ALASKA GEOBOTANY CENTER DATA REPORT

AGC 23-01

PERMAFROST & REMOTE SENSING STUDIES: 2022 FIELD REPORT FOR POINT LAY, ALASKA

BILLY G. CONNOR, BENJAMIN M. JONES, MIKHAIL KANEVSKIY, DMITRY J. NICOLSKY, JANA L. PEIRCE, VLADIMIR E. ROMANOVSKY, AND YURI L. SHUR

EDITED BY B. G. CONNOR AND J. L. PEIRCE

JANUARY 2023

NNAIRPS Ice-Rich Permafrost Systems

UAF UNIVERSITY OF ALASKA FAIRBANKS

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On the cover

A thermokarst landscape characterized by small hummocks separated by troughs or hollows can be seen on the ice-rich yedoma slope between the village of Point Lay at right and the Chukchi Sea coast, out of frame at left (credit: J.L. Peirce). **Inset photos, top:** Mikhail Kanevskiy drills a permafrost borehole with a SIPRE corer (credit: B.M.Jones); **middle row from left:** Benjamin Jones shares preliminary images and findings from remote sensing studies with tribal president James Henry (credit: J.L. Peirce); Yuri Shur and Billy Connor inspect house foundations in the village (credit: B.M. Jones); **bottom from left:** Village elder and lifelong resident Marie Tracey takes a photo with researchers Jana Peirce and Tracie Curry following their interview (credit: J.L. Peirce); Vladimir Romanovsky and Colby Wright install a ground temperature sensor near infrastructure (credit: L.M. Farquharson); Longtime resident and project advisory Bill Tracey discusses historical developments and the effects of landscape changes during an interview (credit: J.L. Peirce).

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SUMMARY OF FINDINGS AND RECOMMENDATIONS

Ground ice content and character

- We identified three main terrain units in the townsite: main yedoma surfaces, yedoma slope, and thaw lake basin (Figure 1c).
- The permafrost underlying most of the village was classified as yedoma: fine grained, ice rich permafrost penetrated by large syngenetic ice wedges, which formed during the late Pleistocene in unglaciated areas of northern Eurasia and North America. Wedge-ice content in yedoma may exceed 50% by volume.
- The yedoma terrain appears uniform from north to south. As such, one can expect similar performance throughout the terrain unit in response to climate change and infrastructure development.
- Ice wedges in Point Lay were found to extend to slightly below sea level.
- Most ice wedges in the undeveloped area to the north of the townsite were encountered within 40 to 80 cm (1.5 to 2.5 ft) of the ground surface, making them vulnerable to thermokarst[1] and thermal erosion. These wedges may reach a depth of 10 to 12 m (32 to 40 ft) below the surface.
- Based on measurements of excess ground-ice content, we presume that settlement of frozen soils upon thawing will reach nearly 40% of the initial thickness of the ice-rich permafrost, without taking wedge-ice volume into account.
- The thaw lake basin to the south and east of the townsite is significantly lower in elevation. The basin usually floods in spring due in part to the drainage barrier created by the road to the airport, landfill and old water supply.
- Ice wedges in the drained thaw lake basin are much smaller than in the yedoma terrain, and their vertical extent is approximately 3 m (~10 feet). Wedge-ice content in thaw lake basins usually does not exceed 15-20%.

[1]Thermokarst is the process by which characteristic landforms result from the thawing of ice-rich permafrost or the melting of massive ice. Ice-wedge thermokarst in yedoma terrain is characterized by conical mounds encircled by moist or wet troughs forming a polygonal pattern. During the transition from the late Pleistocene to Holocene, widespread thermokarst within yedoma regions resulted in formation of numerous thaw lake basins.

Thermokarst development accelerated by infrastructure

- It appears that thermokarst and thermal erosion accelerate with the construction of infrastructure, which increases the mean annual surface temperature and active-layer thickness through a variety of processes. Looking at the Point Lay townsite, thermokarst appears most developed under the oldest structures on the yedoma terrain at the south end of the town and less pronounced moving north (Figures 2 & 3).
- The school and the fire station are constructed in the transition from the drained lake basin to the yedoma. The public infrastructure (power plant, water and fuel tanks, water treatment plant and sewage treatment plant) founded on gravel pads in the drained thaw lake basin are generally performing well.
- The role of infrastructure in accelerating thermokarst must be taken into account when planning new construction. We presume we would see similar degrees of thermal erosion and thermokarst develop over time if building on the same yedoma terrain with the same methods.

Implications for pile foundations

- We estimate about 30% of the residential piles in the village are founded in ice wedges.
- If a structure is founded on both ice wedges and ice-rich soils, troughs form over the ice wedges, reducing the embedment of piles founded in wedges. (Areas of ice-rich permafrost will subside, but to a lesser extent.) In cases where all piles are founded within ice wedges, ponding forms under the entire structure. In both cases, the embedment of the piling is significantly reduced (Figure 4).
- Most of the piling beneath village housing was originally embedded 10 feet. Those piling founded in the ice-rich permafrost are embedded between 4 and 6 feet. It appears that those piles embedded in ice wedges have as little as 3 feet of embedment remaining (Figure 5).

Engineering solutions

- While expensive, engineering solutions do exist. It is important that they be implemented soon and perhaps focused on sites showing the least advanced stages of ice wedge degradation first.
- We recommend the following actions:
  - Inspect each structure to determine the extent and severity of cosmetic and structural damage. These data should be used to determine the condition of the structure and the appropriate mitigation.
  - Filling troughs and depressions with fine grained soil will help protect the underlying permafrost and establish drainage throughout the village.
  - When constructing new structures, remove the upper portion of the ice wedges and replace the ice with fine grained thaw stable soils (Figure 6).
  - Pile embedment should be at least 6 m (20 ft) when placed in the thermokarst mounds and at least 9 m (30 ft) when placed in an ice wedge. If practical, avoid placing piles in wedge ice.
  - Implement an active maintenance program including snow management, drainage, and annual thermokarst monitoring.
  - If the new water/wastewater system is an above ground system supported on piling, place the piling in the thermokarst mounds and make the attachment fixtures adjustable. We also recommend the connections to the structures be made as flexible as practical.
  - If post and pad foundations are used, place a 1-to-1.5 m (3-to-5 ft) gravel pad beneath the structure in addition to removal of the upper 5 feet of the wedge ice. The post/pad connection should allow the pad to remain in full contact with the soil as the soil subsides.

METHODS AND RESULTS

Overview

In summer 2022, our team of University of Alaska Fairbanks (UAF) scientists and engineers visited Point Lay to gain an understanding of the permafrost underlying the village, assess the impact of thawing permafrost on the infrastructure, as well as impacts of the infrastructure on thermokarst development, and to identify potential solutions to the damage to the community's infrastructure reported in previous assessments. This report will address each of these goals in turn.

Primary funding for the research is provided by the National Science Foundation (NSF) project, *Navigating the New Arctic: Landscape Evolution and Adapting to Change in Ice-Rich Permafrost Systems* (Award 1928237) with additional support from NSF Awards 1820883, 1806213, 1927708, and the U.S. Army Corps of Engineers. Logistics support was provided by Battelle ARO through a contract with UIC Science, including lodging and transportation in Utqiaġvik and air charter service from Utqiaġvik to Point Lay. Lodging in Point Lay was provided by the North Slope Borough School District. The team thanks the Native Village of Point Lay and Kali School for their hospitality and members of the project's local Steering Committee for their invaluable help before and during the visit.

Understanding permafrost character and ground ice content

Permafrost cores were taken around the village to ascertain the composition of the frozen soils and measure ground-ice content. Ten boreholes up to 3 m (10 ft) deep with total depth of 13.6 m (45 ft) were drilled with the SIPRE corer to describe and sample frozen soils and ground ice, and 19 boreholes up to 5.5 m (18 ft) deep with total depth of 24.9 m (83 ft) were drilled with the Kovacs auger to estimate depth to wedge ice and vertical extent of ice wedges. The 10

