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Climate change and infrastructure development drive ice-rich permafrost thaw in Point Lay (Kali), Alaska

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Abstract

Permafrost thaw and thermokarst development pose urgent challenges to Arctic communities, threatening infrastructure and essential services. This study examines the reciprocal impacts of permafrost degradation and infrastructure in Point Lay (Kali), Alaska, drawing on field data from ∼60 boreholes, measured and modeled ground temperature records, remote sensing analysis, and community interviews. Field campaigns from 2022–2024 reveal widespread thermokarst development and ground subsidence driven by the thaw of ice-rich permafrost. Borehole analysis confirms excess-ice contents averaging ∼40%, with syngenetic ice wedges extending over 12 m deep. Measured and modeled ground temperature data indicate a warming trend, with increasing mean annual ground temperatures and active layer thickness (ALT). Since 1949, modeled ALTs have generally deepened, with a marked shift toward consistently thicker ALTs in the 21st century. Remote sensing shows ice wedge thermokarst expanded from <5% in 1949 to >60% in developed areas by 2019, with thaw rates increasing tenfold between 1974 and 2019. In contrast, adjacent, undisturbed tundra exhibited more consistent thermokarst expansion (∼0.2% yr^{-1}), underscoring the amplifying role of infrastructure, surface disturbance, and climate change. Community interviews reveal the lived consequences of permafrost degradation, including structural damage to homes, failing utilities, and growing dependence on alternative water and wastewater strategies. Engineering recommendations include deeper pile foundations, targeted ice wedge stabilization, aboveground utilities, enhanced snow management strategies, and improved drainage to mitigate ongoing infrastructure issues. As climate change accelerates permafrost thaw across the Arctic, this study highlights the need for integrated, community-driven adaptation strategies that blend geocryological research, engineering solutions, and local and Indigenous knowledge.

1. Introduction

Five million people live in the northern circumpolar permafrost region (Ramage *et al* 2021). Permafrost thaw is projected to be one of the largest climate change related hazards in the 21st century Arctic (Melvin *et al* 2017). Models show that permafrost thaw will threaten more than 40% of the human settlements and nearly 70% of northern infrastructure in permafrost regions by 2050 (Hjort *et al* 2018, Ramage *et al* 2021). The destabilization of permafrost can lead to severe ground subsidence, damaging roads, buildings, and pipelines, and increasing health and safety risks for northern communities (Doré *et al* 2016, Streletskiy *et al* 2019, 2023, Hjort 2022). Moreover, permafrost thaw has cascading environmental consequences, including the release of greenhouse gases like methane and carbon dioxide, further amplifying climate change (Turetsky *et al* 2020).

Permafrost, climate, and infrastructure combine to create a tightly coupled system in which each element affects the other (Streletskiy *et al* 2012). Taken individually, the impact of changing climatic conditions on permafrost temperatures and the impact of human-caused surface disturbance have been studied extensively (Hjort *et al* 2018, Biskaborn *et al* 2019, O'Neill *et al* 2020). However, when climate change and human-induced surface disturbance converge, as is the case in Arctic communities, the synergistic negative impacts on permafrost are amplified in ways that are not well understood, threatening current and future community sustainability (O'Neill *et al* 2020, Larsen *et al* 2021). Arctic communities rely on modern infrastructure to maintain the health and safety of their residents and to provide quality community services such as schools, water and wastewater systems, transportation, and housing. In many communities, these services are increasingly threatened by instability in the permafrost terrain that supports critical infrastructure and Indigenous community livelihoods (Crate *et al* 2017, Gibson *et al* 2021).

Here, we describe catastrophic, coupled permafrost and infrastructure failures in the remote, Indigenous Arctic community of Point Lay (Kali), Alaska, highlighting it as a bellwether for the looming humanitarian and financial crisis across the permafrost region (figure 1). Despite efforts by community planners and the implementation of seemingly appropriate engineering solutions, Point Lay (Kali) has experienced significant permafrost-related infrastructure failures since its relocation to the current village site in the mid-1970s. To better understand the underlying causes, we conducted a multi-faceted investigation that combined field surveys, permafrost coring and augering to analyze cryostructures and measure ice wedge geometry, complemented by remote sensing, field instrumentation, modeling, and interviews to contextualize our findings across spatial and social dimensions. We analyzed environmental sensor network ground temperature data from 1999 to 2019 for the Global Terrestrial Network for Permafrost (GTN-P) Tunalik Site, in conjunction with modeled ground temperature and active layer thickness (ALT) data from Tunalik and Point Lay (Kali) from 1949 to 2019. We also used remote sensing change detection and time-series analysis to map ice wedge thermokarst in and around the community over a 70 year period, spanning from 1949 to 2019, with a focus on changes before (1949–1974) and after (1974–2019) development. Additionally, interviews with community members provided firsthand accounts of the damage caused by permafrost thaw, its direct impact on daily activities, as well as traditional ways of life. Through this work, we identify key elements of community planning and climate change that have contributed to infrastructure failures and propose improvements in design, planning, and future research to mitigate these challenges. As climate change continues to impact the Arctic, Point Lay (Kali) provides valuable insights into the challenges and solutions associated with communities constructed on ice-rich permafrost.

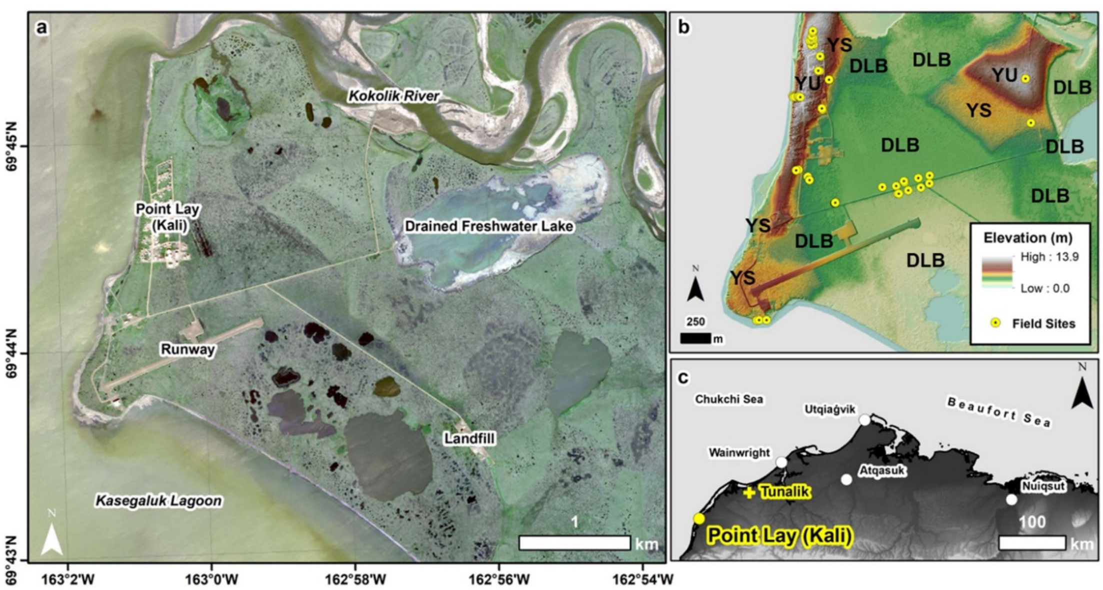

Figure 1. The location of Point Lay (Kali) in northern Alaska. (a) A high-resolution commercial satellite image illustrating the village layout with key features annotated (© Maxar Imagery 2018). (b) An airborne LiDAR-derived digital terrain model overlain on a hillshade, indicating the permafrost field sampling sites for this study. The three primary terrain units are labeled as Yedoma uplands (YU), Yedoma slopes (YS), and drained lake basins (DLB). (c) An inset map situating Point Lay (Kali) on the North Slope of Alaska.

2. Methods

2.1. Study area

The Native Village of Point Lay (Kali) is located on the Chukchi Sea coast of northwestern Alaska, within the North Slope Borough. It is a small, predominantly Iñupiat community with a population of approximately 330 residents based on the 2020 US Census. The village is situated near Kasegaluk Lagoon, a critical habitat for marine and terrestrial wildlife (Frost *et al* 1993, Johnson *et al* 1993), and is accessible only by air and seasonal barge. Point Lay (Kali) experiences an Arctic climate, characterized by long, harsh winters with temperatures frequently dropping below −30 °C and short, cool summers averaging 5 °C–10 °C. Precipitation is low, averaging around 100–200 mm annually, with most moisture falling as snow. Vegetation in Point Lay (Kali) is typical of Arctic coastal tundra ecosystems, consisting primarily of dwarf shrubs, mosses, lichens, and sedges (Walker *et al* 2005). Permafrost in the region is continuous and ice-rich, with large near-surface ice wedges creating a highly dynamic and thaw-vulnerable landscape (Jorgenson *et al* 2014). Point Lay's (Kali) landscape is characterized by low-lying tundra interspersed with thermokarst features, including ice wedge troughs and thermokarst ponds, lakes, and drained lake basins (DLB) (Jones *et al* 2022). The active layer, the portion of soil that thaws seasonally, is relatively thin, ranging from 30–100 cm depending on location and substrate composition (the lowest ALTs are typical of peat), and the mean annual ground temperature (MAGT) at a depth of 1.5 m is typically below −4.0 °C (Romanovsky *et al* 2024). However, permafrost degradation is an increasing concern, as rising air temperatures and changing precipitation patterns contribute to the increase in the ALTs and thawing of ice-rich ground (Connor *et al* 2023).

