows, comparing patterns in permafrost response and dominant influencing factors.

4.1 Taġiuġmiullu Nunamiullu Housing Authority (TNHA)

160   Ground surveys were conducted at the Taġiuġmiullu Nunamiullu Housing Authority (TNHA) site in August 2021, including two intersecting transects of ERT and GPR data, as well as thaw probing. These measurements—covering both the area beneath the building and the surrounding terrain—form the basis of the analysis presented here.

The west–east trending ERT profile (W–E blue line, Figure 2a) at the TNHA site extended 83 m with 1-meter electrode spacing and covered areas both beneath and adjacent to the building. GPR (W–E green line, Figure 2a) was conducted along
165   the same transect, spanning 53 m, but did not extend beneath the structure. Thaw probing was performed along the ERT line as well (Figure 2b), which also include the area beneath the building, but does not cover the gravel pad near the building.

The north–south ERT survey (Figure 2a, N-S blue line) was conducted with electrodes spaced at 1-meter intervals along an 83-meter transect, crossing beneath the building at the midpoint. The GPR survey (Figure 2a, N-S green line) was conducted alongside the ERT for the first 20 m of the transect (north of the building).

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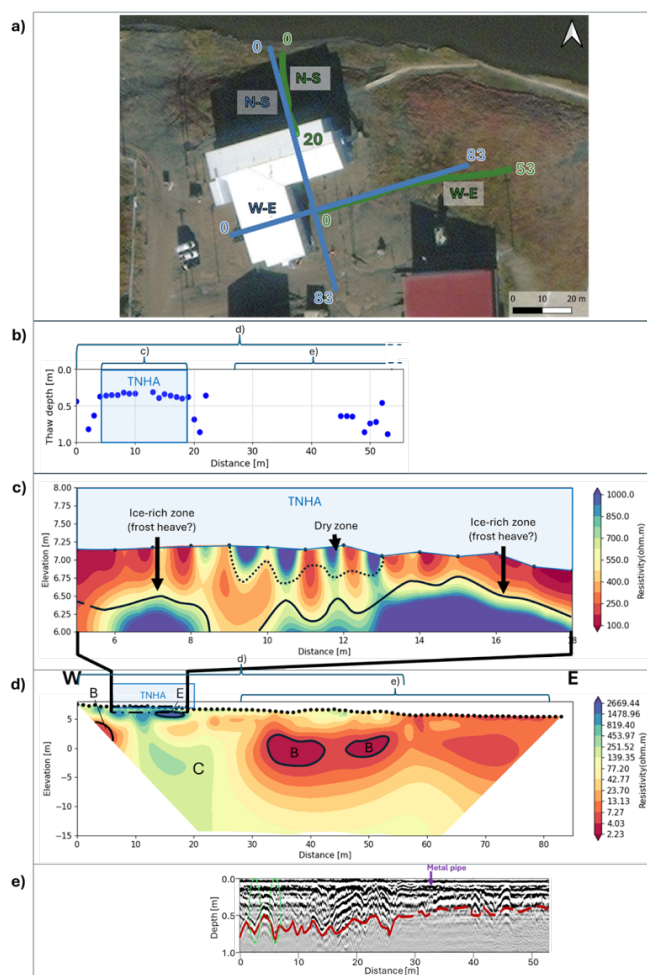
Figure 2: Geophysical survey results along the west–east (W–E) transect at the Taġiuġmiullu Nunamiullu Housing Authority (TNHA) site, Utqiaġvik, Alaska. (a) Survey layout: ERT profile (blue) and GPR profile (green) overlaid on ESRI basemap (QGIS); (b) Thaw probe measurements along the ERT transect; (c) Fine-scale ERT view of upper 1.3 m below the building showing thaw depth (solid black line) and dry zone (dotted line); (d) Large-scale ERT cross-section (~0–15 m depth) with approximate interpretive resistivity zones: A – cryopegs (0.5–10 Ω·m), C – transition zone (400–1,000 Ω·m), D – ice-rich permafrost (>1,000 Ω·m); (e) GPR profile with thaw depth (red line) and potential ice-rich zones (green dashed circles). Elevation is shown in meters above sea level.

The 83 m ERT cross-section (Figure 2d) reveals several zones of very low resistivity (<5 Ω·m), notably on the west side of the building (~5 m depth) and near the center of the transect (~7.5 m depth). These zones likely correspond to cryopegs (Zone A)—saline, unfrozen, water-saturated regions within permafrost. High-resistivity areas (>1,000 Ω·m, Zone D) beneath the building suggest the presence of ice-rich permafrost, possibly including ice lenses. Much of the remaining transect

displays intermediate resistivity values (400–1,000 Ω·m, Zone C), which may indicate frozen ground with variable ice
185   content.

Based on prior studies (e.g., Herring et al., 2023; Tourei et al., 2024) and supported by thaw probing results (Figure 2b),
sediments below ~1 m depth are predominantly frozen. A detailed view beneath the building is shown in Figure 2c,
highlighting vertical resistivity variation due to thaw depth changes (0.2–0.7 m) with shallowing of thaw depth on the east
side, and lateral contrasts likely related to ice content differences.

190   Buildings on elevated pilings can reduce summer ground warming by avoiding direct contact between the ground and the
structure and limiting direct solar radiation through shading. This design often also reduces snow accumulation or limits
snow thickness compared to surrounding undeveloped areas, enhancing winter cooling. In contrast, adjacent areas without
structures tend to retain thicker snow cover, which insulates the ground and leads to higher subnivean temperatures. During
spring, melting snow and roof runoff can saturate soils near the building perimeter, promoting localized thaw. While the area

195   directly beneath the building typically remains shaded and ventilated, increased active layer thickness immediately adjacent
to the building may result from ponding or increased water runoff from the roof, which enhances heat transfer to the ground
through solar exposure. The slightly shallower thaw observed on the east side (~0.2 m) relative to the west (~0.4 m) likely
reflects differences in solar exposure, wind patterns, or snow accumulation. Just beyond the building footprint (starting at 18
m along the transect), thaw depths increase to greater than 0.5 m.