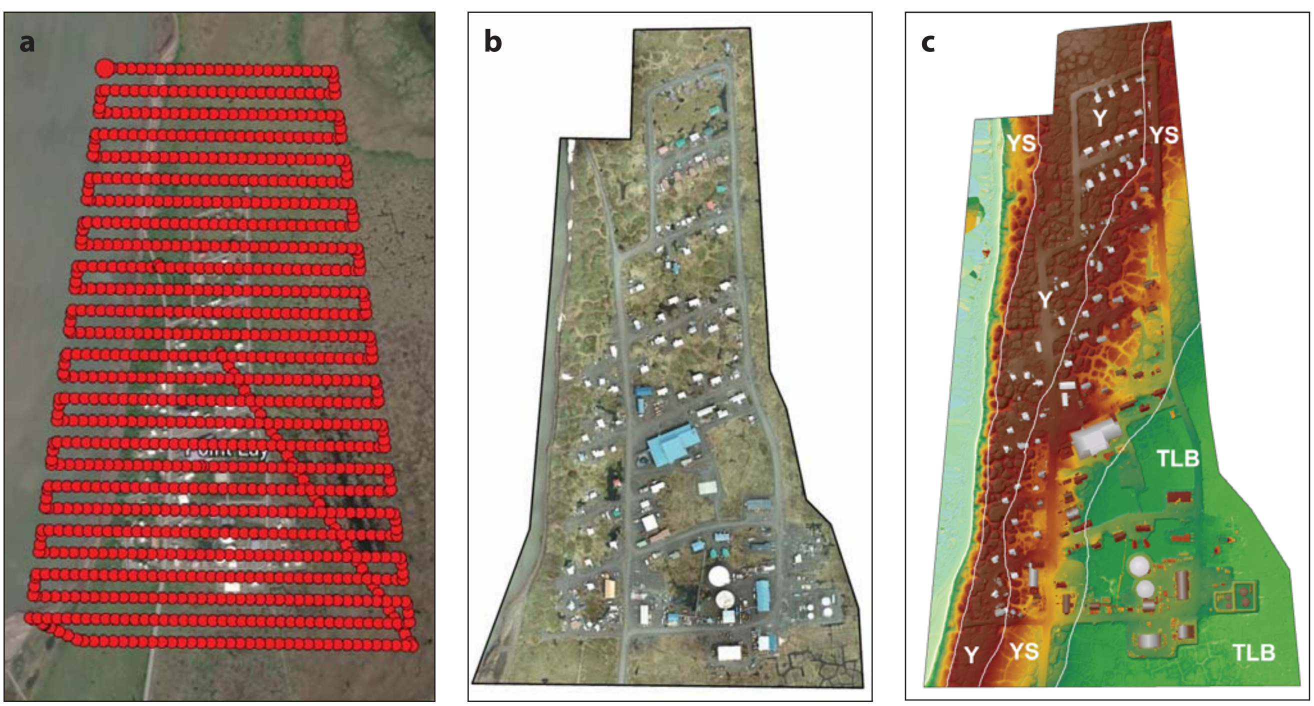


Figure 1. ***a.*** *UAV survey grid over Point Lay with data tied down to WGS84 UTM Zone 3N Ellipsoid Heights.* ***b.*** *High-resolution digital photo of Point Lay townsite acquired by the quadcopter drone.* ***c.*** *A digital terrain model derived from drone imagery reveals three main terrain units in the townsite: main yedoma surfaces (Y), yedoma slope (YS), and thaw lake basin (TLB). Wedge-ice content in yedoma may exceed 50% by volume. (Credit: B.M. Jones)*

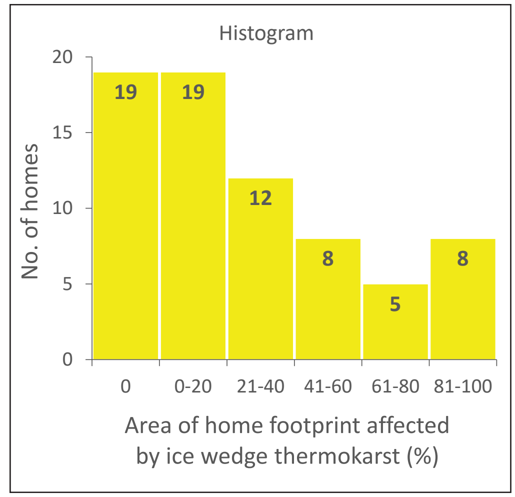


Figure 2. *Generalized terrain units and infrastructure in Point Lay mapped from an orthophoto mosaic and digital terrain model created drone imagery. Estimates of the footprint of particular homes impacted by ice wedge thermokarst are shown in yellow in the inset map at lower right and in the histogram below. (Credit: B.M. Jones)*

cores obtained with the SIPRE corer were described, photographed, and sampled in the field. Additionally, a coastal exposure along the Chukchi Sea coast was described and sampled. A total of 39 soil samples were collected from the SIPRE cores and coastal exposure for evaluation of moisture contents and excess ground-ice content. (See Appendix 1 for borehole data and photos of SIPRE cores.)

We observed substantial differential thaw settlement due to the melting of ice wedges in and around infrastructure. Based on measurements of excess ground-ice content, we presume that settlement of frozen soils upon thawing will reach nearly 40% of the initial thickness of the ice-rich permafrost (without taking wedge-ice volume into account). The permafrost underlying most of the village was classified as yedoma (fine grained, ice rich permafrost penetrated by large syngenetic ice wedges). Ice wedges in Point Lay were found to extend to slightly below sea level. Most ice wedges in and around the townsite were encountered within 40 to 80 cm (1.5 to 2.5 ft) of the ground surface, making them vulnerable to thermokarst and thermal erosion. Ice wedges in the yedoma terrain and adjacent slopes may reach a depth of 10 to 12 m (32 to 40 ft) below the surface. Wedge-ice content in yedoma may exceed 50% by volume. Ice wedges in the drained thaw lake basin are much smaller, with a vertical extent of approximately 3 m (10 ft). Wedge-ice content in thaw lake basins usually does not exceed 15-20%.

Drone-based mapping of ice-wedge thermokarst and impacts on infrastructure

A quadcopter drone was used to acquire high-resolution digital photography for the community to understand the extent of the yedoma and to map ice wedge thermokarst within and adjacent to the community (Figure 1). Figure 2 depicts the layout of the village along with generalized terrain units mapped from images acquired by the drone and processed into an orthomosiac and digital terrain model. Elevations are shown in green and depressions (ice wedge troughs) are shown in red. Note: ice wedge thermokarst was not mapped in the drained thaw lake basin, where the extent of thermokarst is far less than on the yedoma.

Yedoma terrain. The yedoma terrain unit, characterized by thermokarst mounds rimmed by ice wedge troughs, runs parallel with the lagoon and is bound to the east by a drained lake basin shown in beige. (See Y and YS in Figure 1c.) It is important to note that the yedoma terrain in Point Lay appears uniform from north to south, but the development of ice wedge thermokarst appears to follow development in the village with the most developed troughs forming under the oldest structures to the south. We will explore this more later.

Thaw lake basin. The drained thaw lake basin parallels the yedoma terrain unit to the east of the village (TLB in Figure 1c). The elevation of the basin is significantly lower and the ice wedges are much smaller and younger than in the yedoma terrain. The basin usually floods during the spring in part due to the drainage barrier created by the road to the airport, landfill and old water supply. Cores near the Airport Road show the development of a thick layer of peat north of the road as a result of several decades of water impoundment caused by the road. (In comparison, we found 81 cm (31.9 in) of peat at borehole PLAY-9, but just 32 cm (12.6 in) peat at borehole PLAY-10 south of the road (Figure A1.5).

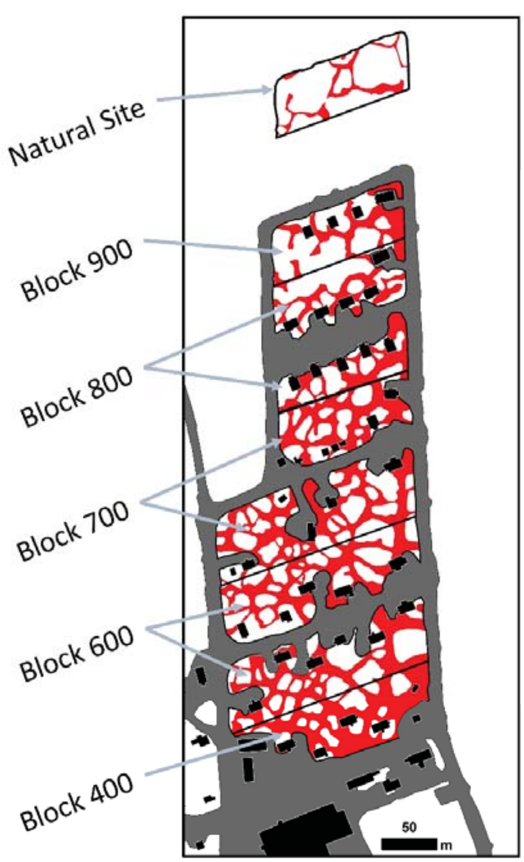
It is noteworthy that most of the public infrastructure in Point Lay, including the power plant, water and fuel tanks, water treatment plant and sewage treatment plant, are all founded on gravel pads placed in the drained lake basin. These structures are generally performing well. The school and the fire hall are constructed in the transition from the drained lake basin to the yedoma.

Thermokarst development accelerated by infrastructure

Looking at thermokarst features throughout the village, it appears that thermokarst develops following the construction of roadways and accelerates after homes are constructed. By comparing the 900 block to the older blocks to the south, a timeline of the formation of the thermokarst in the Point Lay townsite can be reconstructed as shown in Figure 3.

As infrastructure ages, the area affected by ice wedge thermokarst increases in a relatively linear fashion due to an increase in mean annual surface temperature (MAST) and active-layer thickness due to multiple processes related to the presence of infrastructure:

- While roads cleared of snow maintain similar temperatures to those before their construction, the accumulation of snow on the road's shoulder results in the development of thermokarst parallel to the roadway. This can be seen to the north of



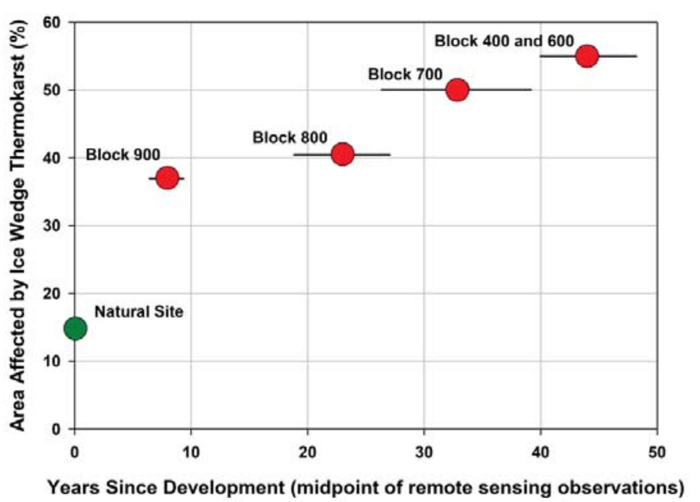


Figure 3. *Area of ice wedge thermokarst in relation to years since development using the drone data. (Credit: B.M. Jones)*

the road that runs along the 900 block. Since there is no other infrastructure here, it can be concluded that these thermokarst features are due to the roadway and the associated snow accumulation.