In the 1990s, geotechnical investigations were performed at Point Lay (Kali) by Duane Miller & Associates (Miller 1995). These investigations were conducted to support the planning and design of a community-wide water and sewer system. Three infrastructure options were presented at the time: an above-ground piped system, a below-ground piped system, and an enhanced truck-haul system. The community selected the below-ground system in coordination with the North Slope Borough, with engineering designs that incorporated findings from borehole investigations documenting massive ice and saline permafrost at depth. While the geotechnical data informed utility corridor alignment, it was not used to evaluate permafrost sensitivity beneath residential housing foundations, which has since resulted in widespread subsidence and structural damage. In 1994–1995, 15 boreholes up to 6.5 m deep were drilled in various parts of the village, and properties of frozen soils, including gravimetric moisture content and salinity, were determined (Miller 1995). All 12 boreholes drilled on the high surface and adjacent slopes encountered ice-rich soils (mainly organic-rich silts and sandy silts with massive ice), while the three boreholes drilled in the thaw-lake basin encountered ice- and organic-rich soils underlain by ice-poor saline soils (from depths of 4.5–5 m, or ∼1.5 m below sea level). The documentation of these subsurface conditions, particularly the presence of massive ground ice near the surface, provides important historical context for understanding present-day thaw-related infrastructure failures. In our study, the 1990s borehole records serve as a baseline for comparing more recent cryostratigraphic findings and highlight how critical early geotechnical data were either underutilized or constrained by available engineering options at the time.

Point Lay (Kali) is a key site for permafrost and infrastructure studies due to its unique environmental conditions and the pressing need for sustainable adaptation strategies (figure 2). The built environment in Point Lay (Kali) consists of ∼65 single-family homes, 12 new multi-plex housing units, public buildings (school, church, store and community center), and essential infrastructure such as the airstrip, roads, power plant, fire hall, and water treatment facility. Initially, linear infrastructure associated with a Distance Early Warning Line station provided the roads and runway for the village when it was relocated to its current site in the mid-1970s (figure 3). Most of the residential infrastructure was constructed on pile foundations between 1974 and 1985 on Yedoma (a type of ice-rich syngenetic permafrost with large ice wedges formed primarily during the Pleistocene) terrain, starting at the south end of town and expanding northward, with most of the municipal infrastructure developed between 1985 and 2003 on thick gravel pads on the Yedoma slope and thaw-lake basin to the south and east. Runway extensions and a new road to the landfill were developed after 2003. Most residential structures in the village are supported by pile foundations due to the presence of permafrost. Recent interviews by the Cold Climate Housing Research Center indicate that almost two-thirds of village housing is in need of major repair, and 94% of homes surveyed have issues associated with changes in permafrost conditions due to thaw consolidation associated with active-layer thickening, ice wedge degradation, and differential thaw settlement, leading to structural instability or failure (Cold Climate Housing Research Center 2023). Roads and buried water and sewer lines have also been affected by thaw-induced subsidence, requiring frequent and costly maintenance and repair (supplemental information). The integration of scientific research with local knowledge is crucial in identifying the area most susceptible to permafrost degradation and developing tailored, culturally relevant mitigation approaches.

Figure 2. Interactions between degrading permafrost and infrastructure in Point Lay (Kali), Alaska. (a) Where residential pilings were founded in ice wedges, nearly 2 m of thaw subsidence has occurred below some homes leaving less than 1 m of pile embedment (Photo: Peppi Bolz). (b) Thermokarst has disconnected several of the fire hydrants in the northern portion of the community (photo: Benjamin Jones). (c) A North Slope Borough Housing Authority home that has been abandoned due to ice wedge thermokarst (Photo: Billy Connor). (d) A residential home in Point Lay (Kali) showing differential thaw settlement (Photo: Billy Connor). (e) A sinkhole on a residential street associated with underground thermal erosion due to a waterline failure (Photo: Bill Tracey Sr.). (f) Water and sewer utility failure at a home in Point Lay (Kali) (note the exposed ice wedge to the left of the maintenance crew) (Photo: Bill Tracey, Sr.).

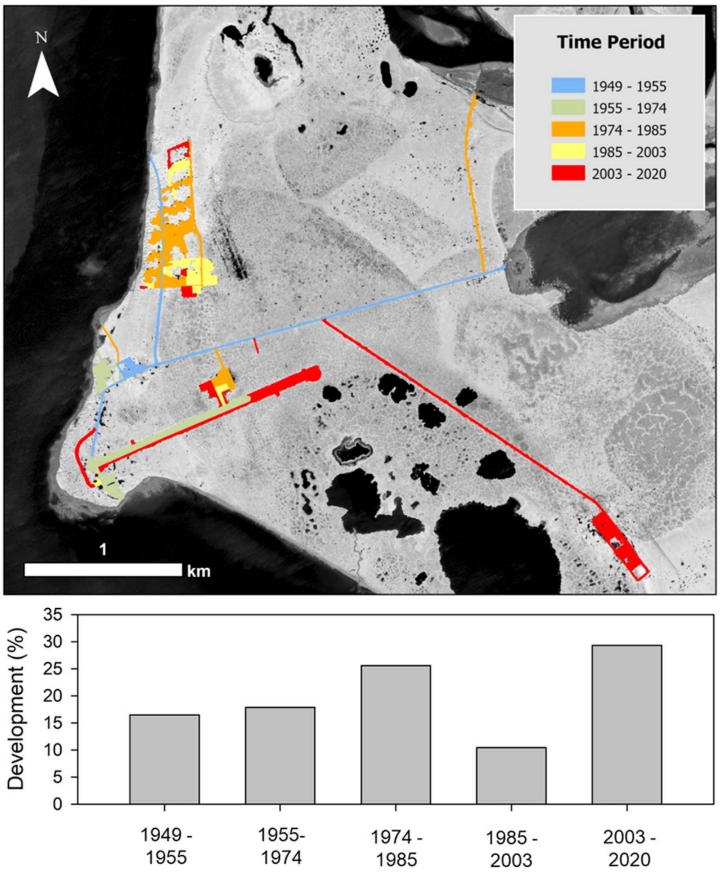

Figure 3. The development of the Native Village of Point Lay (Kali) footprint between 1949 and 2020. The village was relocated to this site in the mid-1970s from the Kokolik River delta, taking advantage of a pre-existing runway and road network constructed by the U.S. military for the Distant Early Warning (DEW) Line station.

2.2. Permafrost field studies and core sampling

We started our permafrost field studies in Point Lay (Kali) in June 2022 and continued them in July 2023 and June 2024 (supplemental information). The primary objectives were to investigate the cryostratigraphy, ground-ice content, and structural properties of permafrost across three distinct terrain units that the village is built on: the main Yedoma surface, Yedoma slopes (YS), and DLBs. Yedoma is the ice- and organic-rich syngenetic permafrost, that accumulated during the late Pleistocene in unglaciated regions of Siberia, Alaska, and some parts of northern Canada (Strauss *et al* 2021). Specific Yedoma landforms include low hills with a flat top surface and gentle slopes penetrated by deep thaw lakes and divided by erosional valleys and DLBs. Small thermokarst landforms such as baydzherakhs (conical thermokarst mounds framed by partially degraded ice wedges) and deep wide troughs above degrading ice wedges are also typical of Yedoma. All these landforms were observed in Point Lay (Kali) and the surrounding area. The depth of thermokarst lake basins in this area reaches up to 8–9 m, suggesting that the thickness of Yedoma exceeds 15 m. Field sampling efforts focused on characterizing the extent of ice wedges, evaluating excess ground-ice content, and obtaining samples for laboratory analyses of moisture content and salinity.

We used two drilling methods: the SIPRE corer and the Kovacs auger. The 7.5 cm-diameter SIPRE corer (Rand and Mellor 1985) was used for obtaining intact frozen soil and ice samples from shallow depths up to 3 m, while the Kovacs auger was employed for deeper boreholes up to 8.4 m to evaluate the vertical extent of ice wedges. A total of 62 boreholes were drilled during the study, with 25 boreholes using the SIPRE corer, reaching a cumulative depth of 32.7 m, and 37 boreholes using the Kovacs auger with a total depth of 77.0 m (figure 1). Each extracted core was logged in the field, with descriptions including soil texture, cryostructures, visible ice content, and visible organic inclusions. Ice wedges and other ground-ice features were documented and their dimensions recorded. Additionally, a coastal exposure along the Chukchi Sea was described and sampled to analyze ice-rich, saline permafrost deposits. Field photographs of cores were taken to document cryostratigraphy, and detailed field notes were compiled for later correlation with laboratory results (supplemental information). A total of 110 soil samples were collected for gravimetric and volumetric moisture content analysis, excess ground-ice quantification, and specific electrical conductivity testing. These samples were processed at the Institute of Northern Engineering, University of Alaska Fairbanks. The laboratory workflow included drying subsamples for moisture content determination and measuring ice content by meltwater volume.