200   The high-resistivity zones beneath the structure in Figure 2d coincide with shallower active layer depths measured by
probing, suggesting the presence of underlying frozen material, potentially ice-rich permafrost. A photo taken beneath the
building on June 28, 2024 (Figure 3a) shows raised surface features that may reflect seasonal frost heaving within the active
layer, caused by the formation of segregated ice lenses during freezing. The specific source of moisture for this process
beneath the building remains uncertain—particularly given the absence of direct snow accumulation or roof runoff—and

205   may involve lateral subsurface water movement from surrounding areas.

An additional high-resistivity zone near the surface in the middle of the building footprint was identified (Figure 2c, dotted
line). While high resistivity often indicates frozen ground, temperature and moisture data suggest otherwise. Temperature
profiles from HOBO sensors installed beneath the building show that this zone thawed by mid-July, with temperatures
exceeding 0 °C, followed by a sharp decline in moisture content by August. These observations indicate that the high-

210   resistivity signature likely corresponds to dry upper soils. Below this zone, a decrease in resistivity is observed between 8.5
and 9.8 m along the transect. This feature may correspond to increased thaw depth, but it could also reflect noise in the ERT
measurements caused by the overlying dry sediments and reduced current penetration.

The W–E GPR profile (Figure 2e), aligned with the easternmost 50 m segment of the ERT profile (Figure 2d), shows thaw
depths (solid red line) ranging from 0.5 to 0.8 m—deeper than those beneath the building, as inferred from ERT. On the

215   eastern end of the profile, reflections from frozen ground are unreliable due to signal interference, likely from a nearby metal
pipe. On the western end, two zones of potential high ice content are observed, though these were not independently verified.

A physical thaw probe survey was conducted along the ERT transect (Figure 2b), including the area beneath the building but excluding the gravel-covered area near the building. Measurements revealed thaw depths ranging from 0.3 m to > 1 m (the measurement limit of the probe), with the shallowest values occurring beneath the building. Thaw depth increased

220   immediately adjacent to the building, consistent with ERT and GPR interpretations.

The N–S ERT inversion profile is shown in Figure 3c–d, featuring a coarse-scale view extending to ~15 m depth across the full transect (Figure 3d), and a fine-scale view focusing on the upper 3 m from 30 to 50 m along the profile, including the area beneath the building (Figure 3c).

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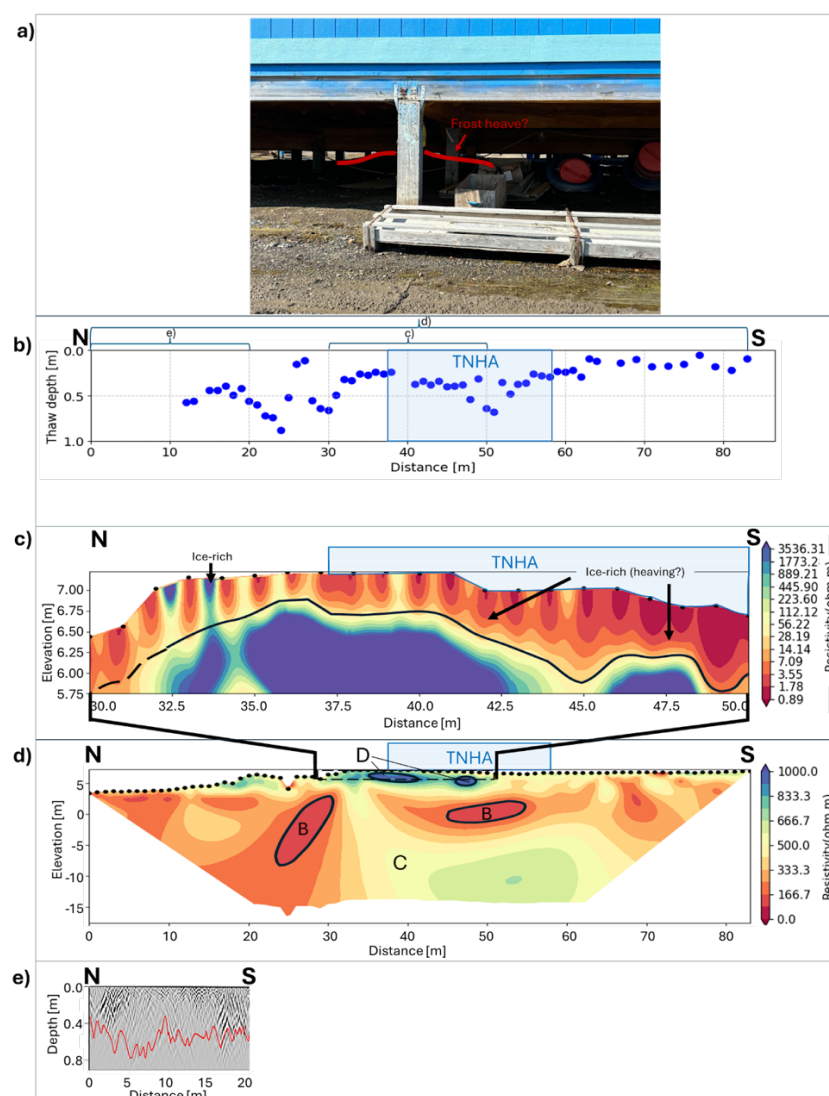
Figure 3: (a) Surface elevation beneath the building at the TNHA site, outlined by the red line, indicating possible frost heave features (28 June 2024); (b) Thaw probe measurements along the N–S ERT transect at the TNHA site; (c) Small-scale view of the

upper 3 m between 30–50 m profile distance, including the building footprint, with thaw depth indicated by solid black line; (d) N–S coarse-scale resistivity cross-section (~0–15 m depth), showing approximate interpretive zones A–E: A – cryopegs (0.5–10 Ω·m),
230 **C – transition zone (400–1,000 Ω·m), D – ice-rich permafrost (>1,000 Ω·m); (e) N–S GPR profile, showing thaw depths (red line). Elevation shown in meters above sea level.**

In the full profile view of the N–S ERT profile (Figure 3d), we observe approximate zones of low resistivity (<5 Ω·m) in the center of the profile (at depths of ~10 m and ~7.5 m), which may correspond to cryopegs (Zone A). High-resistivity zones
235 (>1,000 Ω·m) beneath the building (Zone D) at depths below ~1-5 m are likely indicative of ice-rich permafrost with potential ice lenses. The remainder of the profile, between depths of ~8–12 m and from 35 m to 70 m along the transect, is interpreted as a transitional zone (Zone C) situated between two cryopeg-bearing sections of Zone A. The thickness and depth of this zone vary laterally. In the ERT results, Zone C shows resistivities of 400–1,000 Ω·m, likely reflecting a mixture of frozen and unfrozen material with variable ice content and salinity, and marking the gradual shift between frozen ground
240 and cryopeg-containing sediments.