- Road embankments further promote the development of thermokarst by trapping surface water in the developing ice wedge troughs leading to a deepening of the troughs.
- Homes and other buildings also act as snow fences with snow drifts accumulating on their leeward side. This snow insulates the surface from cold winter air, again increasing the mean annual surface temperature. When the snow melts in the spring, additional heat is added to the ground.
- Homes and other buildings also reflect the sun onto the ground surface.

All these processes raise the mean annual surface temperature and accelerate the thaw of permafrost. They occur even when homes are built on piles to reduce heat transfer to the ground.

The role of infrastructure in accelerating subsidence and ponding must be taken into account when planning new construction. For example, residents have described the flatter area to the north of town (the Natural Site in Figure 3) as a possible location for future development. However, the area is on the same ice-rich yedoma terrain as the area highly affected by thermokarst within the townsite. The primary difference is the presence of infrastructure. If developed in a similar way, we must presume we would see similar degrees of thermal erosion and thermokarst formation over time as we see in the current townsite, unless better methods of construction and snow management are used to mitigate the impacts of roads and buildings on surface temperatures.

Implications for pile foundations

The location of ice wedges in ice-rich permafrost determines the pattern of thermokarst and thermal erosion, with thermokarst troughs forming over the ice wedges as they thaw. This has implications for the placement and stability of pile foundations as depicted in Figure 4. As shown on the left side of Figure 4, if the structure is founded on both ice wedges and

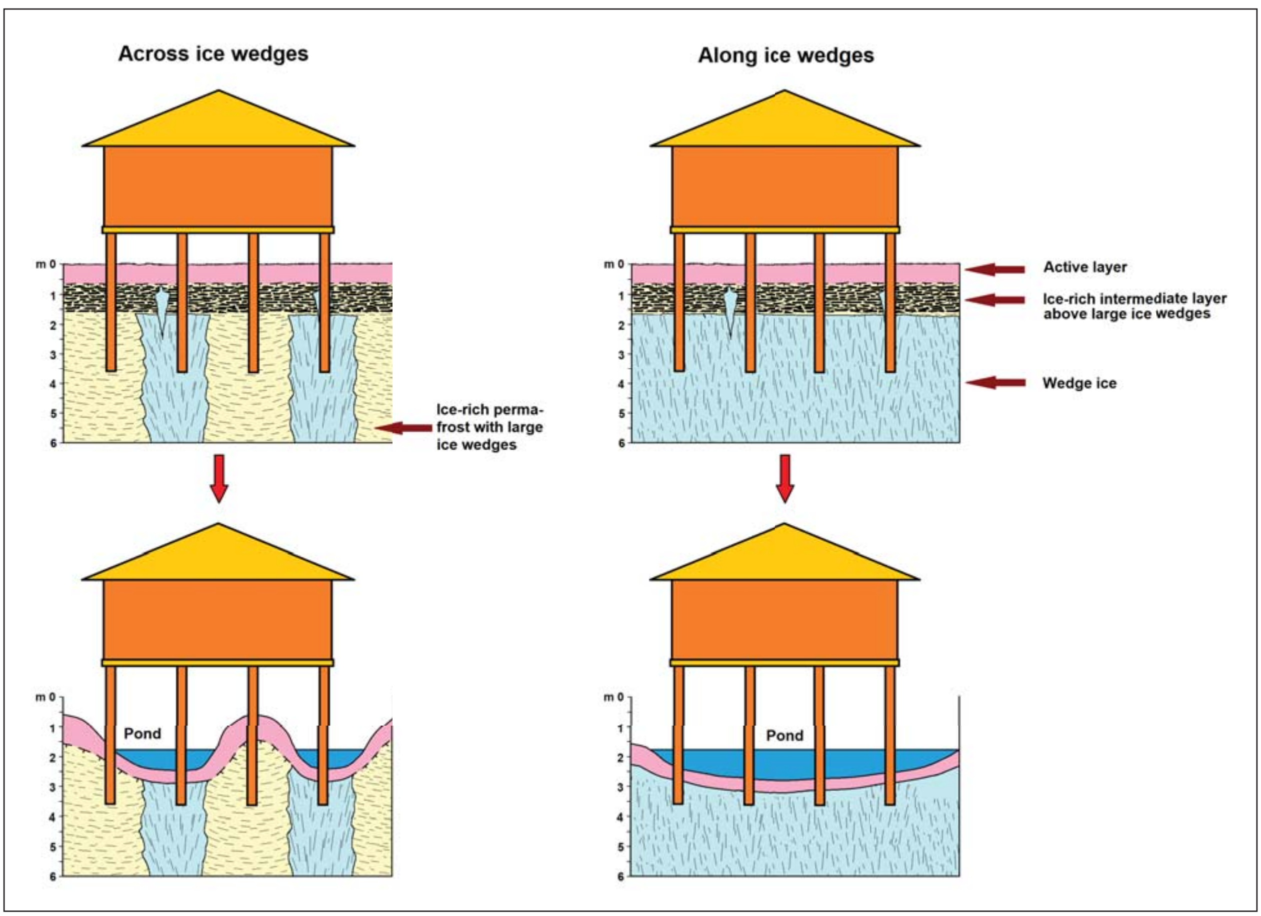


Figure 4. *The impact of ground subsidence on the embedment of pile foundations in ice-rich permafrost depends on the placement of piling relative to ice wedges. (Credit: Y. Shur and M. Kanevskiy)*

Figure 5. *Assessing subsidence below homes in Point Lay. Melting ice wedges below this home have resulted in nearly 2 m (6.5 ft) of subsidence leaving only about 1 m (3.2 ft) of pile embedment. (Credit: P. Bolz)*

ice-rich permafrost soils, troughs will form over the ice wedges, reducing the embedment of piles founded in ice wedges. Areas of ice-rich permafrost soils between ice wedges will also subside, but to a lesser extent, leaving thermokarst mounds between the ice wedge troughs. The right side of Figure 4 depicts the case where all piles are founded within ice wedges. In this case thermokarst ponding forms under the entire structure. In this case, the embedment of the piling is reduced more significantly, which may cause collapse of the entire structure.

Based on our investigation, most of the piling beneath village housing was originally embedded 3 m (10 ft). It appears that those piles embedded in ice wedges have as little as 1 m (3.2 ft) of embedment remaining (Figure 5). Those piling founded in the ice-rich permafrost soils are embedded between 1.2 and 1.8 m (4 to 6 ft). Based on the drone data and ground-survey photos taken of house foundations, we estimate about 30% of the residential piles in the village are founded in ice wedges.

The National Renewable Energy Labs' Cold Climate Housing Research Center (NREL/CCHRC) conducted a housing survey in Point Lay in April 2022. The study indicated that about two-thirds of homes manifest damage due to thaw settlement. Over half of respondents reported surface subsidence (56%) and ponding (70%) around or underneath their homes; many said their homes shake when walking across the floor (59%) or in the wind (79%).

Most of the piling in the community has been braced against lateral movement with wooden or cable bracing since the last study conducted by UAF in 2015. Long-time resident Bill Tracey indicated that some of the homes have been moved twice. Based on these observations, it is apparent that many of the homes remain unstable despite added bracing and require additional corrective measures.

Engineering solutions

While expensive, engineering solutions do exist. It is important that they be implemented soon and perhaps focused on sites showing the least advanced stages of ice wedge degradation first. Without action, the embedment of foundation piles of existing homes will continue to be eroded, especially in those founded in ice wedges. We recommend the following actions:

- Inspect each structure to determine the extent and severity of cosmetic and structural damage. These data should be used to determine the condition of the structure and the appropriate mitigation.
- Filling troughs and depressions with fine grained soil will help protect the underlying permafrost and establish drainage throughout the village.

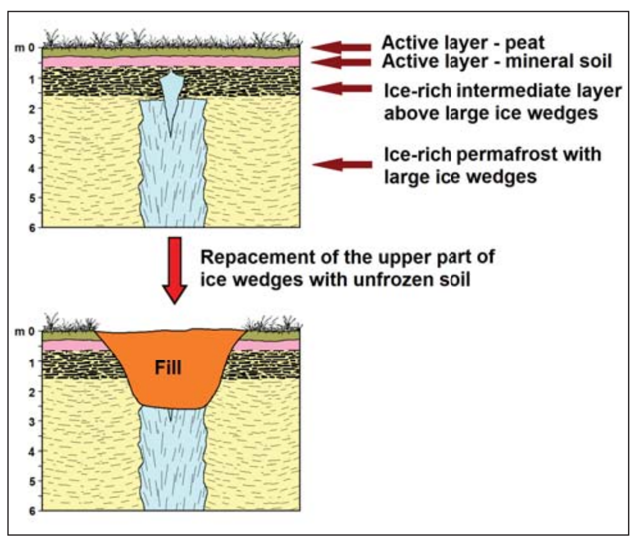


Figure 6. *For new construction, removing the upper portion of ice wedges and replacing the ice with fine-grained thaw stable soils will protect ice wedges from degradation and reduce thermal erosion and ponding beneath the buildings. (Credit: Y. Shur and M. Kanevskiy)*

- When constructing new structures, remove the upper portion of the ice wedges and replace the ice with fine grained thaw stable soils (Figure 6).
- Pile embedment should be at least 6 m (20 feet when placed in the thermokarst mounds and at least 9 m (30 ft) when placed in an ice wedge. If practical, avoid placing piles in wedge ice.
- Implement an active maintenance program including snow management, drainage, and annual thermokarst monitoring.
- If the new water/wastewater system is an above ground system supported on piling, place the piling in the thermokarst mounds and make the attachment fixtures adjustable. We also recommend the connections to the structures be made as flexible as practical.
- If post and pad foundations are used, place a 1-to-1.5 m (3-to-5-ft) gravel pad beneath the structure in addition to removal of the upper 1.5 m (5 ft) of the wedge ice. The post/pad connection should allow the pad to remain in full contact with the soil as the soil subsides.