2.3. Observed and modeled ground temperature data

To contextualize long-term permafrost trends in Point Lay, we include ground temperature and climate data from the Tunalik site (GTN-P code: U25) which is part of the U.S. Geological Survey's (USGS) Permafrost and Climate-Monitoring Network in Arctic Alaska. The site is located at 70°11.756'N latitude and 161°04.687'W longitude, with an elevation of 26 m above mean sea level, and is 90 km to the northeast of Point Lay (Kali). The monitoring station was installed on 20 August 1998. Data collection at Tunalik includes continuous meteorological and permafrost observations to assess long-term climate trends, active-layer dynamics, and near-surface permafrost warming. The station is equipped with instruments to measure air temperature, wind speed and direction, soil moisture, snow depth, precipitation, incident and reflected solar radiation, and surface pressure. Ground temperatures are recorded at multiple depths (5, 10, 15, 20, 25, 30, 45, 70, 95, and 120 cm) to monitor active layer and permafrost conditions. The data from Tunalik undergo rigorous quality control procedures, including automated flagging of anomalies and manual reviews by USGS researchers. These datasets contribute to the GTN-P and are made publicly available by the USGS (Urban and Clow 2018). While Tunalik is less affected by infrastructure and disturbance, it represents the best available observational benchmark for regional thermal conditions on the western Arctic Coastal Plain. These data are not intended to directly characterize Point Lay (Kali)-specific trends, but rather to situate modeled changes within a broader regional climate framework. We note the limitations of spatial extrapolation and emphasize the need for continued site-based monitoring within Point Lay (Kali) to support future validation efforts.

To estimate ALTs at the Tunalik site, we used the ground temperature monitoring array that records temperatures at multiple depths (Circumpolar Active Layer Monitoring Program 2025). These temperature measurements provide a high-resolution dataset for assessing seasonal thaw depth and permafrost conditions over time. Our approach involves filtering the thermistor data to determine the periods when specific depths are frozen or thawed. We identify the thawed portion of the profile by pinpointing the deepest depth where temperatures remain above 0 °C during the thaw season. To refine this estimate, we fit a cubic spline interpolation to the temperature data, allowing for a smooth transition across measurement depths. The deepest thawed point on the fitted curve is then identified as the best estimate of maximum active layer depth for a given year. This method provides a more continuous and accurate estimate of ALT compared to using discrete sensor measurements alone, capturing the variability in thaw progression across the monitoring period.

In addition to field-based measurements, modeled MAGT data at a depth of 1 m and annual ALTs were extracted for the Tunalik site and Point Lay (Kali) using the time series viewer available from the University of Alaska Fairbanks Geophysical Institute Permafrost Laboratory (GIPL) (Nicolsky *et al* 2017, PermaMap 2025). The spatial resolution of the modeled data is 770 m, covering the time period 1949–2019, which aligns with our remotely sensed imagery time series. The projections used to extract the time series were based on the RCP 4.5 climate scenario under natural conditions, providing a representative estimate of historical (1949–2009) and projected (2006–2019) permafrost and active layer dynamics. Modeled ALT data were extracted from the PermaMap web platform, which provides outputs from the GIPL 2.0 model forced by downscaled climate projections under the RCP 4.5 scenario (Nicolsky *et al* 2017). Although RCP-based projections are commonly associated with future scenarios, the GCM forcing begins in 2006. The 2006–2010 period represents a transitional blend of CRU TS3.1 observations and CMIP5 ensemble averages. As such, the 2006–2019 period in our analysis reflects modeled ALT conditions under RCP-forced climate, rather than direct historical observations. These data offer long-term context for evaluating permafrost stability and active layer deepening in conjunction with our *in situ* measurements.

2.4. Remote sensing change detection analysis

To identify and analyze thermokarst development, we utilized high-resolution remote sensing imagery. Historical aerial photographs from 22 June 1949 (1:40 000), 31 July 1974 (1:12 000), and 17 August 2019 (10 cm orthoimagery) were used to assess changes in ice wedge thermokarst over time. The 1949 and 1974 aerial images were georeferenced using the 2019 orthoimagery as a base layer, which was initially resampled to 0.5 m resolution to ensure consistency across all datasets. The mean root mean square (RMS) error of the georeferenced images was less than one pixel (0.5 m), with the maximum RMS error of any individual control point remaining below 1.0 m. Ice wedge thermokarst features were manually interpreted at a scale of 1:500 across the three georeferenced imagery datasets. Black-and-white dynamically stretched imagery was employed to enhance the contrast between ice wedge troughs above degrading wedges and the drier ice wedge polygon centers. The total area of ice wedge thermokarst was delineated and summed for each time period as vector polygons. Additionally, the road network, buildings, and other infrastructure features and other anthropogenic disturbances, such as pads and 55-gallon drum piles, were manually digitized across the time series. Residential blocks were also digitized from city planning maps to facilitate further analysis of ice wedge thermokarst in relation to infrastructure development timing. The three natural areas were selected to mirror the spatial footprint and orientation of a typical residential block (Block 900), extending into adjacent undeveloped terrain to serve as comparative baselines. All image processing, digitization, and spatial analyses were conducted using ArcMap v. 10.2.

2.5. Community interviews

Community interviews were conducted in Point Lay (Kali) in June 2022 to document local observations of permafrost thaw, erosion, and the impacts on infrastructure, daily life, and subsistence activities (figure 4). The interviews were designed to bring together Indigenous knowledge and firsthand experiences alongside scientific observations, recognizing the value of each in contributing to a more comprehensive understanding of landscape change and its community impacts. Participants were identified through recommendations from the Tribal Council and the project's local Steering Committee. Initial interviewees were asked to suggest additional community members, following a snowball sampling approach. A total of eight community members participated in the interviews, including lifelong residents, local leaders, and individuals with specific knowledge of infrastructure and environmental changes (Connor *et al* 2023).

Interviews were conducted following protocols approved by the Institutional Review Board (IRB 1909817-3) at the University of Alaska Fairbanks. Participants were informed of the study objectives and their right to withdraw at any time. Consent was obtained before each interview, and participants were compensated at a rate of \$50 hr^{-1}, up to a maximum of \$100 for two hours. The interviews were semi-structured, allowing flexibility for participants to share their insights while ensuring consistency across key topics. The interviews focused on three main themes: observed changes in the landscape and seascape, impacts of permafrost thaw and erosion on infrastructure, and community adaptation strategies (Connor *et al* 2023). Interviews were recorded, transcribed, and thematically analyzed to identify key patterns and concerns. Interview responses were analyzed manually using a structured thematic coding approach, guided by both the interview protocol and emergent themes identified during review. The modest sample size (eight interviews) enabled detailed manual analysis while ensuring consistency across responses. Frequency counts were used to identify dominant themes, and illustrative quotes were selected to represent perspectives expressed by multiple interviewees. Where appropriate, we report on the number of interviewees supporting

Figure 4. Community-based interviews and knowledge-sharing discussions in Point Lay (Kali), Alaska, in June 2022. (Left) Bill Tracey, Sr. Talks with Tracie Curry of Northern Social-Environmental Research during an interview session, discussing regional landscape changes using historical maps and field notes. This exchange incorporates local knowledge into permafrost and ice wedge thermokarst research. (Right) Fire Chief Kuoiqsik Curtis points out areas of accelerated permafrost thaw south of the runway, contributing valuable place-based observations on environmental change. These participatory methods enhance the understanding of permafrost thaw and their impact on infrastructure and traditional land use (Photos: Jana Peirce).

key findings to enhance clarity and transparency. A summary of responses and the full interview protocol are provided in Connor *et al* (2023). Common observations were categorized by environmental impact, infrastructure vulnerability, and adaptation strategies. Findings from the interviews were compared with remote sensing imagery, borehole data, and permafrost temperature monitoring to correlate community-reported changes with geophysical measurements. This approach helped the process of triangulation, by applying multiple methods and ways of knowing, to improve the credibility of the research findings where there is agreement (Khoa *et al* 2023). The community interviews provided essential insights into the lived experiences of Point Lay (Kali) residents facing permafrost degradation and infrastructure challenges. By drawing on local and Indigenous knowledge and scientific observations, this study highlights the need for collaborative adaptation strategies that reflect both empirical data and community priorities.