The fine-scale view (Figure 3c) shows inferred thaw depths (black line) ranging from ~0.3 m to >1 m. The shallowest thaw (~0.3 m) occurs beneath the northern part of the building while thaw depths on the southern side reach ~0.5 m. Beyond the building footprint, thaw depths increase, consistent with the W–E profile results. The ice-rich zones below the building, as seen in both profiles, may be associated with observed surface elevation changes potentially resulting from frost heaving.

245 The N–S GPR profile, corresponding to the northernmost 20 m of the ERT transect, is shown in Figure 3e. Inferred thaw depths (red line) range from ~0.5 to 0.9 m—deeper than those inferred from ERT beneath the northern side of the building (~0.3 m).

A physical thaw-probe survey was conducted along the ERT profiles (Figure 3b). Measured thaw depths ranged from 0.2 m to > 1 m. Beneath the building, thaw depths were consistently ~0.4–0.6 m, deeper than the ~0.3 m inferred from ERT on the
250 northern side but similar to ERT values (~0.5 m) on the southern side (Figure 3c). To the north of the building, probe measurements indicated deeper thaw, while shallower values on the south likely reflect contact with compacted gravel rather than frozen soil. In general, probe results correspond more closely with GPR-inferred depths than with ERT, particularly beneath the northern side of the building.

Based on the combined dataset, the following interpretations are proposed for the TNHA site. The building is elevated
255 ~1.5 m on wood piles, consistent with standard design practices in permafrost regions (Kudryavtsev et al., 1974), which reduces heat transfer by promoting airflow beneath the structure, and limiting solar radiation and snow accumulation. In winter, this exposure allows for enhanced ground cooling, while in summer, shading and limited solar penetration delay thaw, maintaining sub-zero conditions beneath the building until mid-July (as confirmed by temperature sensors).

Moisture sensors indicate high volumetric water content (40–50%) below the building due to delayed thaw. This moisture
260 promotes frost heave during refreezing. Although surface drying occurs late in the summer, sediments remain moisture-rich (~40%) below. These conditions may support permafrost aggradation rather than degradation. Field observations suggest

that frost heaving is most pronounced on the north and east sides, while the west shows less activity. Thaw depths on the south side align with site averages.

Adjacent areas show deeper thaw, reaching ~1 m—especially near the west-side parking lot, where geophysical and probe
265   measurements record ~0.9 m. While the north and east building margins appear stable, the south and west sides are more vulnerable to thaw-related subsidence. Continued monitoring is recommended to assess both frost heave beneath the building and degradation risks at its periphery.

4.2 Permafrost Conditions and Cryoturbation Near the Old Section of Cakeeater Road

ERT and GPR surveys were conducted in early September 2021 near an old spur of Cakeeater Road (a short side road
270   perpendicular to the main Cakeeater Road; see Figure 4a, between green GPR transects #11 and #10). One ERT transect was collected perpendicular to this spur (and parallel to the main road), accompanied by a parallel GPR profile. Two additional GPR profiles were oriented longitudinally along the spur.

The SE–NW ERT profile (Figure 4a, blue line) spans 83 m, with electrodes spaced at 1 m intervals. GPR profile #12 (Figure 4a, green line) is aligned with the ERT transect and extends 80 m. The additional GPR profiles—#10 (140 m) and
275   #11 (120 m)—follow the road alignment. The site is located within an ice-wedge polygon landscape, and the geophysical lines intersect several polygon boundaries (Figure 4a).
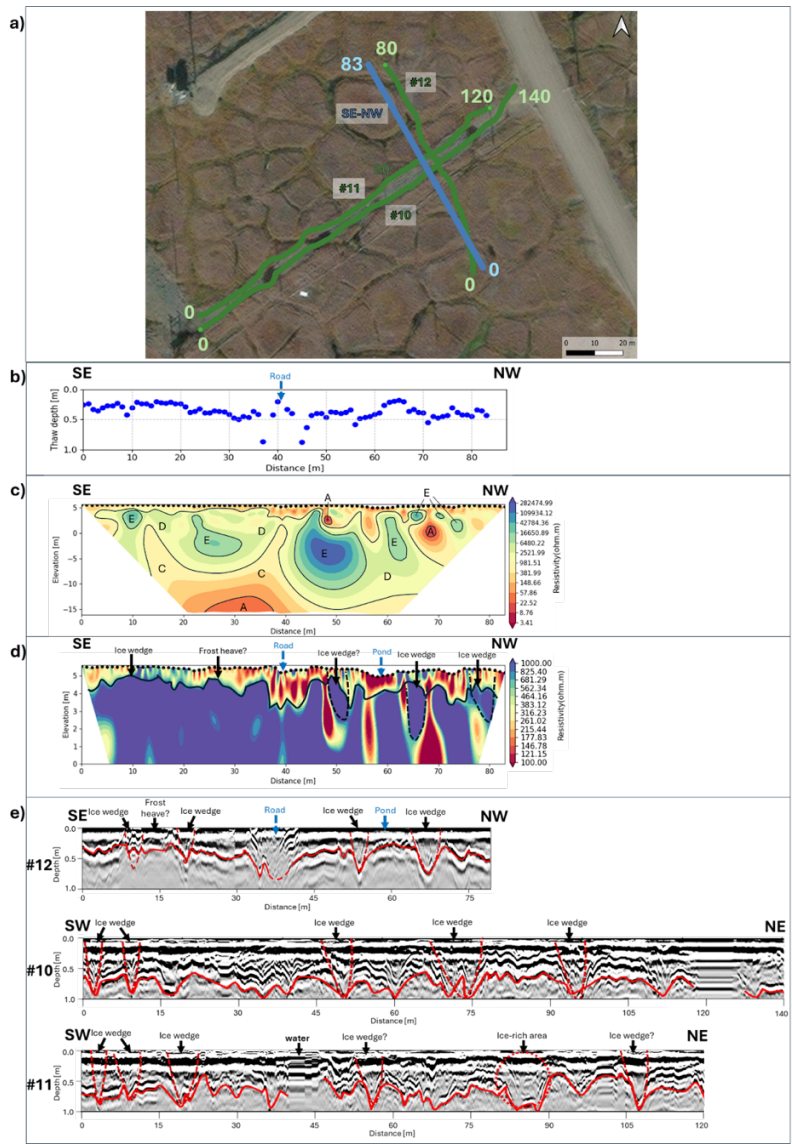
Figure 4: (a) Location of ERT (blue, SE–NW) and GPR (green) profiles near the old section of Cakeeater Road, shown on ESRI satellite imagery (QGIS); **(b)** Thaw probe measurements along the ERT profile and GPR profile #12; **(c)** Coarse-scale SE–NW ERT resistivity cross-section (~0–20 m depth), with black dots indicating electrode positions and zones A–E denoting approximate permafrost features based on resistivity values; **(d)** Fine-scale SE–NW ERT profile (~top 5.7 m), showing thaw depth variability; **(e)** GPR profiles: #12 (aligned with the ERT transect) shows thaw depths (red line) and hyperbolic reflections interpreted as ice wedges (red dashed lines), while profiles #10 and #11 (parallel to the road) show similar features, with #11 also indicating a possible ice-rich zone (red dashed circle).