Community interviews

We interviewed eight community members about their observations of landscape change and the impacts of permafrost thaw and erosion on local infrastructure. Members of the Tribal Council and project Steering Committee recommended several individuals to interview who were knowledgeable about the topics, and these individuals were asked to suggest additional community members to interview.

Interview questions and protocols were approved in advance by the Institutional Review Board at the University of Alaska Fairbanks (IRB 1909817-3). Interviewees were given an opportunity to opt out if they wished. If they consented to be interviewed, they were reimbursed for their time at the rate of $50 per hour to a maximum of $100 for two hours. (See appendix 2 for a list of interview questions and an anonymized summary of responses.)

Each of the community members interviewed said they had observed significant changes to the landscape and seascape around Kali in recent years, and they described how these changes are impacting life, health and safety in the community, describing risks to housing, roads and trails, food security, and the subsistence cycle. Among their observations:

- Large icebergs are no longer seen off the coast. Both snow and sea ice arrive one to two months later than in the past. Wind patterns have changed.
- With little sea ice, walrus (a traditional diet staple) haul out on the beach in the thousands where they cannot be hunted without risk of stampede.
- The coastal bluff has eroded so you can now see the lagoon from areas of town where you previously could not see water. There is more permafrost exposed along the bluff edge.
- The ground is commonly described as falling or sinking, where it used to be flat, destabilizing buildings, exposing buried waste, and opening up cracks in the tundra that have required new and longer routes to reach traditional hunting areas.
- Houses that were once close to the ground now

Figure 7. ***a.*** *Bill Tracey talks with Tracie Curry of Northern Social-Environmental Research who conducted joint interviews with us for a project with the Army Corps of Engineers Cold Regions Research and Engineering Laboratory.* ***b.*** *Fire chief Kuoiqsik Curtis points out areas of accelerated thaw as well as exposed military waste. Other community members interviewed were Jack Henry, Jr., Lupita Henry, Felicia Hawley, Gerilynn Stalker, Marie Tracey, and Sophie Tracey. (Credit: J.L. Peirce)*

appear to be on stilts and shake in the wind.

- Ponding around homes has become a major problem. A contributing factor is the failure of culverts due to subsidence.
- Thermokarst is worse in areas where snow is piled.
- Subsidence and ponding are more evident in areas with infrastructure compared with undisturbed areas outside of town.
- The use of gravel seems to accelerate thaw. Some are experimenting with using tundra that has fallen from the bluff as fill instead of gravel.

There was no consensus on when these changes first became apparent, but many observed that the speed of change has accelerated over the past few years. Frequent breaks in buried water and sewer lines resulting in underground leaks are thought to contribute to the more rapid thaw.

Community outreach and regional engagement

On our final day in Point Lay, we shared our observations and preliminary results with Point Lay residents, including several members of the Tribal Council and the project's local Steering Committee, during a community open house and barbecue.

Before and after the trip to Point Lay, we met with several North Slope Borough departments and other agencies involved in the design, construction, and maintenance of residential and public infrastructure in Point Lay, including representatives from:

- NSB Mayor's Office
- NSB Departments of Planning and Community Services, Public Works, and Capital Improvement Program Management
- UMIAQ Design
- Taġiuġmiullu Nunamiullu Housing Authority (TNHA)
- Iñupiat Community of the Arctic Slope (ICAS).

The goal of these meetings was to understand regional perspectives, plans and priorities for addressing permafrost-related issues in the community, to share our plans and observations, and to discuss data sharing. Based on these conversations, our team was invited to participate in a design charrette for the planned above-ground water and sewer system hosted by UMIAQ Design in mid-July where we shared the recommendations included in this report.

Permafrost temperature monitoring in collaboration with NNA PIPER project

Two permafrost scientists from the University of Alaska Geophysical Institute visited Point Lay from 7–10 August 2022 to conduct field work for our project and the *Resilience and Adaptation to the Effects of Permafrost Degradation and Coastal Erosion (PIPER)* project led by Ming Xiao of Pennsylvania State University. They installed long-term ground temperature

Figure 8. *On our last day in Point Lay we hosted a community open house and barbecue at the community center to share our field observations and preliminary results.* ***a.*** *Ben Jones shows drone-derived imagery and a digital terrain model to Tribal President James Henry.* ***b.*** *Yuri Shur talks with residents in front of a poster on permafrost properties in Point Lay.* ***c.*** *Community member Bill Tracey, Sr. volunteered his grill and services for the barbecue, which was well-attended by community members.* ***d.*** *Following lunch, we provided an informal presentation and question and answer session to a small group of community leaders. Credits: J.L. Peirce, (a, d) and B.M. Jones (b, c).*

Figure 9. *Map showing locations of permafrost temperature sensors installed in natural (green dots) and infrastructure sites (red dots). Water depth sensors were also installed in several locations (blue dots).*

monitoring stations in 14 natural sites and 13 infrastructure sites in Point Lay (Figure 9).

We worked with Bill Tracey, Cully Corporation, and other members of the Point Lay Steering Committee to select locations for the sensors. Sensors in natural sites were installed across a range of vegetation, topography, and hydrology, including in polygon troughs and sensors. For infrastructure sites, locations with and without foundation skirting, ponding, and other variables were chosen to explore the impact of infrastructure on ground temperature regimes (Figure 10). A map of ground temperature sensor locations is available on the project website (www.geobotany.uaf.edu/nna/point-lay). A small number of water depth sensors were also installed in small thermokarst ponds.

Ground temperatures and water depth data are logged six times per day. The first data from these stations will be available in August 2023. The PIPER team has also installed temperature monitoring networks in Wainwright and Utqiaġvik and is collecting of temperature data from existing boreholes logs in publicly available reports for inclusion in a geospatial database.

The goal of their research is to: 1) Model and predict the rate, magnitude, and mechanisms of permafrost

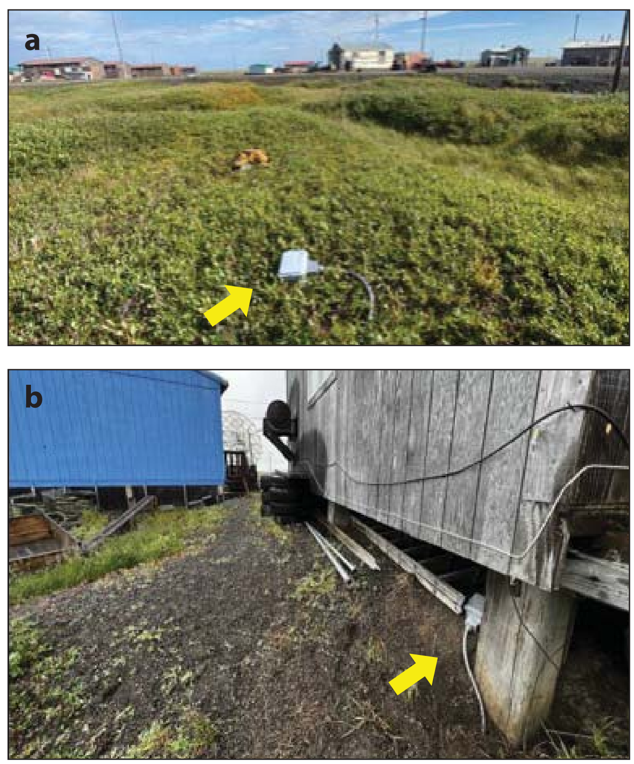
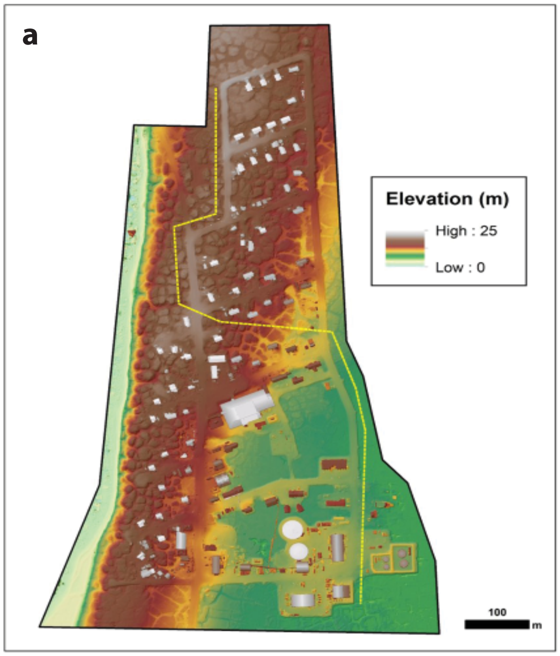


Figure 10. ***a.*** *A ground temperature station installed on dry tundra in a natural site.* ***b.*** *A ground temperature station located on a foundation pile on a house without skirting. (Credits: D. Nicolsky)*



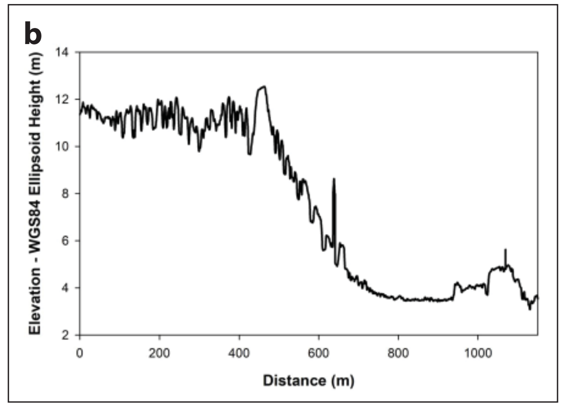


Figure 11. ***a.*** *Using drone-derived elevation maps, elevation profiles can be produced for any transect desired.* ***b.*** *Fill quantities can also be calculated for any transect.*

degradation and associated land loss within Point Lay; and 2) Develop an infrastructure hazards map of the northern Alaskan coastal region under the effects of permafrost degradation and coastal erosion.