3. Results

3.1. Permafrost characteristics and ground-ice content

Between June 2022 and June 2024, 62 boreholes (25 SIPRE and 37 Kovacs) were drilled across three distinct terrain units within the Point Lay (Kali) study area: the main Yedoma surface where most of the residential buildings are located and drained thermokarst lake basins (figure 1; supplemental information). Borehole depths reached up to 8.4 m, and 110 soil samples were collected to analyze gravimetric and volumetric moisture content, as well as excess ground-ice content. Ice wedges were systematically investigated to determine their depth and extent. The results confirmed that permafrost in the Point Lay (Kali) area has high ground-ice content, particularly within the Yedoma and Yedoma slope terrain units. Excess-ice content in perennially frozen soils averaged 40.3 ± 20.7% in Yedoma and YS ($n = 41$) and 38.8 ± 17.2% in DLBs ($n = 44$). Ice wedges were widespread, with vertical extents exceeding 12 m in some Yedoma areas. For instance, borehole PLAY-51 (lower part of the Yedoma slope) revealed wedge ice from 0.90 m to 8.40 m deep, suggesting extensive vertical growth, indicating its syngenetic nature (Kanevskiy *et al* 2016, 2022). We estimate that wedge-ice content in Yedoma exceeds 50% of the total volume of the terrain unit layer containing ice wedges. In comparison, perennially frozen soils of DLBs contained less ground ice and showed lower ice wedge content. With ice wedges averaging 2.8 m in width and ∼4.0 m in vertical extent, and average diameter of polygons of ∼15 m, we estimate the average wedge-ice content to be ∼18% (within the ∼4 m-thick soil layer that contains ice wedges) in the DLB. Unlike the Yedoma unit, ice wedges in DLBs are mostly epigenetic and not as wide. However, in some profiles, such as PLAY-40, we could detect rather large ice wedges, whose widths could exceed 4 m (supplemental information). Depths to ice wedges from the ground surface varied from 36 to 93 cm (average 62.6 cm, $n = 31$), and the values for Yedoma, Yedoma slope, and DLB were approximately the same. A coastal exposure in Kasegaluk Lagoon along the Chukchi Sea coast revealed large ice wedges embedded in saline, ice-rich silty sand deposits with excess-ice content ranging from 37.8% to 55.6%. Ice wedges ∼2 m wide were exposed in the coastal bluff from 2.8 to 0.6 m a.s.l., though more likely they extended below sea level. The high excess-ice content across all terrain units suggests significant potential for thaw settlement, with possible ground subsidence reaching approximately 40% of the initial thickness of the soil layer before thawing, excluding additional volume loss from melting ice wedges. Thaw settlement is expected to be particularly pronounced in Yedoma and YS due to their high wedge-ice content. In the lower Yedoma slope, ice wedges extending from shallow depths to over 8 m deep also indicate a high risk for differential thaw settlement, potentially impacting local infrastructure and landscape stability. Our cryostratigraphic observations from the 2022–2024 field campaigns reveal extensive ice-rich deposits across all three major terrain units in Point Lay: upland tundra (main Yedoma surface), DLBs, and YS. These findings align closely with the 1990s borehole investigations, which similarly documented massive ice bodies and high ice content—especially in former thermokarst lake basins and Yedoma terrain. Both datasets reveal long-term vulnerability to thaw-driven deformation.

3.2. Permafrost warming and increasing ALTs

Ground temperature data from the Tunalik site (figure 5(a)) indicate strong seasonal variability, with the most pronounced fluctuations occurring at 10 cm depth, where temperatures range from ~ -35 °C in winter to above 10 °C in summer. MAGTs at 45 cm and 95 cm depths exhibit a muted response to seasonal changes, with long-term warming trends evident. Notably, the 45 cm sensor, which initially recorded permafrost conditions, transitioned to the active layer in 2004, marking a significant thermal shift at this depth, indicating permafrost thaw. The sensor at 95 cm has remained in the permafrost since it was installed but has continued to warm over the 20 year period of record. Observed thermistor temperatures show a stronger warming trend than the gridded model output (figure 5(b)), highlighting the limitations of comparing point-scale field measurements with coarsely resolved (~770 m) modeled data. The discrepancy is likely to reflect local surface controls—such as vegetation, snow cover, and soil properties—not fully captured by the ecosystem-type averages used in model parameterization. Nevertheless, the model output does reproduce the general warming direction observed over recent decades. Notably, modeled Point Lay temperatures are generally higher than those at Tunalik, reinforcing regional differences in permafrost

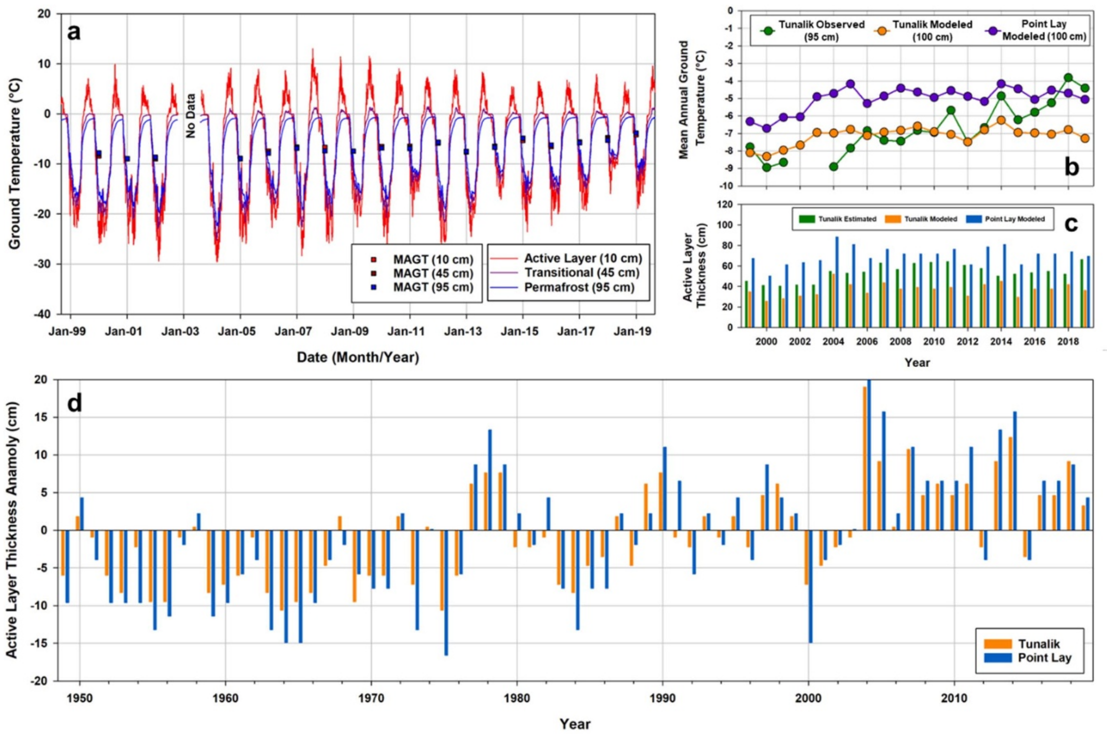

Figure 5. Observed and modeled ground temperature data and ALT for Tunalik and Point Lay. (a) Daily and mean annual ground temperatures at the Tunalik site from 1999 to 2019, measured at depths of 10 cm (red), 45 cm (purple), and 95 cm (blue). A gradual warming trend is evident at all depths, with increasing mean annual ground temperatures and reduced winter cooling, particularly at 45 cm and 95 cm depths. The sensor at 45 cm transitioned from being in the permafrost to active layer in 2004. (b) Mean annual ground temperature and (c) active layer thickness at the Tunalik and Point Lay sites from 1999 to 2019. The top panel shows observed permafrost temperatures at 95 cm depth for Tunalik (green) alongside modeled permafrost temperatures at 100 cm for both Tunalik (orange) and Point Lay (purple) (PermaMap 2025). Observed ALT values were measured in a localized ice-rich terrain unit, while modeled values reflect ecosystem-averaged ALT over a 770 m grid cell. The persistent bias likely reflects cryostratigraphic heterogeneity and model resolution limitations. However, the patterns suggest deepening of the active layer over time. (d) Active layer thickness anomaly from 1949 to 2019 based on modeled data for Tunalik (orange) and Point Lay (blue). Anomalies are calculated relative to the mean modeled active layer thickness of 33 cm for Tunalik and 65 cm for Point Lay between 1949 and 2019.

thermal regimes and suggesting that Point Lay experiences a relatively warmer permafrost environment than the Tunalik site. The mean modeled ALT for Point Lay was 65 cm (from 1949 to 2019). We also estimated ALT based on our study of cryostructures of frozen cores (a big portion of the active layer was still frozen during our drilling campaigns) (Jones *et al* 2024). ALT estimated based on drilling data varied from 32 to 83 cm ($n = 28$) with average values of 55.3 cm for Yedoma and YS ($n = 10$) and 51.6 cm for DLB ($n = 18$). These values are only slightly lower than average depths to ice wedges measured within all terrain units, which makes the wedges extremely vulnerable to thermokarst.

While observed ALT values exceed those of the model across most years, both datasets indicate a general increasing trend since the early 2000s (figure 5(c)). The discrepancy in magnitude reflects a known limitation in comparing point-based field observations to modeled outputs averaged across 770 m grid cells, which may not fully capture local soil, vegetation, or microclimatic conditions. The modeled data for Point Lay (Kali) indicate similar increasing ALT trends, albeit with slightly greater interannual variability and overall thicker modeled data relative to Tunalik. The ALT anomaly data (figure 5(d)) provide further insight into these trends, particularly for Point Lay. Negative anomalies dominate the mid-20th century, while positive anomalies become more frequent and pronounced from the late 20th century onward, indicating a trend of increasing ALT, which in turn increases probability of continued ice-wedge degradation in the future.

3.3. Ice wedge thermokarst mapping

Analysis of ice wedge thermokarst extent across different time periods (1949, 1974, and 2019) reveals a substantial increase in thaw-related permafrost degradation over time. The Yedoma permafrost terrain unit exhibited a clear trend of increasing thermokarst, with affected ice wedges expanding from ∼2% in 1949 to ∼5% in 1974, and surging to ∼22% by 2019 (figure 6). This suggests that Yedoma terrain is particularly susceptible to thermokarst, with notable spatial patterns of heightened degradation occurring near community infrastructure.