The SE–NW ERT inversion profile provides a coarse-scale view to ~20 m depth along the transect (Figure 4c). Several high-resistivity zones are evident. One prominent feature, centered at ~10 m depth in the middle of the profile, exceeds 10,000 Ω·m and is interpreted as excess ice (Zone E), likely associated with ice lenses or wedges. Additional ice-rich zones (Zone D, >1,000 Ω·m) are distributed at ~2.5 m, 7.5 m, and 12 m depths. In contrast, three very low-resistivity zones (<5 Ω·m, Zone A) may indicate cryopegs; however, their small size (~1 m) approaches the resolution limit of ERT, adding uncertainty to this interpretation.

The fine-scale resistivity inversion (Figure 4d), focused on the upper ~5.7 m and resistivity values between 100–1,000 Ω·m, resolves shallow permafrost structure and highlights spatial variability in thaw depth. The deepest thaw zone (>1 m) is observed where the SE–NW transect crosses the gravel spur road—even when accounting for its ~60 cm elevation above the surrounding tundra, the thaw beneath the road is deeper than in adjacent tundra. While elevated surfaces might reduce thaw by exposing the ground to cooler air, the thermal properties of the gravel pad—specifically its high conductivity and low albedo—enhance heat absorption and transfer into the ground. These effects likely contribute to the observed deepening of the thaw layer beneath the road (Chen et al., 2020; Qi et al., 2012; Walker et al., 2022). This interpretation aligns with modeling and field studies by Schneider von Deimling et al. (2021), who demonstrated that gravel embankments can intensify subsurface warming by replacing insulating peat, clearing snow from the road center, and facilitating greater summer heat penetration.

The shallowest thaw (~0.2 m) is observed on the southeast (right) side of the road, where polygonal ground appears relatively undisturbed and surface conditions remain intact. In contrast, the northwest (left) side lies between two spur roads—one of which is actively used—and shows visibly smaller polygons and more densely spaced ice-wedge cracks in satellite imagery. This pattern aligns with findings from Walker et al. (2022), who reported that areas within 25 m of gravel roads often experience increased thermokarst activity, altered polygon morphology, and ecological change. The more disturbed surface on the northwest side of the spur road in our study likely reflects similar infrastructure-driven impacts. Here, deeper thaw (~0.5 m) may result from a combination of altered drainage, surface compaction, and localized warming. Low-resistivity zones detected in this area may correspond to ice wedges, although their signatures are less distinct—possibly due to increased moisture content, reduced ice volume, or recent thermal degradation. These variations in thaw depth are consistent with thaw probe measurements collected along the profile (Figure 4b).

GPR profile #12, which follows the SE–NW ERT transect (Figure 4e), further supports the interpretation of thaw depth variability and subsurface structure. It displays multiple vertical hyperbolic reflections—characteristic of ice wedges—resulting from strong dielectric contrasts between ice and surrounding soil. These features align spatially with polygon boundaries visible in satellite imagery (Figure 4a), reinforcing their interpretation as wedge ice. Thaw depths inferred from this profile range from ~0.2 m on the southeast and northwest flanks of the road to >1 m directly beneath it, corroborating the ERT results (Figure 4d) and emphasizing the enhanced thaw associated with the gravel surface.

Additional GPR profiles #10 and #11, which follow the alignment of the spur road but are located outside the raised gravel section (Figure 4e), reveal thaw depths ranging from ~0.5 to 1.0 m. These measurements indicate that the thermal influence

of gravel infrastructure extends beyond the elevated portion of the road. Both profiles also exhibit hyperbolic reflections characteristic of ice wedges, supporting the presence of ice-rich features throughout the area. Notably, GPR profile #11 shows two anomalies: one near +40 m, marked by minimal reflections and likely corresponding to a ponded or saturated zone with low dielectric contrast; and another near +85 m, where strong reflections suggest the presence of an ice-rich

325 body—possibly an ice wedge or another frozen feature. Thaw depths inferred from these profiles, including areas exceeding 1 m, are consistent with the enhanced thaw previously identified in the SE–NW ERT transect (Figure 4d).

Thaw probe measurements collected along the SE–NW ERT and GPR #12 profiles (Figure 4b) ranged from 0.2 m to just under 1 m, closely aligning with geophysical results. The shallowest thaw was found on the south side of the road, where surface disturbance was minimal, while slightly deeper thaw occurred on the north side, adjacent to more visibly altered

330 polygonal ground. Probes placed immediately beside the elevated gravel surface recorded even greater thaw depths, and those inserted directly on the road surface exceeded the penetration limit of the probe—reinforcing ERT and GPR evidence of substantial thaw beneath the road despite its elevation above the surrounding tundra.