Data sharing and discovery

Data in this report will be archived at the Arctic Data Center (ADC), a publicly accessible, long-lived repository for NSF-funded Arctic research. For easy discovery, data will be available from the Ice-rich Permafrost Systems project portal at ADC (arcticdata.io/catalog/portals/nna-irps) and may be shared with the community in other formats on request. We may also be able to produce custom products, such as elevation profiles and fill quantities for different transects (Figure 11).

The community can use and share Point Lay data collected by our team without restrictions. Use by researchers will be guided by the CARE Principles for Indigenous Data Governance (datascience.codata.org/articles/10.5334/dsj-2020-043).

LIST OF APPENDICES

APPENDIX 1 Permafrost Borehole Data

Table A1.1. *Permafrost borehole summary, Point Lay, Alaska, 26-29 June 2022.*

Borehole ID	Date (dd/mm/yyyy)	Depth (cm)	Latitude (DD WGS84)	Longitude (DD WGS84)	Elevation (m a.s.l.)	Drill	Terrain or location
PLAY-1	6/26/2022	115	69.74522	-163.01349	3.07	SIPRE	Base of the yedoma slope, trough
PLAY-2	6/26/2022	34	69.74515	-163.01335	5.73	SIPRE	Yedoma slope, baydzherakhs, refusal (gravel)
PLAY-3	6/26/2022	161	69.74515	-163.01296	9.16	SIPRE	Yedoma slope, baydzherakh
PLAY-4	6/26/2022	48	69.7450981	-163.0133152	5.43	Kovacs	Yedoma slope, trough, refusal
PLAY-5	6/26/2022	449	69.7451296	-163.0129095	8.55	Kovacs	Yedoma slope, trough
PLAY-6	6/26/2022	65	69.7451581	-163.0123743	9.43	Kovacs	Yedoma slope, trough
PLAY-7	6/26/2022	97	69.7451476	-163.0121097	9.73	Kovacs	Yedoma slope, trough
PLAY-8	6/26/2022	87	69.7450807	-163.0118585	9.72	Kovacs	Yedoma slope, trough
PLAY-9	6/27/2022	169	69.73806	-162.99138	2.68	SIPRE	Thaw lake basin, polygon center
PLAY-10	6/27/2022	140	69.73748	-162.99109	2.31	SIPRE	Thaw lake basin, polygon center
PLAY-11	6/27/2022	82	69.737477	-162.990889	2.28	SIPRE	Thaw lake basin, trough
PLAY-12	6/27/2022	298	69.74911	-163.00887	11.79	SIPRE	Yedoma, polygon center
PLAY-13	6/27/2022	550	69.74905	-163.00855	11.29	Kovacs	Yedoma, trough
PLAY-14	6/27/2022	60	69.74905	-163.00905	11.53	Kovacs	Yedoma, trough
PLAY-15	6/27/2022	60	69.74933	-163.00914	11.8	Kovacs	Yedoma, trough
PLAY-16	6/27/2022	54	69.74938	-163.00934	11.71	Kovacs	Yedoma, trough
PLAY-17	6/27/2022	41	69.74941	-163.00895	11.44	Kovacs	Yedoma, trough
PLAY-18	6/27/2022	62	69.74949	-163.00851	11.29	Kovacs	Yedoma, trough
PLAY-19	6/27/2022	51	69.74963	-163.00855	11.49	Kovacs	Yedoma, trough
PLAY-20	6/27/2022	48	69.74973	-163.00885	11.12	Kovacs	Yedoma, trough
PLAY-21	6/27/2022	54	69.75002	-163.00865	11.43	Kovacs	Yedoma, trough
PLAY-22	6/27/2022	41	69.75011	-163.00859	11.4	Kovacs	Yedoma, trough
PLAY-23	6/28/2022	203	69.73904	-163.01073	3.23	Kovacs	Thaw lake basin, trough
PLAY-24	6/28/2022	273	69.73874	-163.01038	3.17	Kovacs	Thaw lake basin, trough
PLAY-25	6/28/2022	76	69.73899	-163.01081	3.26	SIPRE	Thaw lake basin, polygon center, refusal
PLAY-26	6/28/2022	273	69.73874	-163.01053	3.41	SIPRE, Kovacs from 182 cm	Thaw lake basin, polygon center
PLAY-27	6/28/2022	104	69.73873	-163.0104	3.16	SIPRE	Thaw lake basin, trough
PLAY-28	6/28/2022	86	69.7470387	-163.0073798	8.5	Kovacs	House 810, southeast pile
PLAY-29	6/28/2022	66	69.7470611	-163.0076818	8.65	Kovacs	House 810, midwest pile
PLAY-EXP	6/29/2022		69.72816	-163.02304			4.8-m-high coastal exposure
N=10		**13.6 m**				**SIPRE**	**Total depth**
N=19		**24.9 m**				**Kovacs**	**Total depth**

Figure A1.1. *Map of permafrost borehole locations. (See online map at www.geobotany.uaf.edu/nna/point-lay)*

Table A1.2. *Cryostratigraphy, moisture and ground-ice content of soil sampled from permafrost boreholes, Point Lay, Alaska, 26-29 June 2022.* ***Cryostratigraphic units:*** *Code descriptions are listed below the table.* ***Ground ice contents: GMC****: gravimetric moisture content (% weight).* ***VMC****: volumetric moisture content (% volume).* ***EIC:*** *excess ice content (% volume).* ***EC:*** *electrical conductivity.*

Borehole ID	Type of drilling	Depth (cm)	Cryostratigraphic units	Sample depth (cm)	Ground ice contents				Notes
					GMC (% wt)	VMC (% vol)	EIC (% vol)	EC (µS/cm)	
PLAY-1	SIPRE	0-23	ALU, peat, org-rich vf silty sand						In the lower part of the yedoma slope, in the trough (See Figure A1.2 for location)
		23-76	ALF+TL, vf silty sand, peat, with some gravel	30-37	66.88	63.09	0	-	
				56-60	29.64	45.64	0	-	Ice samples (stable water isotopes): 94-105; 105-115
		76-86	IL-PD, peat, vf silty sand	77-84	74.12	65.45	9.74	311	
		86-93	IL-WD, vf silty sand	85-91	86.52	71.02	42.44	461	
		93-115	IW, with gravel from ~105						
		115	Refusal (gravel)						
PLAY-2	SIPRE	0-15	ALU, moss, peat, vf silty sand with some gravel						Yedoma slope, top of the baydzherakh (thermokarst mound) (See Figure A1.2 for location).
		15-34	ALF, vf silty sand, peat, with gravel (up to 15-20%)	25-34	31.6	47.24	1.44	263	
		34	Refusal (gravel)						
PLAY-3	SIPRE	0-8	ALU, moss						Yedoma slope, top of the baydzherakhs (See Figure A1.2 for location)
		8-18	ALU, silty peat						
		18-40	ALF, silty peat, cavities at 20-30 cm						Peat (C14): 148-152 cm
		40-61	ALF+TL, sandy silt with clay, with peat inclusions	44-52	99.77	71.83	0	-	
		61-161	QSP, sandy silt/peat vertical structure; less peat from ~100	86-97	159	77.94	16.23	736	
				105-115	143.84	78.61	52.32	638	
				122-134	253.74	87.79	75.15	484	
				152-161	172.96	81.55	59.66	568	
PLAY-4	Kovacs	0-48	ALU+ALF						Yedoma slope, trough (See Figure A1.2 for location)
		48	Refusal (gravel)						
PLAY-5	Kovacs	0-55	ALU+ALF+TL						
		55-449	IW						
		449	Refusal (gravel)						
PLAY-6	Kovacs	0-60	ALU+ALF+TL						
		60-65	IW						
PLAY-7	Kovacs	0-92	ALU+ALF+TL+IL						
		92-97	IW						
PLAY-8	Kovacs	0-82	ALU+ALF+TL+IL						
		82-87	IW						
PLAY-9	SIPRE	0-15	ALU, peat						Wet thaw lake basin (TLB), polygon center (See Figure A1.5 for location)
		15-45	ALF, young sedge peat						Water 10 cm
		45-57	ALF, peat						
		57-63	TL, peat						Peat (C14): 70-73, 81-84
		63-81	IL-WD, peat, ice belts						
		81-120	IL, peat/silt vertical structure, ice rich	90-100	249.6	84.72	40.67	257	
		120-150	IL, vf sandy silt with peat, ice rich	121-132	169.45	82.76	66.24	421	
				141-150	244.4	84.45	39.98	432	
		150-169	SP, vf sandy silt with peat	159-169	264.63	81.52	13.94	592	