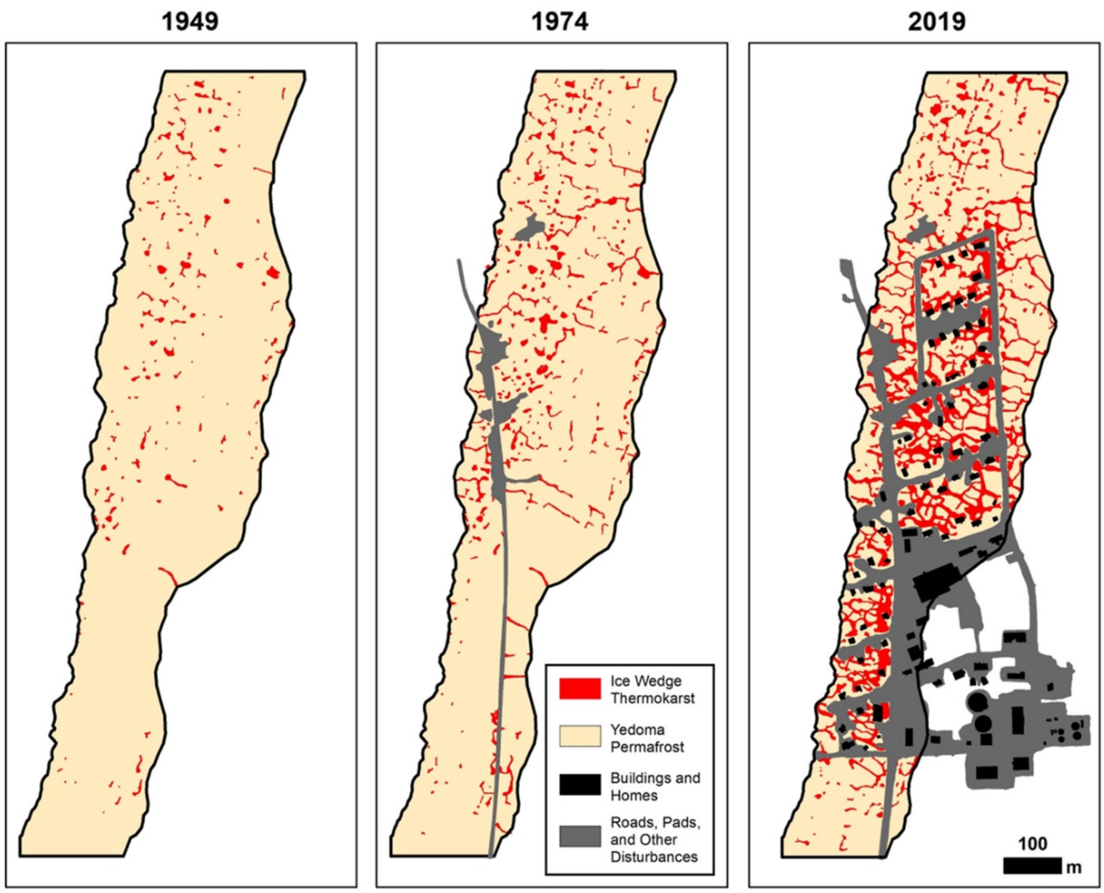

Figure 6. Temporal progression of ice wedge thermokarst and infrastructure development in Point Lay (Kali) from 1949 to 2019. Maps show the extent of ice wedge thermokarst (red), Yedoma permafrost (beige), and anthropogenic features including buildings (black) and roads, pads, and other surface disturbances (gray). The total area of degrading ice wedges expanded from ∼2% in 1949 to ∼5% in 1974 and surged to ∼22% by 2019. The 2019 panel highlights the concentration of thermokarst features within the developed portion of the landscape, indicating the impact of infrastructure on permafrost degradation when compared to adjacent undeveloped terrain subjected primarily to climate change impacts.

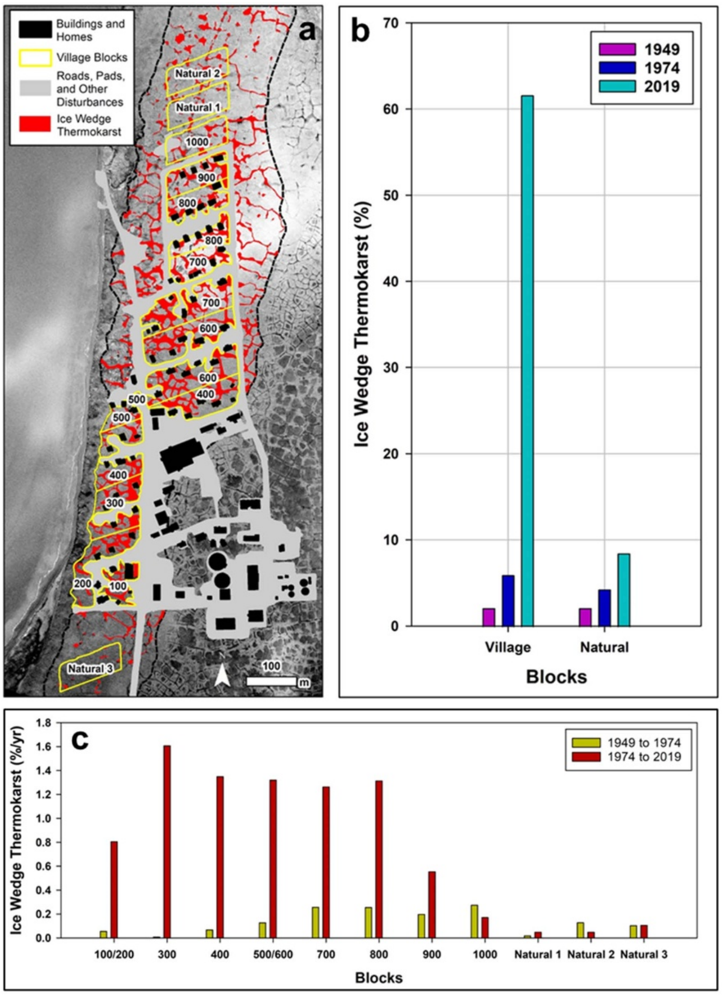

Figure 7. The analysis of ice wedge thermokarst across residential blocks versus 'natural-site blocks' reveals a significant acceleration in permafrost degradation over time in the built-up areas (a). (b) When comparing village and natural blocks, ice wedge thermokarst in village areas remained low in 1949 and 1974 but surged past 60% by 2019, whereas natural areas showed a more moderate increase. (c) Older residential blocks such as 300, 400, 500/600, 700, and 800 exhibit the highest thermokarst rates in the latter period, with values exceeding 1.5% yr^{-1}, suggesting a marked shift in permafrost stability after construction began in the mid-1970s. This pattern highlights the influence of human activities, such as infrastructure development, and climate change interacting to accelerate permafrost thaw.

The extent of ice wedge thermokarst was minimal in 1949 across areas that would later become developed as village blocks, with percentages generally below 5% (figures 7(a) and (b)). By 1974, minor increases were observed in some future development blocks, occasionally exceeding 5%. However, by 2019, ice wedge thermokarst had expanded dramatically in developed village blocks, particularly Blocks 300, 500/600, 700, and 800, where ice wedge thermokarst affected more than 60% of the area, which likely corresponds to ice wedge content values for the terrain unit (figures 7(a) and (c)). In contrast, natural blocks (Natural 1, 2, and 3) showed much lower levels of degradation, with ice wedge thermokarst coverage increasing but remaining below 10% in 2019 (figures 7(a) and (b)).

Measuring rates of ice wedge thermokarst expansion revealed a striking acceleration, particularly after 1974. Between 1949 and 1974, the annualized increase in thermokarst extent remained low, generally below 0.2% yr^{-1}. However, from 1974 to 2019, thermokarst expansion rates exceeded 1.5% yr^{-1} in several residential blocks, while natural blocks exhibited much lower increases, typically below 0.3% yr^{-1} (figure 7(c)). By 2019, ice wedge thermokarst affected over 60% of ice wedges in village areas, whereas natural areas remained below 10%. The stark difference in ice wedge thermokarst, nearly an order of magnitude higher in village areas (∼1.3% yr^{-1}) compared to natural areas (∼0.2% yr^{-1}), strongly suggests that infrastructure, surface disturbance, and other anthropogenic factors, in concert with climate change, significantly accelerate permafrost degradation, thaw consolidation, and ice wedge thermokarst. The three natural areas were selected to mirror the spatial footprint and orientation of a typical residential block (Block 900), extending into adjacent undeveloped terrain to serve as comparative baselines. Natural Area 2 shows slightly higher thermokarst activity during the 1949–1974 period, likely related to legacy surface disturbances associated with historical U.S. Air Force storage activities and later cleanup efforts. This local anomaly is not representative of natural trends across all undeveloped zones, and the post-1974 acceleration in thermokarst remains most pronounced in infrastructure-dense blocks.

3.4. Community perspectives: infrastructure impacts and thermokarst development

The Native Village of Point Lay (Kali) has experienced increasing thermokarst development, directly impacting infrastructure, including housing, roads, and public utilities. Community interviews provided valuable firsthand observations that offered unique insights into local environmental and infrastructure changes, as well as historical land use, adaptation strategies, and community-led mitigation efforts that would not be readily available from other sources. Point Lay (Kali) has a history of relocation due to environmental challenges, including coastal erosion, flooding, and permafrost degradation. Long-time residents, including Bill Tracey Sr., described how past land use patterns, including military and industrial activities, have influenced permafrost conditions in different parts of the village. Some of the most severe subsidence has occurred in areas where past development disturbed the ground surface, accelerating thaw. Additionally, community members highlighted that traditional land-use areas, such as hunting and fishing sites, are also being affected by thermokarst, altering access routes and subsistence practices.