Interpretation of the combined datasets indicates clear infrastructure-related impacts at the old spur of Cakeeater Road, even though this section is no longer actively used. ERT and GPR profiles consistently show deeper thaw beneath the road,

335 attributable to the thermal behavior of gravel fill in permafrost regions. While gravel can sometimes offer insulation, in this context it typically enhances heat transfer into the ground due to its high thermal conductivity, low albedo, and tendency to retain moisture (Fortier et al., 2011). Compared to vegetated tundra, gravel absorbs more solar radiation, promoting surface warming. Although gravel can improve drainage and allow cold air infiltration through pore spaces, these cooling effects are often outweighed in compacted roadbeds by enhanced heat absorption and conductive transfer—ultimately deepening the

340 active layer (Schneider von Deimling et al., 2021).

Gravel roads also alter natural hydrology by impeding surface water flow and concentrating meltwater along their margins (Schneider von Deimling et al., 2021). In addition, the raised gravel surface promotes snow drifting and accumulation on the leeward (northwest) side, driven by prevailing ENE winds. Snow accumulation along road shoulders has been shown to increase winter ground temperatures and active layer thickness (Fortier et al., 2011; Schneider von Deimling et al., 2021), a

345 pattern reflected in our observations near the spur road. The nearby second spur road to the north likely amplifies wind disruption and snow deposition, intensifying these effects. The resulting increase in ground insulation and soil moisture promotes thaw and degradation near road margins—a pattern also observed near snow fences and confirmed by our geophysical and thaw probe data.

Additionally, snowmelt and runoff frequently lead to surface ponding along the road edges, particularly on the leeward side.

350 This ponded water, with its high thermal capacity and conductivity, further enhances ground heat flux and accelerates thaw. These processes are consistent with our field observations of meltwater accumulation near the road edge.

Although the gravel road alters local thermal and moisture regimes, ERT and GPR profiles still detect well-preserved ice-rich features, such as ice-wedge polygons, in the adjacent tundra. Thaw depths between 0.2 and 0.5 m outside the immediate road margins imply that infrastructure-related impacts have not yet propagated more widely into the landscape.

355 The preservation of ice wedges in the surrounding tundra, despite adjacent disturbance, may indicate that early-stage ecological feedbacks are active. Although not specifically quantified in this study, mechanisms such as plant regrowth, accumulation of organic matter, and drainage improvements—outlined by Jorgenson et al. (2022)—have been shown to promote surface stabilization and ice reformation in disturbed permafrost environments.

4.3 Permafrost Conditions and Cryoturbation Near the Snow Fence along Cakeeater Road

360 In 2022, one ERT transect was sampled at the snow fence site along Cakeeater Road, accompanied by a parallel GPR survey. Data collection occurred on 29 August 2022. The ERT profile (Figure 5a, blue line) spans 163 m with 1-meter electrode spacing and crosses the snow fence perpendicularly. The GPR profile (Figure 5a, green line), acquired along the same alignment, extends 250 m with measurements taken at 1-meter intervals, providing broader spatial coverage of the study area.

365
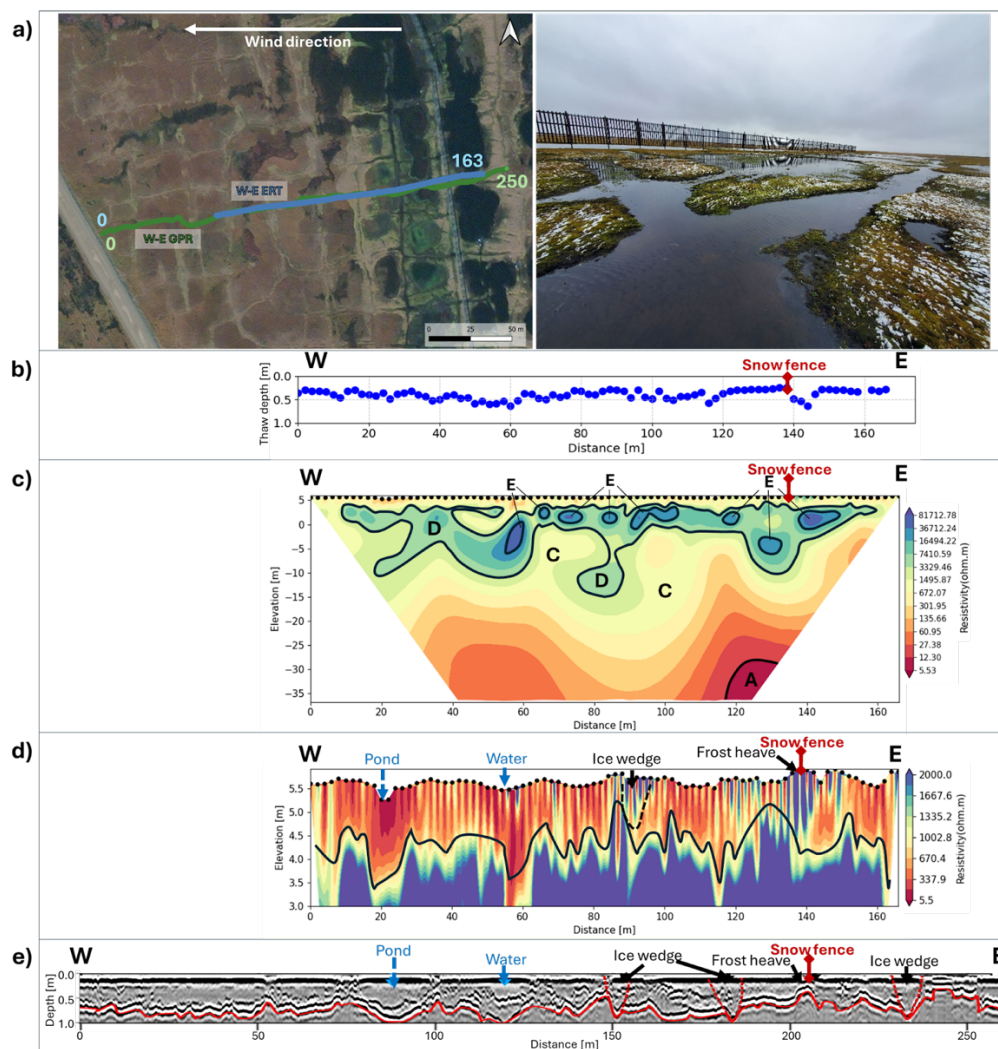
Figure 5: (a) Map showing locations of W–E ERT (blue) and GPR (green) profiles at the snow fence site near Cakeeater Road (ESRI satellite imagery), with an inset photograph illustrating site conditions and surroundings; (b) Thaw probe measurements along the ERT profile; (c) Coarse-scale W–E ERT profile (~0–40 m depth); (d) Fine-scale ERT profile (~0–3 m depth); (e) GPR profile showing thaw depths (red line) and hyperbolic reflections indicative of ice wedges (red dashed lines).