Table A1.2 *(continued)*

Borehole ID	Type of drilling	Depth (cm)	Cryostratigraphic units	Sample depth (cm)	Ground ice contents				Notes
					GMC (% wt)	VMC (% vol)	EIC (% vol)	EC (µS/cm)	
PLAY-10	SIPRE	0-21	ALU, young sedge peat						Thaw lake basin (TLB) with wet low-centered polygons (LCP), polygon center (See Figure A1.5 for location)
		21-32	ALF, peat						
		32-50	ALF, limnic vf sandy silt	32-42	43.52	52.66	4.22	249	Peat (C14): 29-32
		50-55	TL, limnic vf sandy silt	46-55	86.2	68.78	4.36	231	
		55-76	IL-PD, peat, some silt						
		76-140	IL-WD, peat/silt vertical structure	78-88	264.64	85.47	33.4	421	
				104-114	287.62	88.02	63.94	372	
				130-140	270.24	85.72	29.85	568	
PLAY-11	SIPRE	0-21	ALU, sedge peat						Ice-wedge trough near PLAY-10 (See Figure A1.5 for location)
		21-38	ALF, sedge peat						
		38-51	ALF, limnic silt						Ice sample (O18): 72-82
		51-57	TL, limnic silt						
		57-72	IL, limnic silt, peat						
		72-82	IW clean						
PLAY-12	SIPRE	0-14	ALU, moss, peat						Yedoma, north of the village, HCP, polygon center (See Figures A1.1 and A1.8 for location)
		14-22	ALF, peat						
		22-33	ALF, silt	24-32	27.79	44.05	0	-	Peat (C14): 255, 290 (from inclusions)
		33-40	IL, silt	32-40	78.87	66.84	18.7	189	
		40-87	IL, peat with silt	60-68	191.89	81	31.65	251	
		87-102	IL, sandy silt	92-102	140.28	78.19	43.26	338	
		102-298	IL-SP, Peat/sandy silt	132-142	161.68	80.51	34.99	360	
				150-160	122.62	75.81	31.28	410	
				180-190	213.24	84.5	61.54	329	
				220-230	167.16	81.03	32.62	494	
				270-280	188.08	82.78	46.17	505	
PLAY-13	Kovacs	0-67	ALU+ALF+TL+IL						Yedoma, north of the village, ice-wedge trough (See Figures A1.1 and A1.8 for location)
		67-550	IW						
PLAY-14	Kovacs	0-55	ALU+ALF+TL+IL						
		55-60	IW						
PLAY-15	Kovacs	0-55	ALU+ALF+TL+IL						
		55-60	IW						
PLAY-16	Kovacs	0-49	ALU+ALF+TL+IL						
		49-54	IW						
PLAY-17	Kovacs	0-36	ALU+ALF+TL						
		36-41	IW						
PLAY-18	Kovacs	0-57	ALU+ALF+TL+IL						
		55-62	IW						
PLAY-19	Kovacs	0-46	ALU+ALF+TL						
		46-51	IW						
PLAY-20	Kovacs	0-43	ALU+ALF+TL						
		43-48	IW						
PLAY-21	Kovacs	0-49	ALU+ALF+TL+IL						
		49-54	IW						
PLAY-22	Kovacs	0-36	ALU+ALF+TL						
		36-41	IW						
PLAY-23	Kovacs	0-51	ALU+ALF+TL+IL						TLB south of the village, trough (see Figure A1.10 for location)
		51-203	IW						
		203	gravel						
PLAY-24	Kovacs	0-80	ALU+ALF+TL+IL						
		80-270	IW						
		270-273	sand						

Table A1.2 *(continued)*

Borehole ID	Type of drill-ing	Depth (cm)	Cryostrati-graphic units	Sample depth (cm)	GMC (%)	VMC (%)	EIC (%)	EC (µS)	Notes
PLAY-25	SIPRE	0-19	ALU, moss, sedge peat						TLB, south of the village, wet LCP/HCP, polygon center
		19-25	ALF, peat						(See Figure A1.10 for location)
		25-45	ALF, silty sand, peat						
		45-51	TL, silty sand						Peat (C14): 24-25
		51-76	IL-PD, vf-f silty sand, peat	65-76	199.79	81.62	36.73	201	
		76	Refusal (gravel)						
PLAY-26	SIPRE, Kovacs	0-14	ALU, moss, peat						TLB, south of the village, small dry LCP/HCP, polygon center, near PLAY-24; Kovacs from 182 cm (See Figure A1.10 for location)
		14-23	ALF, peat, silty sandy						
		23-46	ALF+TL, silty sand, peat						Ice samples (O18): 110-120, 132-140, 172-182
		46-96	IL, silty sand, peat	50-60	178.49	79.86	28.18	431	
				67-78	220.33	84.92	49.07	275	
				78-88	119.31	75.3	44.2	360	
		96-108	Silty sand/IW boundary						
		108-268	IW						
		268-273	Saline silty vf-f sand						
PLAY-27	SIPRE	0-20	ALU, sedge, peat						TLB, south of the village, trough, 3 m from PLAY-24
		20-29	ALF, peat						(See Figure A1.10 for location)
		29-40	ALF, silty vf sand	30-38	82.39	67.8	0	-	
		40-50	TL, Peat, silty sand						Ice sample (O18): 96-104
		50-90	IL-PD, silty sand	50-60	90.02	69.7	12.47	156	
				79-89	100.61	72	32.06	453	
		90-104	IW						
PLAY-28 Kovacs	Kovacs	0-76	ALU+ALF+TL+IL						House 810, Southeast pile (see Figure A1.12 for location)
		76-81	IW						
PLAY-29	Kovacs	0-56	ALU+ALF+TL+IL?						
		56-61	IW						
PLAY-EXP			Large ice wedge (~2 m wide) was observed at 0.6 to 2.8 m a.s.l. The wedge was enclosed in ice-rich saline deposits – silty vf-f sand with vertical peat inclusions	11-1.5 m	75.58	68.17	45.37	5650	4.8-m-high coastal exposure
				12-1.3 m	69.82	66.42	37.76	10,900	(See Figure A1.13 for location)
				13-1.3 m	81.91	69.88	45.92	6060	
				14-0.6 m	112.34	76.09	55.55	6820	Ice samples (O18): #1 to #6, #10; Peat samples (C14): #7 to #9; Soil samples: #11 to #14 (0.6 to 1.5 m a.s.l.)

Cryostratigraphic unit codes

AL	active layer
ALU	unfrozen active layer
ALF	frozen AL (ice-poor; often with dry friable soil horizons closer to the base of the AL)
TL	transient layer (relatively ice-poor, mainly with reticulate and/or braided cryostructures)
ALF-TL	undifferentiated AL/TL (no distinctive boundary between AL and TL)
IL-WD	intermediate layer, well developed (thick belts, mainly ataxitic cryostructure, EIC >30-40%)
IL-PD	intermediate layer, poorly developed (relatively ice-poor, no well-developed belts)
SP	syngenetic permafrost (thin belts, micro-cryostructures)
QSP	quasi-syngenetic permafrost (buried intermediate layer)
IW	ice wedge
vf	very fine (sand)
f	fine (sand)

Figure A1.2. *Boreholes PLAY-1 to 8 were drilled to the west of the townsite (near the 600 block) on the yedoma slope terrain along the coast on 26 June 2022. (See Figure A1.1 for general location map.)*

Figure A1.3 ***a.*** *Borehole PLAY-1, elevation 3.1 m above sea level (a.s.l)., was drilled with the 3-inch diameter SIPRE corer in an ice-wedge trough.* ***b-c.*** *Photographs of the frozen core. At left (**b**), the protective intermediate layer of the upper permafrost (depth 76-93 cm) above the ice wedge is shown. Note inclined soil layers and ice lenses above the ice wedge (**b**) and gravel inclusions in wedge ice from ~105 cm (**c**). (Credit: M. Kanevskiy)*

Figure A1.4 ***a.*** *Borehole PLAY-3, elevation 9.2 m a.s.l., was drilled at the top of the baydzherakh (thermokarst mound).* ***b.*** *Analysis of the core at a depth of 147-161 cm shows an ice-rich sandy silt with vertically oriented peat inclusions and ataxitic cryostructure in silt. (Credit: M. Kanevskiy)*

Figure A1.5. *Boreholes PLAY-9 to 11 are in a large thaw lake basin along the Airport Road between the Airport Access Road and the Landfill Access Road. Borehole PLAY-9 and 10 were drilled from polygon centers. Borehole PLAY-11 was drilled from a thermokarst trough. All boreholes were drilled on 27 June 2022. (See Figure A1.1 for general location map.)*

Figure A1.6. ***a.*** *Borehole PLAY-9 was drilled with a SIPRE corer in a wet thaw lake basin, at 2.7 m a.s.l..* ***b.*** *The permafrost core shows ice-rich sandy silt with ataxitic cryostructure from 122 to 141 cm beneath the surface. (Credit: M. Kanevskiy)*

Figure A1.7. ***a.*** *Borehole PLAY-10 was drilled with a SIPRE corer in a wet thaw lake basin with low-centered polygons, elevation 2.3 m a.s.l.* ***b.*** *Core shows ice-rich sandy silt with ataxitic cryostructure at depth of 104 to 117 cm. (Credit: M. Kanevskiy)*

Figure A1.8. *Boreholes PLAY-12 to 22 are located on yedoma terrain in the undeveloped area just north of the townsite townsite (boreholes PLAY-12 to PLAY-14 are not shown; they are located south of PLAY-15, see Figure A1.1 for general location map). Borehole PLAY-12 was drilled in a polygon center with a SIPRE corer to describe and sample frozen soils and ground ice. All other boreholes in this area were drilled in polygon troughs with a Kovacs auger to estimate the depth to wedge ice and vertical extent of ice wedges. All boreholes were drilled on 27 June 2022.*

Figure A1.9. ***a.*** *Borehole PLAY-12 at elevation 11.8 m a.s.l. was drilled with a SIPRE corer on a high surface north of the village.* ***b.*** *The core sample shows an ice-rich sandy silt with mainly ataxitic cryostructure at a depth of 230-255 cm. (Credit: M. Kanevskiy)*