According to five of eight interviewees, warming temperatures, wetter conditions, and longer summer seasons have contributed to accelerated permafrost thaw and widespread ground subsidence, destabilizing homes, roads, and traditional travel routes. Consequences of thermokarst, such as failing foundations, leaning homes and power poles, and frequent breaks in water and sewage lines, were consistently reported across interviews. Residents widely agreed that many homes that were originally less than 1 m above the ground surface have effectively gained an extra story as pilings become partially unearthed due to severe ground subsidence. The resulting structural instability has led some residents to evacuate to the school during high-wind events. Stairways, porches, and arctic entryways have detached from homes, and doors and windows no longer close properly as the ground continues to sink and shift.

Critical infrastructure failures—particularly related to water systems, roads, and buildings—were a key concern among six of eight interviewees, who linked these issues to thaw-induced ground instability and surface water accumulation. In addition, the North Slope Borough and several community members during the 2016 workshop (supplemental material) raised concerns about the increasing frequency of water and sewage line breaks due to differential settlement, leading to service disruptions and forcing many homes to revert to using 'honey buckets' and water truck haul services. The village's one-million-gallon water storage tank suffered a bottom failure due to the loss of foundation support, underscoring the severity of thaw-related impacts. Power infrastructure has also been compromised, with newly installed utility poles leaning due to installation in thawing permafrost. Residents expressed concern over the loss of fire hydrants due to subsidence, which has reduced emergency response capabilities (figure 2(b)).

In response to these challenges, various mitigation strategies have been recommended to slow permafrost thaw and stabilize infrastructure, including elevated gravel pads beneath new buildings, experimental thermosyphon installations, and seasonal water diversion measures to reduce local surface runoff and ponding. More specifically, the application of gravel to roads and around building foundations has been a widely used strategy, with material sourced from local borrow pits. However, residents noted that in some areas, gravel alone has been insufficient to counteract thaw settlement. Another major issue raised by multiple interviewees was the failure of drainage infrastructure. Many road culverts have collapsed or become ineffective due to permafrost degradation, exacerbating surface water ponding and flooding near homes and critical infrastructure. Community members emphasized that the accumulation of stagnant water has led to additional health and safety risks, including concerns over contamination and drowning. Community members emphasized the urgent need for improved snow management, drainage solutions, and thermokarst monitoring while also proposing alternative adaptation strategies, including deeper pile embedment and the application of sod to slow thaw (Connor *et al* 2023, Peirce 2024). These insights highlight the critical role of local knowledge in addressing permafrost-related challenges and underscore the need for greater support to develop long-term, sustainable solutions.

4. Discussion

4.1. Thawing permafrost, infrastructure, and climate change impacts in Point Lay (Kali)

Point Lay (Kali), Alaska, is confronting a crisis driven by the interplay of climate change and infrastructure on ice-rich permafrost. Recent warming and permafrost thaw observed at the Tunalik site since 1999 provide a representative case for ongoing changes in Point Lay, where ground temperatures have also increased, and active layer thickening has accelerated, leading to thermokarst development. To contextualize changes in modeled ALT, we further assessed summer air temperature and degree days of thaw from the Tunalik site (supplemental figure 1). These data show a progressive warming trend, with variability as well as two especially warm summers—2007 and 2019—aligning with notable ALT increases. It is plausible that the post-2004 rise in ALT not only reflects continued atmospheric warming but also causes the breaching of an ice-rich intermediate layer, which may affect large, buried ice wedges in Yedoma deposits and initiate widespread thermokarst development. Long-term modeled data (figure 5(d)) indicate that since 1949, ALT has deepened, with a more pronounced shift occurring during the 21st century. The remote sensing time periods we consider, 1949–1974 and 1974–2019, correspond well with these shifts in ALT anomalies. The latter period, characterized by persistent positive ALT anomalies, aligns with substantial increases in thermokarst activity observed in remote sensing imagery. This suggests that permafrost degradation has accelerated in response to increasing ALT and associated subsidence processes, particularly in Point Lay (Kali), where warmer temperatures and deeper thaw penetration may have enhanced ice-rich permafrost thaw and terrain instability. The transition of the 45 cm sensor at Tunalik from permafrost to the active layer in 2004 underscores the rapidity of these changes and highlights the vulnerability of permafrost in coastal regions of northern Alaska. Our findings show that MAGT is a poor indicator of active layer thickening and thermokarst development because it masks critical seasonal, summer extremes and short-term thaw events that can drive permafrost degradation and ground surface subsidence.

These trends in increasing ALT align with observed infrastructure failures and increased thermokarst formation underscoring the role of permafrost degradation in driving landscape and community-level impacts. Collectively, the interviewees in Point Lay (Kali) reported the impacts of widespread thermokarst development, including subsiding roads, failing foundations, disrupted utility services, and increased health and safety risks. Subsidence is causing road hazards, structural damage to buildings, water and sewage failures, and instability in power poles and fire hydrants, compromising safety, accessibility, fire response capabilities, and infrastructure reliability. The fire hall has also been affected and no longer able to house the fire truck and ambulance. Across the community, infrastructure is failing catastrophically before the end of its design life, disrupting essential services, jeopardizing health and safety, and resulting in huge financial costs to repair and replace failing infrastructure. These findings highlight the immediate challenges faced by Point Lay (Kali) residents and emphasize the critical need for investment in adaptive infrastructure solutions to cope with ongoing permafrost degradation.

The presence of infrastructure has accelerated thermokarst in Point Lay. Buildings, roads, and other infrastructure often disrupt natural snow and water distribution and drainage patterns, creating depressions and channels where water pools or flows across the landscape, conducting heat and deepening permafrost thaw (Hjort *et al* 2022). In Point Lay, residents observed that ‘our homes create snowdrifts, and the drifts add to the ponding, which contributes to the subsidence and gets down into our pilings’ (Peirce 2024, page 13). This direct connection between snow and water management and localized permafrost degradation is a key insight that is being given to increasing attention in Arctic communities. Snow that drifts and accumulates around infrastructure not only extends the duration of snowmelt but also acts as an insulating layer, slowing wintertime refreezing and exacerbating thaw processes (Peirce 2024, p 27). In addition, underground water and sewer systems, especially direct-bury systems, have been a persistent source of permafrost thaw, as undetected leaks release warm water into frozen ground, leading to further degradation, ground collapse, and sinkholes. For example, ‘leaks in buried water lines are a significant issue in Point Lay,’ where water flow beneath the ground has caused ongoing permafrost degradation and structural damage (Peirce 2024, p 34). These challenges underscore the need for active snow and water management strategies, including community-wide drainage assessments and snow dispersal plans that avoid piling near vulnerable infrastructure (Peirce 2024, p 27). They also highlight the importance of transitioning to aboveground utility systems to prevent heat transfer into permafrost, an approach currently being designed for communities like Point Lay (Peirce 2024, p 37). Incorporating local knowledge—such as observations of where thaw is worst near snow piles—will be crucial for designing effective, place-based adaptation strategies.

We hypothesize that many of these failures have been difficult to anticipate because they are caused by the convergence of recent climate change and human activities, which have exacerbated the negative impact on cold, continuous permafrost stability nearly 50–70 yr faster than model projections in the region (Nicolsky *et al* 2017). This, in turn, has led to irreparable damage to the infrastructure and the loss of bearing capacity beneath community infrastructure. Most of the community sits atop a Yedoma hill underlain by the ice-rich permafrost, which can lose up to 40% of its volume after thaw, in addition to differential thaw settlement due to melting ice wedges. Our remote sensing change detection results implicate the interaction between climate change and infrastructure, rather than climate change alone, as being the cumulative stressor on the permafrost, contributing to heat retention, altered snow and water dynamics, lack of drainage, and disrupted vegetation insulation. The spatial distribution of ice wedge thermokarst further supports the role of human activity in accelerating degradation (figures 6 and 7). The most severely impacted blocks are concentrated in the older areas of the village, whereas the undisturbed (natural) sites show comparatively limited degradation. These findings underscore the importance of land use in driving permafrost thaw and suggest that continued infrastructure expansion in permafrost regions could accelerate ice wedge thermokarst in the future, especially in the absence of adaptive engineering techniques and snow and water management to reduce permafrost impacts (Vincent *et al* 2017, Kokelj *et al* 2023). This exacerbates differential thaw subsidence of the surface and consequent structural failures, including water storage tank collapse, abandoned homes, and unsafe roads.

The ongoing deterioration of infrastructure due to thermokarst processes highlights the urgent need for mitigation strategies that integrate engineering solutions, drainage plans, monitoring efforts, and community engagement. To enhance long-term stability, researchers and local stakeholders have proposed deeper pilings, alternative foundation designs, and improved road drainage systems, along with engineering approaches such as filling ice wedge troughs with fine-grained soil material, constructing soil pads for new buildings, improving road drainage systems, and embedding pilings deeper into stable ground (or the most stable ground available, while avoiding wedge ice). Increased monitoring efforts, including permafrost temperature sensors and community-led subsidence tracking, are recommended to better assess permafrost degradation and inform future adaptation measures. Additionally, high-resolution remote sensing and permafrost coring are necessary for planning and construction improvements. Community engagement remains central to these efforts, ensuring that local and Indigenous knowledge, scientific research, and regional collaborations contribute to construction and maintenance of resilient infrastructure that supports both modern development and the subsistence lifestyle essential to Point Lay (Kali)'s identity (Flynn *et al* 2019, Jungsberg *et al* 2022). These initiatives highlight the importance of partnerships that prioritize community-led solutions to adapt to the intensifying impacts of climate change.