The W–E ERT inversion profile provides a coarse-scale view to ~40 m depth along the full transect (Figure 5c). Several high-resistivity zones (>10,000 Ω·m) appear within the upper 10 m and are interpreted as highly ice-rich features, likely representing excess ice such as ice lenses (Zone E). In addition, resistivity values exceeding 1,000 Ω·m (Zone D) occur almost continuously between 2 and 10 m depth, indicating widespread ice-rich permafrost.

At depths >30 m, a low-resistivity anomaly (<5 Ω·m) appears near 120 m along the profile and may suggest the presence of a cryopeg. However, interpretation at this depth remains uncertain due to the reduced resolution and sensitivity of ERT in deeper layers—particularly beneath overlying frozen ground.

The fine-scale ERT profile (~top 3 m; Figure 5d), with resistivity capped at 2,000 Ω·m, highlights spatial variability in the
380 near-surface permafrost structure. Thaw depths reach ~0.8 m near 20 m and exceed 1 m around 60 m along the profile—both areas coinciding with surface depressions interpreted as thaw ponds, likely resulting from ice-wedge degradation. A vertical high-resistivity anomaly at ~90 m may represent an intact ice wedge, while another zone centered beneath the snow fence at ~140 m shows consistently elevated resistivity throughout the upper profile. This feature, coupled with a slightly raised surface at this location, supports interpretation of localized frost heaving, likely caused by upward ice segregation in a
385 moisture-rich active layer.

The GPR profile (Figure 5e) similarly indicates deep thaw beneath the thaw ponds, with depths approaching 1 m—consistent with ERT interpretations. The potential ice wedge identified at ~150 m in the ERT data is clearly resolved as a strong hyperbolic reflection. Additional hyperbolic features near ~180 m and ~230 m further suggest the presence of wedge ice within the surrounding polygonal tundra.

390 The shallowest thaw depths were observed on the leeward side of the snow fence and may be associated either with frost heave from localized ice accumulation or with a shallower permafrost table caused by reduced snow insulation near the fence. This interpretation is supported by high resistivity values, elevated surface topography, and hyperbolic GPR reflections. Thaw depths generally increase from the road toward the snow fence and beyond. Between the road and ~60 m along the transect, average probe depths are deeper, followed by a shallower interval, and then a further increase approaching
395 and extending past the fence. Between the road and the fence, thaw depths range from ~0.5 to 1 m in the geophysical profiles, while probe measurements range from 0.25 to 0.6 m. In the first thaw pond (~20 m), the probe indicated ~0.5 m depth—shallower than the >0.8 m depths inferred from both ERT and GPR. In the second pond (~60 m), the probe measured ~0.8 m, closer to geophysical estimates, though ERT and GPR indicated slightly greater depths, possibly reflecting the influence of high water content on the geophysical response. Beyond the snow fence, probe depths generally range between
400 0.2 and 0.7 m, with the deepest values immediately east of the fence.

Based on the geophysical results, the Snow Fence site is underlain by high-resistivity permafrost, consistent with ice-rich ground. However, several other zones with resistivity >10,000 Ω·m are located along the transect, likely indicating excess ice features such as lenses and wedges. The GPR profile corroborates this interpretation, revealing multiple hyperbolic reflections typical of ice wedges within polygonal tundra.

405 Thaw depths exhibit clear spatial variability influenced by microtopography and surface conditions. Between the road and the snow fence, thaw depths reach ~1 m beneath degraded polygons and thaw ponds, with an average of ~0.7 m. Beyond the snow fence, depths decrease to ~0.5 m on average and remain <0.7 m. These observations align with field notes showing ponding and sparse vegetation—hallmarks of polygon degradation—in the section between the road and snow fence (Figure 5a).

410   Snow fences trap wind-blown snow by disrupting airflow and causing deposition, which produces asymmetrical drifts typically shaped like a skewed bell curve, with maximum accumulation forming a few meters downwind of the fence (Hinkel & Hurd, 2006). These thick drifts develop after the active layer has refrozen in early winter and reduce heat loss from the ground during the coldest months. The resulting insulation leads to warmer winter ground temperatures and can promote increase in the active layer depth in summer; however, this effect may be offset by the higher albedo of snow and

415   the later melt associated with thicker drifts (Yershov, 2004). Meltwater from accumulated snow can saturate the active layer and promote surface ponding during the thaw season.

At this site, the shallowest thaw depths were observed immediately to the west of the snow fence. Snow depth measurements from May 2025 indicate that the deepest accumulation—up to ~2 m—occurred west of the fence, while snow depths dropped sharply upwind. This pattern likely reflects prolonged, high-albedo snow cover west of the fence reducing spring insolation,

420   while meltwater from the thickest part of the drift flowed eastward and ponded, increasing thermal uptake of the exposed tundra and deepening the active layer.

These melt-season effects—especially increased moisture from deeper snowpack—can enhance ground thaw in adjacent permafrost due to the higher thermal conductivity and heat capacity of water. Saturated soils, combined with freeze–thaw cycling, may also promote frost heave through the formation of seasonal ice lenses and localized surface uplift. Elevated

425   resistivity zones and slight topographic rises observed in the geophysical data near the fence are consistent with these processes.

The thermal effects of snow are seasonally complex. During winter, snow acts as an effective insulator, reducing ground heat loss despite its high reflectivity. In spring, thick snowpacks delay ground warming by impeding the transfer of air temperatures to the surface, which—combined with persistent high albedo—can slow the onset of thaw. As melting

430   progresses, however, deep snowdrifts become sustained sources of meltwater, and in adjacent exposed tundra this increased soil moisture can promote thaw through the high thermal conductivity and heat capacity of water. These combined effects contribute to pronounced spatial variability in thaw depth, particularly where snow distribution is modified by infrastructure such as roads and fences. Prior studies in Utqiaġvik have demonstrated that snowdrift accumulation near fences alters ground temperatures and promotes localized thaw and subsidence (Hinkel and Hurd, 2006; Kim et al., 2025). The degradation

435   observed over the ~130 m between the road and the snow fence likely reflects infrastructure-modified snow and meltwater regimes. Less-intense degradation is also evident on the east side, most likely resulting from the smaller snow drift that typically forms upwind of the fence. While these findings are based on one season of data, the mechanisms observed—such as increased snow accumulation and meltwater effects—are expected to intensify under projected trends of rising cold-season precipitation in a warming Arctic.