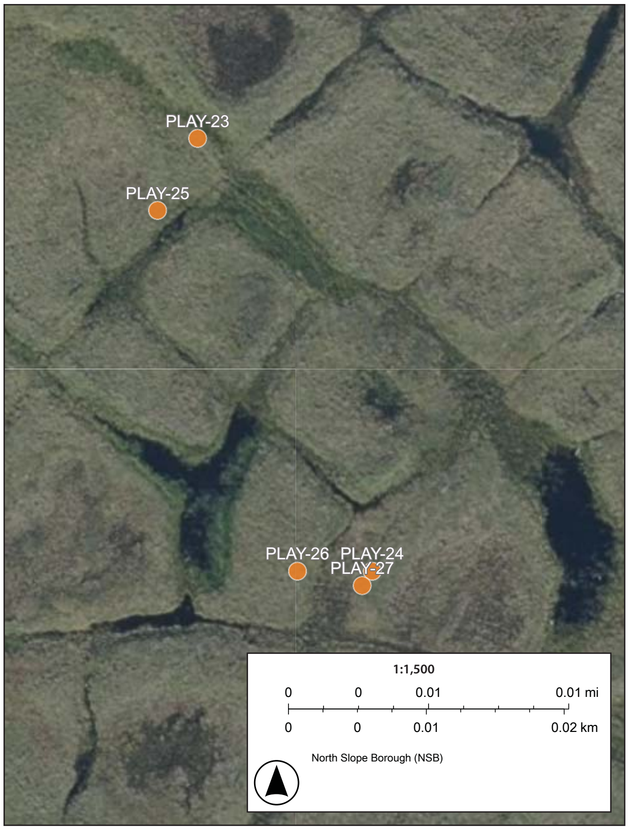


Figure A1.10. *Boreholes PLAY-23 to 26 were drilled in the thaw lake basin to the south of the townsite on 28 June 2022. PLAY-23, 24 and 27 were drilled in polygon troughs. PLAY-25 and 26 were drilled in polygon centers. (See Figure A1.1 for general location map.)*

Figure A1.11. ***a.*** *Borehole PLAY-26 at the center of a dry ice-wedge polygon, elevation 3.4 m a.s.l., was drilled with a SIPRE corer to 182 cm and with the Kovacs auger from182 to 273 cm.* ***b.*** *The drilling analysis shows ice-rich silty sand from a depth of 68 cm and a buried ice wedge from 108 cm to 268 cm. (Credit: M. Kanevskiy)*

Figure A1.12. *Two boreholes PLAY-28 and 29 were drilled with the Kovacs auger near the foundation of the TNHA house No. 810 on 28 June 2022, near the southeast and midwest piles respectively. (See Figure A1.1 for general location map.)*

Figure A1.13. *Permafrost exposure PLAY-EXP with the exposed ice wedge was examined on the bluff south of the airport on 29 June 2022. (See Figure A1.1 for general location map.)*

Figure A1.14. *Sampling locations in the face of the coastal exposure PLAY-EXP to examine exposed wedge ice and adjacent frozen soils in the bluff behind the airport. The height of the bluff was measured at 4.8 m a.s.l. (which corresponds to the lower parts of yedoma slope), exposed part was ~0.6 to 2.8 m a.s.l. Exposed ice wedge ~2 m wide was enclosed in saline ice-rich very fine to fine silty sand with vertical peat inclusions. More likely, this ice wedge extends below sea level. (Credit: Mikhail Kanevskiy)*

APPENDIX 2 Ground Temperature Sensors

Table A2.1. *Locations of long-term ground temperature monitoring stations installed in Point Lay from 7-10 August 2022 in collaboration with the NSF-funded Navigation the New Arctic collaborative research project,* Resilience and adaptation to the effects of permafrost degradation induced coastal erosion (PIPER).

ID	Location type	Location notes	Longitude	Latitude
PL-24N	Natural	North of town in area of proposed development	-163.0071125	69.74938097
PL-25N	Natural	Private property, coast	-163.0149513	69.74088966
PL-26N	Natural	Private property, coast	-163.0153316	69.74117595
PL-27N	Natural	Coast, north of town	-163.0109830	69.74930000
PL-28N	Natural	Proposed Location	-162.9701590	69.73376100
PL-U1N	Natural	Area of potential new development	-162.9675607	69.74574014
PL-U2N	Natural	South of village	-163.0148614	69.73908046
PL-U4N	Natural	East of village, near road	-163.0047487	69.74254889
PL-U5N	Natural	West of northern end of village	-163.0110514	69.74689666
PL-U6N	Natural	North of airport road	-162.9914862	69.73845025
PL-U7N	Natural	North of airport road	-163.0078148	69.73672168
PL-U8N	Natural	East of northern part of village	-163.0049905	69.74689666
PL-U9N	Natural	South of airport road	-162.9931618	69.73690689
PL-U11N	Natural	Suggested at the community meeting	-163.0276008	69.73149519
PL-AF1N	Infrastructure	Non-residential building	-163.0181610	69.73567200
PL-01a	Infrastructure	House, non-skirted	-163.0137421	69.74074205
PL-04	Infrastructure	Gravel pad	-163.0035430	69.74155392
PL-09	Infrastructure	Fire station, ponded water, settlement	-163.0105035	69.74206281
PL-14	Infrastructure	TNHA, water ponding pile	-163.0074173	69.74719263
PL-10	Infrastructure	TNHA, adjustable foam pad, 2-channel	-163.0074680	69.74819533
PL-606	Infrastructure	House, edge of the water pond/ice wedge	-163.0096164	69.74460103
PL-606 Trough	Infrastructure	Residential property, trough	-163.0096961	69.74449421
PL-606 Center	Infrastructure	Residential property, polygon center	-163.0095526	69.74445918
PL-01b	Infrastructure	House, skirted	-163.0136336	69.74092137
PL-14 Dry	Infrastructure	TNHA housing, dry pile	-163.0074331	69.74713351
PL-14 Center	Infrastructure	TNHA housing, polygon center	-163.0074177	69.74709308
PL-605	Infrastructure	Residential property, 2-channel logger	-163.0096484	69.74505880

APPENDIX 3 Community Interviews

Interview Questions

IRB No. 1909817-3

Permafrost thaw and erosion

Changes observed in the landscape and seascape

- What changes have you personally observed in the landscape and seascape around Kali and areas of traditional use? Discuss with aid of maps.
- When did you start noticing these changes? In which locations, do they seem to be happening more quickly or slowly?

Issues and concerns related to infrastructure

- Here are the permafrost thaw and erosion issues we know about based on available information. Present list of known erosion and thaw issues/concerns related to:
    - Housing foundations
    - Roads, runway
    - Water/Wastewater system
    - Other utilities (electricity, fire hydrants, communication, etc.)
    - Wildlife and fish?
    - Is there anything missing?
- What other concerns do you have about the impacts of permafrost thaw and erosion on local infrastructure?

Telling your story

- What message about living with and adapting to climate change would you like to tell the outside world?
- What do you want your children and grandchildren to know about Kali?

Closing

- Is there anything we haven't covered that you would like to discuss?
- May we contact you if we have follow-up questions?

Additional questions were asked by Tracie Curry of Northern Social-Environmental Research (NSER) for the Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL) project, Engaging local knowledge to inform measures protecting Alaskan coastal communities from erosion and permafrost thaw. *These included questions about knowledge of Department of Defense (DoD) infrastructure sites, landscape conditions near DoD sites, Point Lay priorities and information needs, best practices for engagement, guidelines for sharing information and traditional knowledge, and project planning. When completed, results from the CRREL project will be shared with the community.*

Summary of Interview Responses

Changes observed in landscape and seascape

- **Loss of sea ice**
  - Historically, sea ice would be present into May. Now the ice is melting earlier, and there are no longer big icebergs. [3,8]
- **Changes in weather**
  What we used to do in September, now we're doing in late November—two months ahead. Ten years ago we had full snow the first week of September and were already driving on the lagoon and rivers. Now about the first or second week of November. [6]
  - Freeze up is later. Ice fishing used to start in September. There would be 7-8 inches of snow, people would be driving snow machines out. Now people are boating into October. [3,4]
  - It's wetter than it's ever been. [4]
  - There is less wind from the northeast; more is coming from the south (and north?). There are fewer blizzards. [3]
  - People used to be able to tell the weather. Now it is unpredictable, which is scary. [8]
- **Changes in wildlife abundance**
  - Thousands of walruses haul out on the beach due to the lack of sea ice. The community no longer hunts them due to the danger of stampede and keeps planes and boats away. [3]
  - More predators are being caught. [1]
  - More brown bears make their way across the lagoon and harass the walrus. [4]
  - They are seeing a lot more ground squirrels. [3]
  - There are more caribou than when the coal mine was active and there was more helicopter traffic. As long as young hunters allow the first caribou to go through, the rest will follow. [1,7]
- **Changes in the landscape**
  The ground falls off now. We're sinking and there's no way to stop it. [3]
  By living here, we've instigated more change than what would have naturally occurred. [4]
  - The village used to have flat ground. Now the terrain is rougher, and there are deep gullies. It's a dramatic change. [3,4,8]
  - Big crevices have developed in the tundra. Cracks are worse after driving vehicles on it, so people now avoid driving on the tundra. [1]
  - The bluff along the beach used to be much higher, and you could not see the lagoon from town. Now it's much more visible. [1,3]
  - There is much more permafrost exposed along the bluff edge. [1,8]
  - There are many more new small ponds or little lakes showing up all over the place. [3,5]
  - The rivers are getting wider and deeper. [5]
  - The barrier island protects the village from winter storms, and residents depend on the lagoon for food. If the island disappears due to climate change, the community will be forced to relocate. [3,7]
- **Rate of landscape change**
  In late 2019, when I'm outside on my porch, I couldn't see the lagoon. I would stand up literally on top of my [porch railing]..., just to see what the tide is like, or if it's blowing or if it's rough.... Nowadays, I could just go step outside and look, and there's the water right there [due to erosion of the bluff]. [6]
  - One person reported seeing changes start as far back as the mid-'80s to '90s. Others started noticing in the mid- to late 2000s. [2,3,7]
  - It's still changing for the worse. The last three years has had the fastest thaw. Subsidence is happening much faster because of the warming temperatures [2,4,8].
  - The village had a good base of very good gravel and good roads, but things have not been the same since the buried water and sewer lines were installed. [4]
- **Location of greatest changes**
  Honestly, I haven't noticed anything that's not changing. Everything changes daily, weekly, yearly, whether it's permafrost, tundra or structures. [2]
  - Thaw subsidence is happening faster where there are snow drifts; it's especially bad at the ends of the streets where snow is piled. [3,4]
  - Thermokarst is worst on the west side of town, by St. Albans church, where most of the houses are, and all the way to the dump. [6,7,8]
  - There is a lot of erosion by the old freshwater lake. The crevices are as tall as a person. [8]
  - Thermokarst is bad where there are ponds. [7]
  - The fastest changes are observed where there is gravel. The tundra is not as bad where it's untouched. [1]
  - Subsidence is being observed everywhere. The only place where the ground does not seem to be falling is at the dock. [2,8]
- **Community life**
  - In the past, everything was very well coordinated. People did things not just for themselves