4.2. Engineering solutions for infrastructure stability in Point Lay (Kali)

The permafrost conditions in Point Lay (Kali) present significant challenges for infrastructure stability, particularly for foundations. The widespread presence of ice-rich permafrost with large ice wedges has resulted in differential subsidence, leading to structural damage to homes, roads, and utility systems. Engineering solutions must address both the immediate effects of subsidence and the long-term challenges posed by continued permafrost degradation to ensure the resilience of community infrastructure (Vincent *et al* 2017, Hjort *et al* 2022, Burn *et al* 2025). In addition, there is a need for community planners and engineers in the Arctic to view the impacts of infrastructure as a system rather than a collection of individual structures. For example, road embankments, buildings, and utilities often exacerbate the impact of snow drifts and snow accumulation; roads often impede drainage which accelerates permafrost thaw; and culverts concentrate water flow, facilitating thermal erosion (O'Neill and Burn 2017, Schneider von Deimling *et al* 2021, Walker *et al* 2022). Guidelines and best practices to combat these integrated challenges currently do not exist.

One of the primary recommendations for improving foundation stability is to enhance pile foundation design. Current assessments indicate that many residential piles are embedded in ice wedges or ice-rich permafrost soils, which are highly susceptible to thaw-induced settlement (figures 2 and 8). As a result, the embedment depth of many piles has been significantly reduced since their installation, compromising structural integrity. To mitigate this issue, new pile installations and if possible, all foundations, should avoid placement where near-surface ice wedges are located, and when unavoidable, deeper embedment is necessary. Additionally, flexible connections between piles and structures can help accommodate differential settlement, reducing stress on buildings and utilities. Structures placed on frozen impermeable, fine-grained, thaw-stable soil may also prevent the through-flow of surface water that could promote underground thermal erosion (Connor *et al* 2023).

Another critical engineering recommendation is the preemptive removal and replacement of the upper portion of ice wedges before construction (figure 9). This method involves excavating the top layers of ice wedges and replacing them with fine-grained, thaw-stable soils to reduce the risk of thermokarst development beneath structures (Connor *et al* 2023). However, this is an untested solution that will require careful implementation to prevent unintended surface water ponding and sub-surface thermal erosion. For existing structures, stabilization efforts can focus on filling troughs and depressions with fine-grained soil to ensure proper drainage, restore surface stability, and minimize or reverse permafrost thaw and ground-ice melt. Additionally, active maintenance programs, including snow and water management, and annual thermokarst monitoring, are essential for detecting early signs of structural instability and implementing corrective measures before severe damage occurs (O'Neill and Burn 2017, Kokelj *et al* 2023).

Road and utility infrastructure require targeted adaptation strategies to withstand permafrost degradation (Doré *et al* 2016). Road embankments designed to minimize snow accumulation along shoulders would preclude thermokarst formation due to excessive snow accumulation. Improved drainage systems are also crucial to preventing water impoundment, which may result in further permafrost

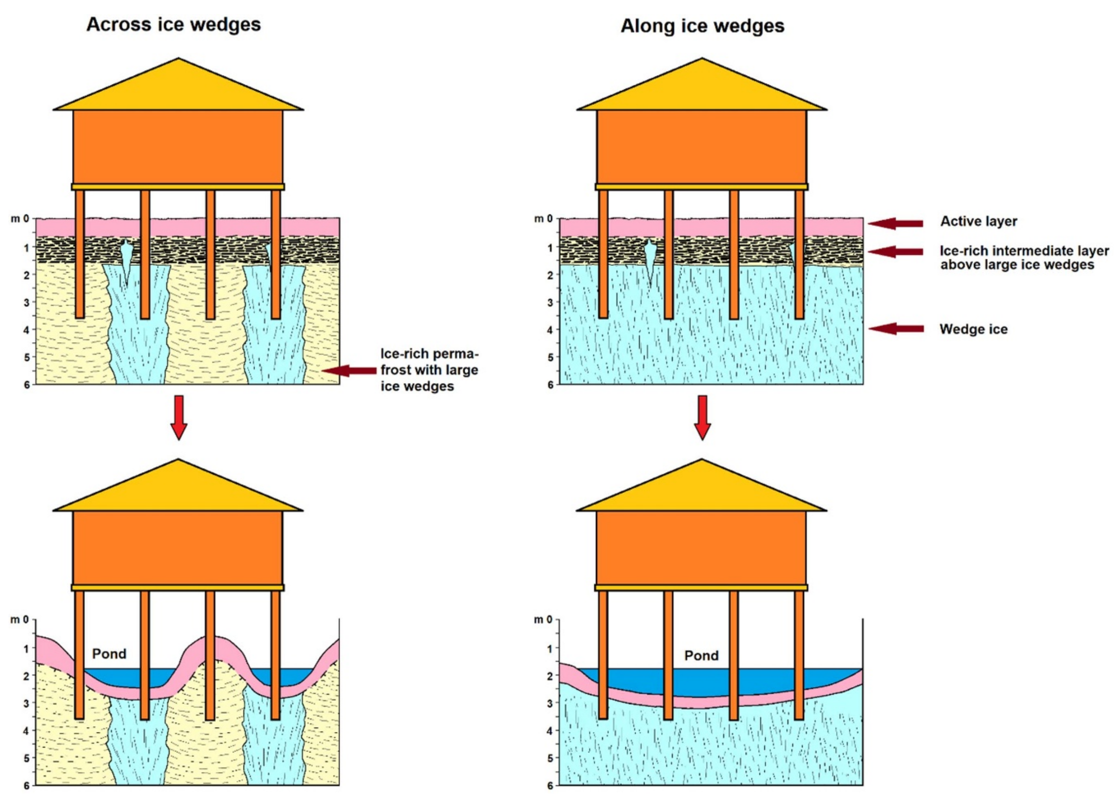

Figure 8. The impact of ground subsidence on the stability of pile foundations in ice-rich permafrost is largely determined by their placement relative to ice wedges. (Left) An example of piles embedded across ice wedges, alternating between polygon centers and wedges. Thaw settlement is significantly less when piles are founded in polygon centers. (Right) An example of piles placed along an ice wedge. In these cases, subsidence is more uniform but can lead to collapse of piles and total failure of the overlying infrastructure.

degradation. For utility systems, aboveground water and wastewater pipelines supported on adjustable piling foundations and equipped with thermosyphons for passive cooling can provide greater flexibility and reduce the risk of damage from thawing permafrost, thermokarst, and thermal erosion (Connor *et al* 2023). By balancing immediate stabilization needs with long-term adaptation strategies, these engineering solutions can help mitigate the impacts of subsidence, enhance structural resilience, and support the community's long-term viability in the face of ongoing climate change (Wang *et al* 2023).

4.3. Northern communities built on ice-rich permafrost

Northern communities built on ice-rich permafrost face significant challenges as the interaction between climate change and built environments accelerates permafrost thaw, leading to ground instability and infrastructure failure. Addressing permafrost thaw and infrastructure challenges in Point Lay (Kali) is a deeply complex issue that goes beyond technical fixes, touching on broader concerns about community identity, sustainability, and future development. While the symptoms of permafrost thaw—such as collapsing ground, ponding water, and damaged homes—are clearly visible, community members are also grappling with the practical and emotional challenges of how to move forward. Several critical capital improvement projects are currently on hold due to multiple interrelated barriers, including a shortage of gravel and fill material needed to stabilize building sites and elevate homes above thawing ground, and the urgent need to identify a new, reliable source of drinking water after their previous freshwater lake was lost to permafrost degradation (Wolken *et al* 2021, Peirce 2024). At the same time, residents must collectively decide whether to pursue relocation of the entire village to more stable ground or adopt strategies to enable them to protect in place, weighing both the cultural importance of place, access to traditional subsistence resources, and the risks of staying on rapidly thawing terrain. Capital investments to replace failing infrastructure, including the direct-bury water-sewer system, have reportedly been paused while waiting for the community to decide on its future. Regardless of the decision, substantial funding will be required not only for new development but also for basic adaptation measures such as improved drainage, snow management, and moving or retrofitting existing infrastructure. Point Lay (Kali)'s situation illustrates how permafrost thaw is not simply an environmental issue but one that touches every aspect of community and subsistence ways of life—from housing and water access to cultural survival and long-term planning. Addressing these concerns