440   The adjacent gravel-surfaced road likely further contributes to permafrost degradation by impeding natural drainage, resulting in surface ponding and elevated soil moisture. Increased water content raises the soil's thermal conductivity, enabling more efficient penetration of temperature fluctuations into the ground. Similar effects were observed near the old spur of Cakeeater Road, underscoring the consistent influence of gravel infrastructure on subsurface thermal regimes. On

average, thaw depth decreases from the road—where the maximum thaw is observed—toward the snow fence. In the zone
445   between the road and the fence, thick snow drifts and disrupted drainage appear to promote permafrost degradation.
Altogether, the combined effects of snow redistribution, meltwater accumulation, and altered drainage explain the
heterogeneous thaw pattern, with marked degradation between the road and the fence, and less intense degradation near and
beyond the fence.

Taken together, these findings indicate that the Snow Fence site is influenced by a combination of natural processes and
450   infrastructure-induced changes. While areas windward the fence appear less degraded, the zone between the road and the
fence exhibits clear signs of ice-wedge degradation, deeper thaw, and modified surface and subsurface conditions.

4.4 Barrow Environmental Observatory (BEO) Site: Natural Polygonal and Frost-Heave Terrain

ERT and GPR surveys were conducted at the Barrow Environmental Observatory (BEO) site on August 9, 2023. Both ERT
(blue line) and GPR (green line) profiles extended for 163 m with 1-m electrode and measurement spacing, as shown in
455   Figure 6a.
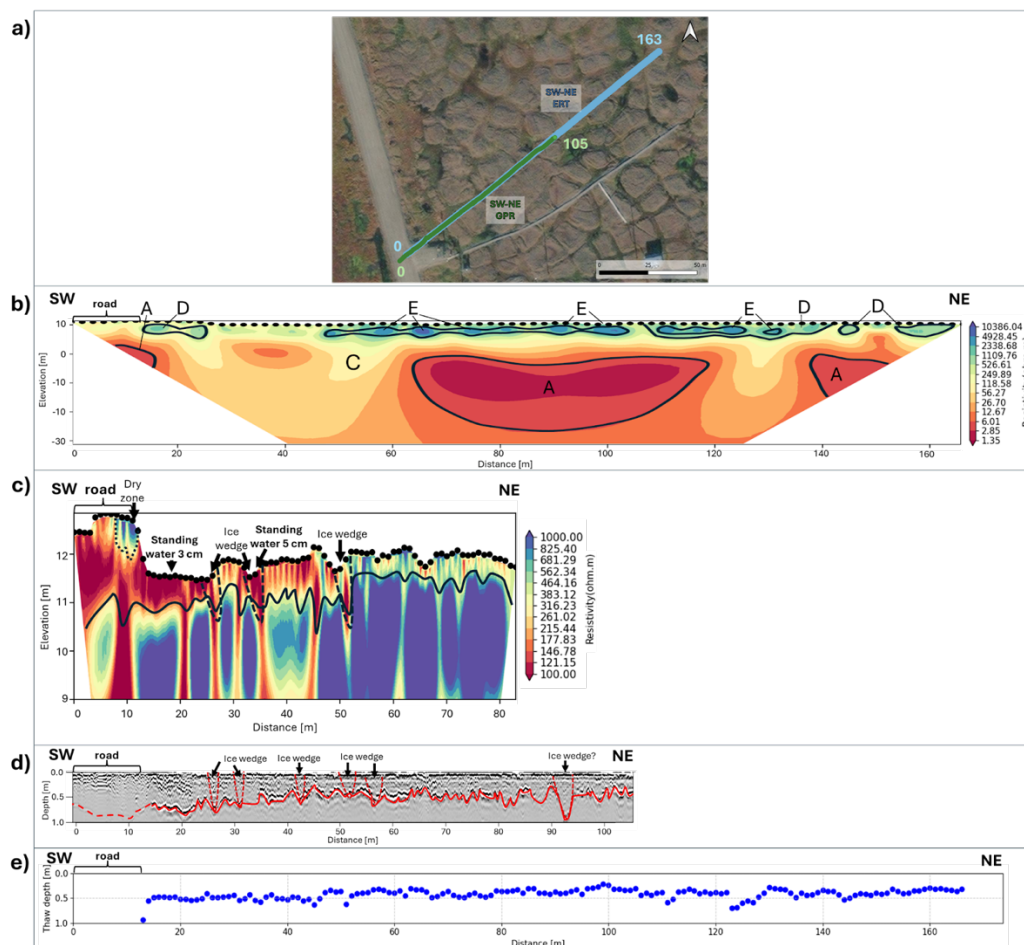
Figure 6: (a) Location of SW–NE ERT (blue) and GPR (green) profiles at the BEO site in Utqiaġvik, Alaska (ESRI satellite imagery); (b) Thaw probe measurements along the ERT profile. SW–NE ERT profile: (c) Coarse-scale view (~0–40 m depth along the entire profile); (d) Fine-scale view (~0–2 m depth, from 0 to 82 m distance along the profile); (e) SW–NE GPR profile showing thaw depths (solid red line) and hyperbolic reflections was interpreted as ice wedges (red dashed lines).

The SW–NE ERT inversion profile (Figure 6c–d) includes a coarse-scale view (~40 m depth, Figure 6c) and a small-scale view (~3 m from 0 to 82 m, Figure 6d). In the coarse-scale cross-section, the upper 5 m shows consistently high resistivity values (1,000–10,000 Ω·m), with localized zones exceeding 10,000 Ω·m—interpreted as ice-rich permafrost (Zone D) and excess ice features such as ice lenses (Zone E).

Very low resistivity zones (<5 Ω·m) are also present and may represent cryopegs. One circular anomaly (~5 m diameter) is located at ~10 m along the transect and ~15 m depth. A broader zone between 65 and 120 m extends from ~10 to 30 m depth, spanning ~55 m horizontally and ~20 m vertically. Another low-resistivity feature is located between 135 and 155 m at 10–25 m depth.

The depth-focused ERT section (Figure 6d) highlights thaw variability across the site. The deepest thaw (>1 m) occurs beneath and adjacent to the road, which is raised ~0.8 m above the surrounding tundra. The roadbed shows elevated resistivity, likely due to dry gravel. Near the road, low-resistivity zones reflect standing water observed during fieldwork. From the road to ~50 m, the profile crosses degrading ice-wedge polygons. These polygon boundaries are also visible in

475   satellite imagery (Figure 6a), aligning with low-resistivity zones interpreted as thawing ice wedges and thaw ponds.

Thaw depths in this segment range from ~0.6 m to >1 m, indicating advanced permafrost degradation. Beyond 50 m, the landscape transitions into frost-heave-dominated terrain with shallower thaw depths (0.2–0.6 m).

The SW–NE GPR profile (Figure 6e) confirms deep thaw near the road, though signal quality is reduced by gravel and ponded surface water. Strong reflections are lacking in this section, but several hyperbolic reflections—indicative of ice

480   wedges—are evident up to 40 m along the profile and correspond well with features seen in the ERT profile. In this zone, thaw depths range from ~0.5 to 1 m. Beyond 45 m, the thaw depth drops to 0.2–0.7 m, consistent with the frost-heave terrain and ERT results. A distinct hyperbolic reflection near 90 m may correspond to an additional ice wedge, not clearly resolved in ERT but aligned with polygonal surface cracking visible in satellite imagery (Figure 6a).

Physical thaw probing (Figure 6b) reveals substantial variability in thaw depth across the BEO site. Within the first 50 m of

485   the transect—corresponding to the ice-wedge polygon zone—thaw depths ranged from 0.4 m to >1 m, with the deepest values near thaw ponds and degraded wedges. Beyond 50 m, in the frost-heave-dominated section, thaw depths generally decrease to 0.2–0.5 m, with only isolated spots exceeding 0.5 m (~0.7 m max). This spatial pattern aligns closely with ERT and GPR observations (Figure 6c–e).

Interpretation of geophysical and probe data indicates that the site is underlain by ice-rich permafrost, including ice lenses

490   and ice wedges. The transition from ice-wedge polygon terrain near the road to frost-heave terrain further away is confirmed by field observations and satellite imagery (Figure 6a). Strong hyperbolic reflections in the first 40 m of the GPR profile (Figure 6e) confirm the presence of ice wedges, while a single potential wedge appears farther along the transect—possibly a relict feature from earlier polygonal development.

Thaw depth variability reflects multiple interacting factors. In the polygonal zone, wedge degradation and pond formation

495   increase surface water coverage, which enhances ground heat transfer due to the high thermal conductivity of water. Loss of surface vegetation further reduces insulation, accelerating thaw. Conversely, frost-heave terrain is drier, elevated, and retains vegetation, which supports shallower thaw by maintaining lower surface energy fluxes.

Additionally, the nearby gravel road influences local permafrost. As at the Snow Fence and Cakeeater Road sites, road-induced changes to surface hydrology likely cause ponding and deeper thaw in adjacent areas. This underscores how both

500   natural features and infrastructure shape subsurface thermal and hydrological conditions. Together, these observations illustrate the complex interactions among permafrost landforms, seasonal processes, and infrastructure in governing permafrost response to environmental change in Arctic landscapes.

4 Conclusions

This study provides an integrated geophysical assessment of near-surface permafrost characteristics within an Arctic city. By
505   integrating ERT, GPR, and thaw probing surveys across contrasting land use types at four sites, we developed a unique
dataset that reveals the structural variability of permafrost in Utqiaġvik, Alaska, and how infrastructure and local
environmental conditions can jointly influence the active layer depth through a complex interplay of surface process that
affect the thermal balance at the ground surface.

At all four sites, variations in active layer depth were consistently linked to land use and surface characteristics. Ice-wedge
510   polygon terrain near infrastructure—particularly roads and snow fences—showed the deepest thaw (>0.5–1.0 m), with low to
moderate resistivity in ERT (10–1,000 Ω·m) and disrupted GPR reflections, indicating wedge degradation and water-
saturated soils. In contrast, frost-heave-dominated terrain with intact vegetation and natural drainage maintained shallower
thaw (0.2–0.5 m) and high resistivity (>1,000 Ω·m), consistent with stable, ice-rich permafrost. Snow thickness variations,
and pooling of meltwater caused by infrastructure emerged as a key driver of active layer depth variability, producing sharp
515   contrasts between zones of enhanced thaw and frost-heave development. Our data showed that not only do elevated
buildings decouple anthropogenic heat impacts on underlying permafrost, but they can also foster permafrost aggradation
through self-shading —but could also promote degradation at their margins through meltwater accumulation from roofs and
snow accumulation.

Building on these results, repeat or real-time ERT–GPR monitoring combined with thaw probing can form the foundation of
520   a robust permafrost monitoring strategy. Other methods—such as borehole observations, snow depth measurements, and
remote sensing—can complement these efforts to track thaw fronts, frost heave, and other near-surface permafrost changes
over time. Integrating these datasets will help identify ice-rich zones and thaw-prone areas, supporting risk-informed siting,
maintenance, and adaptation. Achieving this vision will require strong partnerships with local communities, as demonstrated
in Utqiaġvik, where collaboration with tribal and private landowners was essential for access and sustained observation.

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Data availability. Data archiving is underway. The raw electrical resistivity tomography (ERT), ground-penetrating radar
(GPR), and thaw-probe datasets collected in Utqiaġvik, Alaska (2021–2023) are archived at Zenodo
(https://doi.org/10.5281/zenodo.17096203) and are embargoed until December 2025. Upon acceptance, the record will be
made public and the DOI will be cited in the final article. GPR data were processed with GPRPy and ERT data were inverted
530   with ResIPy (both open-source Python packages).

Author contributions. Conceptualization—VE; Methodology—TS, VE; Investigation—VE, MAN, TS; Formal analysis—
VE; Data curation—MAN; Visualization—VE, MAN, TS; Writing – original draft—VE; Writing – review & editing—
MAN, TS, TAD, HEE, MGJ, VE; Supervision—TAD, HEE, MGJ; Funding acquisition/Project administration—HEE, MGJ.

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