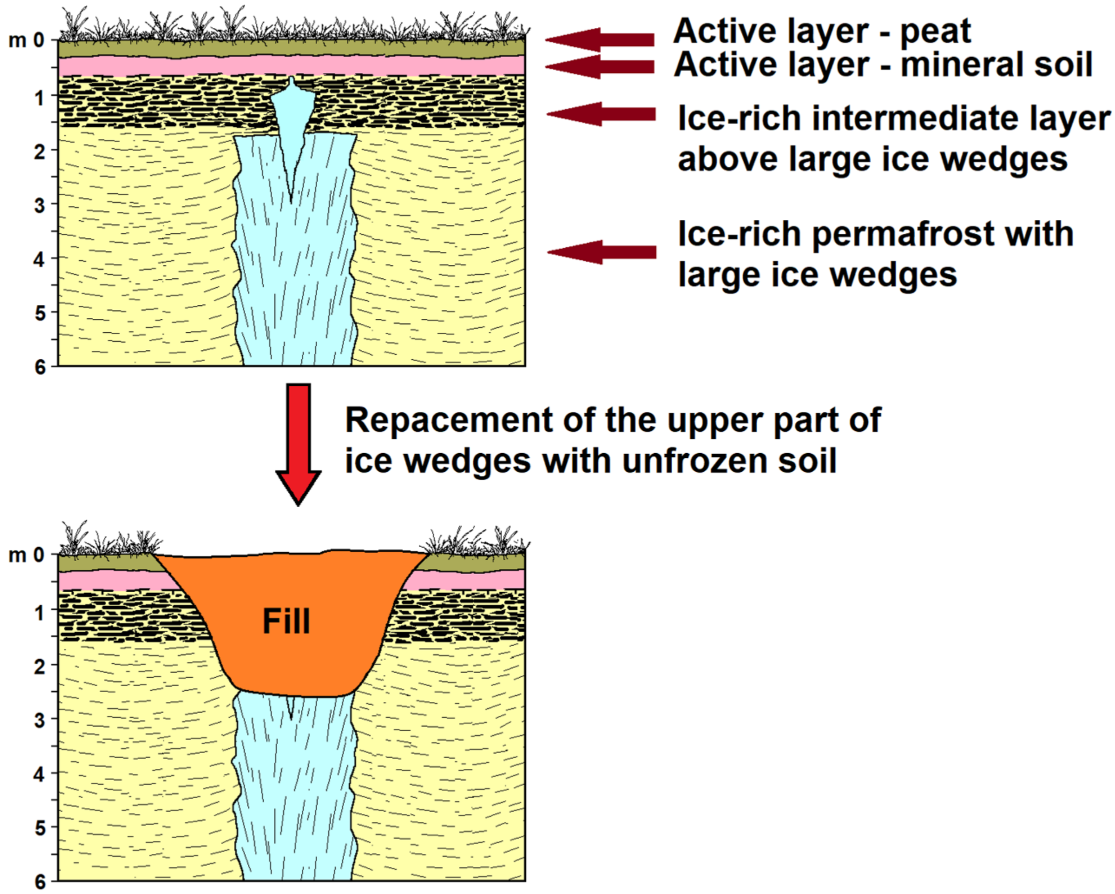

Figure 9. Schematic representation of ice wedge excavation and infill with unfrozen soil. (Top) The initial permafrost profile consists of an active layer composed of peat and mineral soil, an ice-rich intermediate layer (Shur 1988) with small active ice wedges, and ice-rich Yedoma permafrost containing large, buried ice wedges. (Bottom) As a potential solution, the upper portion of the ice wedge has been intentionally excavated and replaced with fine-grained soil (fill). This process offers a potential stabilization measure to mitigate ground subsidence caused by ice-wedge thaw, reducing the risk of thermokarst development by resisting surface water intrusion and providing added protection above the buried ice wedge, thereby improving terrain stability for infrastructure in permafrost regions. However, this untested solution will require careful implementation to prevent unintended surface water ponding and sub-surface thermal erosion.

will require integrating engineering solutions with community-led decisions and securing sustained financial investment that reflects the scale and urgency of the problem.

Many Arctic settlements, historically planned without anticipating the risks of permafrost degradation in a warming world, are now experiencing severe consequences as increasing ALTs are causing ice-rich ground to thaw and subside (Creel *et al* 2024, Streletskiy *et al* 2024, Tanguy *et al* 2024). Studies have documented widespread impacts in communities such as the Inuvialuit settlement of Paulatuk, south of Darnley Bay, northern Canada, where rapid coastal erosion and permafrost thaw are forcing residents to consider relocation (Tanguy *et al* 2023). Similarly, in Norilsk, Russia, one of the largest permafrost-based cities, thaw-induced ground instability has led to extensive damage to buildings and industrial infrastructure, with economic losses in the billions (Streletskiy *et al* 2023). In Alaska, the village of Newtok has become a well-known example of a community severely affected by permafrost degradation and erosion, prompting one of the first federally funded, climate-driven relocations in the United States (Bronen and Chapin 2013). The challenges faced by these communities underscore the need for adaptive infrastructure design, improved engineering solutions, and proactive policy measures to support long-term sustainability in permafrost regions (Alessa *et al* 2023).

As ice-rich permafrost continues to thaw and degrade, there is an urgent need for collaborative research and investment in climate-resilient development strategies to mitigate risks and protect Arctic communities. The integration of insights from the 2016 Point Lay workshop (supplemental material), 2022 interviews (Connor *et al* 2023), and 2024 Permafrost & Infrastructure Symposium (Peirce 2024) reflects a deliberate, iterative engagement process. While thematic overlap exists across these dialogues, each encounter occurred within a distinct temporal and environmental context, capturing the evolution of community concerns as permafrost thaw and infrastructure impacts intensified. Repeated engagement also allowed researchers to build trust and develop a more nuanced understanding of local priorities—an essential feature of knowledge co-production in Arctic communities.

Looking ahead, the ACTION project (Arctic Coastal Community-driven Transdisciplinary Research and Innovation for Adaptation and Resilience) is a collaborative initiative that is funded by the U.S. National Science Foundation designed to support Arctic communities facing increasing risks from erosion, flooding, and permafrost degradation. Recognizing the limitations of existing governance frameworks, ACTION prioritizes community-driven research and co-production of knowledge to develop more effective resilience strategies. By centering Indigenous governance and knowledge, the project builds on long-standing partnerships with Arctic coastal communities and applies a social-ecological-technological systems approach to identify adaptation pathways that reflect local priorities (Alessa *et al* 2015). This model also aligns with Mercer *et al* (2023) by demonstrating how community-based monitoring programs—such as those in Tuktoyaktuk, Canada—enhance understanding of environmental changes while supporting Indigenous self-determination in research.

A key component of ACTION is the Community Research Lead (CRL) Program, which funds local leaders to drive research efforts, operate environmental monitoring programs, and facilitate communication between Indigenous communities and scientists. On the North Slope of Alaska, Ukpeaġvik Iñupiat Corporation Science (UICS), is coordinating the implementation of the CRL program in Point Lay (Kali). UICS is a subsidiary of UIC, based in Utqiaġvik, Alaska, that provides scientific research, environmental consulting, and logistical support for Arctic-focused studies. Specializing in permafrost, coastal erosion, wildlife, and ecosystem monitoring, UICS collaborates with federal agencies, academic institutions, and Indigenous communities to advance climate resilience and sustainable development in the Arctic. The organization plays a crucial role in facilitating community-driven research, offering field support, data collection services, and expertise in Arctic environmental science while prioritizing Indigenous knowledge and local engagement in research initiatives. The CRLs will receive training, mentorship, and professional development through the ACTION project, ensuring that climate adaptation efforts are rooted in community expertise and priorities rather than top–down decision-making. By embedding Indigenous leadership in research and hazard response planning, ACTION not only improves scientific understanding of permafrost and coastal hazards but also empowers Arctic communities to take an active role in shaping their future in the face of climate change.

5. Conclusion

The findings from this study highlight the accelerating degradation of ice-rich permafrost in Point Lay (Kali), Alaska, and its profound implications for community infrastructure. Borehole data, measured and modeled ground temperature data, remote sensing change detection analysis, and community observations collectively illustrate the rapid expansion of thermokarst processes, particularly in areas with high wedge-ice content. Since the mid-1970s, ice wedge thermokarst extent has increased dramatically, particularly in developed areas where human activities exacerbate permafrost thaw through heat transfer, ground disturbance, and altered drainage, leading to safety hazards, structural damage, and service failures. In turn, the accelerated thaw destabilizes critical infrastructure, disrupting essential services and straining financial resources and community resilience. The convergence of climate-induced permafrost degradation and localized anthropogenic stressors underscores the urgent need for targeted engineering solutions and adaptive strategies. Observations of the residents of Point Lay (Kali) demonstrate the need for community planners and engineers in the Arctic to consider infrastructure affected by permafrost-related hazards as a system rather than a collection of individual structures.

In response to these challenges, this study emphasizes the necessity of integrating scientific research and engineering perspectives with local and Indigenous knowledge to develop sustainable adaptation measures. Engineering recommendations such as deeper pile foundations, improved drainage systems, and proactive thermokarst management strategies offer viable pathways for mitigating further damage. However, ensuring the long-term viability of Point Lay's (Kali) infrastructure will require not only continued investment in long-term monitoring, remote sensing applications, and community-driven planning but also a more deliberate integration of scientific and Indigenous knowledge into engineering practice. As Arctic permafrost regions face escalating climate pressures, the experiences of Point Lay (Kali) serve as an important example for other northern communities confronting similar environmental and infrastructural vulnerabilities. Addressing these challenges will require a coordinated approach that combines local expertise, scientific innovation, and policy interventions to foster resilience in the face of ongoing permafrost thaw.

Data availability statement

The data that support the findings of this study are openly available at the NSF-funded Arctic Data Center and cited in the list of references (Connor *et al* 2023, Kanevskiy *et al* 2023, Jones 2025) and available through the University of Alaska Fairbanks Geophysical Institute Permafrost Laboratory (GIPL) (PermaMap 2025).

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Ethical statement

This study involved human participants through semi-structured interviews conducted in Point Lay (Kali), Alaska. All research involving human participants was reviewed and approved by the Institutional Review Board (IRB) at the University of Alaska Fairbanks (Approval No. IRB 1909817-3). The study was conducted in accordance with the principles embodied in the Declaration of Helsinki and adhered to all applicable local and institutional ethical guidelines. All participants provided written informed consent to participate in the study. Participants were informed of the study's objectives, their rights to withdraw at any time, and how their contributions would be used. Consent was also obtained for publication of anonymized quotes and data derived from interviews. No animal experiments were conducted as part of this research.

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