but for the whole community. Everyone went to church on Wednesday night and Sunday morning—the whole village. [3]

Issues and concerns related to infrastructure

- **Housing issues**
  You [used to have] to duck to get underneath the house, but today... when you go under, you have to jump to touch the bottom. [1]
  - Houses appear to be on stilts that used to be level with the ground. A two-story house now appears to be three stories [1,3,6,7,8].
  - Houses shake in the wind or even when children run indoors. During blizzards, some families go to the school to feel safer and sleep better, because houses are so high off the ground and shake so badly [1,4,8].
  - House pilings were hand dug, so the foundations are not the best. In the mid-70s, when they were dug, there was 8–12" of summer thaw. Now there is ~3–4 ft of thaw in August/September. [4]
  - On the 800 block the pilings are exposed down to the plastic at the bottom. [1]
  - Stairs, porches and kunechuks [Arctic entryways] are separating from houses. [6]
- **Water and sewer / road issues**
  Every time they dig up the road to do repairs, it immediately caves in. [2]
  - The biggest change is the water and sewer lines. Leaks in the lines undermine the buried pipe and cause sink holes. [2,3,4]
  - Roads are constantly changing. Caverns have formed under roads that could swallow a dump truck or school bus if a heavy vehicle drives over. [4]
  - There are more potholes in the roads. Some have opened up just from someone walking over the road. An adult can sink in knee deep. [7]
- **Ponding and drainage issues**
  All I had was a small pond right in the front of my house... maybe [7x11 feet].... And now this pond… goes all the way in back of my neighbor's house, [and] almost clearly around her [house]. [6]
  - Houses and other buildings create snow drifts, which melt in spring. Roads block the water flow, and the drainage isn't adequate. Because of subsidence, the culverts are too high. So the pooling along the road backs up and causes pooling under houses. That water makes it down to the pilings and causes more thaw and the houses start shaking. [4]
  - Each time a pond is drained it's a little deeper. [7]
- **Gravel and fill resources**
  We would like to get a dredge and share it with other villages. We have really good gravel. [3]
  - More gravel is needed to fill in holes. Gravel resources are low, and the North Slope doesn't have a dredge. [3,8]
  - Using tundra that has fallen off the bluffs to fill in under homes, instead of gravel, is being tried, since gravel seems to speed up thaw. [1]

Life, health and safety risks

- **Fire safety**
  It is starting to become hazardous to store fire trucks in the fire station [due to subsidence]. It's crucial to store the equipment in a warm secured place, where we can keep an eye on it. [2]
  - There has been a foot and a half of subsidence beneath the fire station since 2008. A lot of water has also collected there, which is accelerating thaw. [2]
  - The fires station is critical for the life, health and safety of the whole community, as well as the increasing numbers of boaters who float down the river and whom the community also provide emergency services and medical care. [2]
  - The fire hydrant on the 700 block is no longer operable due to thaw subsidence. It poses a big risk if there were a fire on the 700 or 800 blocks. The ground around other hydrants is also sinking. [2,7]
  - Power poles lean due to subsidence and have to be addressed every few years. [4]
- **Food security**
  Due to [the water lake trail] being eroded, we now have to travel a lot longer and farther to get caribou and berries... and people are getting lost because they don't know the trail too well. [2]
  - The community is having to find new and longer trails to subsidence resources like caribou and berries, because the main trails they used to use have been badly eroded and are unsafe. Hunters are getting lost and stuck more often on the softer trails. It's gotten especially hard for the younger generation. [2,6,8]
  - The whaling season is shorter due to earlier break up. Spring whaling used to extend from

March until the end of May. Whaling ended in early May in 2023 when the rivers started flowing. They had to give their quotas to crews from other communities. [8]
  - Loss of working ice cellars. [3]
  - The community used to hunt walrus on ice, which was a staple of the diet. They no longer hunt walrus due to the risk of stampede when they are hauled out on land. [3,4]
  - The foundation of the only store in the village is moving. There is a crack going all the way down the middle of the store on the ceiling and the floor. [7]
- **Water security and sanitation**
  - Permafrost thaw resulted in the drainage of the freshwater lake used for drinking water. The community is looking for a permanent water source. [2,3,8]
  - When the lake drained, waste from the old DEW line was exposed in the village water source. There is also military waste in the river where they now pump drinking water from. [8]
  - A municipal water storage tank drained overnight because the floor had become rotten. [3]
  - Parts of the community haven't had running water for six months due to leaks in the water and sewer system, as well as service disruptions during extended repairs. Families have had to repeatedly go back to honey buckets. [7]
- **Overcrowding**
  - Families are overcrowded and there is no land to build on. [3]
- **Child safety**
  - Young children riding vehicles on the tundra can completely disappear or get stuck in the deep crevices between the thermokarst mounds. [6,8]
  - A boy fell off a piece of plywood at the school playground into a 15-ft deep pond and nearly drowned. The village and the borough then started filling ponds in with gravel, but gravel tends to speed up the thaw. [2]
- **Safe travel**

  We have quite a few main trails that we go out on, and we can't go through those trails anymore because the permafrost split the land open so much. So we got to go on different routes. The trails we used to take all the time, we can't take them anymore. It's really not safe. [6]
  - There's only so long before new trails have the same problems as the older trails. The tundra is softer, and people are getting stuck more—almost every time they go out. [2,8]
  - Subsidence is causing more use of ATVs and the extra use is causing more subsidence. [1,2]
  - Wintertime landmarks have changed, so the perception of where you are at changes, and it's easier for hunters to get lost. [5]
  - The bridge at the second bend of Mukpik Creek that was usually put out seasonally for summer travel can no longer be used because of the amount of permafrost thaw and erosion. They now have to use more resources to make it accessible. People are having to travel a lot farther and a lot more dangerously. [2]
- **Emergency services**
  - In the past two years the community has had 45-50 call outs for Search and Rescue because of equipment failure or people getting lost because they don't know the new trails well. [2]
  - When responding to emergency calls, fire and EMT crews are more limited in their response tactics at houses that used to be one story, but are now more like two story houses due to thaw subsidence. [2]
- **Hazardous waste**
  - Anything that was buried by the military from the old DEW line station is resurfacing due to subsidence and erosion: battery parts, oil barrels, heavy equipment parts. Landfills were on the shoreline and are being exposed. There is metal all over that was never cleaned up. [3,4,8]
- **Airport safety**
  - There is a significant amount of erosion around the hangar for the DEW line (~2 ½-3 ft from the bluff down to the beach) as well as quite a bit of subsidence, which poses a threat to the runway if it keeps going. [2]

Telling your story

- **To the outside world**
  - *All of this permafrost loss is something really new to us that we are slowly adapting to, but it's kind of like we're getting pushed. It's all happening so quick. We're still learning and trying to figure out how to live with and adapt to it. But this is our home so we are going to have to learn to deal with it. [6]*
  - *Climate change is a slow moving disaster. We're in the heart of it now. We know that things are*

changing. We have to adapt, but we can't do it overnight. We can't become green overnight. So, we have to become good stewards like we are with the walruses. Instead of just sitting there complaining, what can you do to make life a little easier for yourself? If we aren't eating caribou,as often as we used to, do we want to consider raising reindeer again? Will we start hunting musk ox? [4]

- *We understand that we're feeling the effects a lot more than other areas, but I think each area is feeling it in a personal way, such as California with the fires. I think if we all just could come together and sit at the table and figure it out, that's what we need to do. More cooperation, more organization, and less left and right. [4]*
- *It's a lot of change. There are always little adaptations to deal with, like having to switch between running water and honey buckets, and using different trails for hunting. [7]*
- *I used to think, "What are they talking about, global warming?" Until the last couple years. I so see it now, and I just fear... global warming is a lot worse than what we think. In 100 years I don't know that this place is going to be here.... From last year to this year, there are big changes. The last couple years have been the hottest summers we've had. It got in the 80s, and it never does up here. When you ride along the beach, instead of just little trickles of water it's gushing waterfalls, and you know it's the permafrost melting drastically, and the ground is falling so bad along the edge. And every year it's worse and worse. I fear for my great-grandkids. Are they going to be able to live in this area, hunt, and do what we do now? [1]*
- *Our little village is functioning, and for me I'm real proud of it. [3]*
- *We live off the land, and the ocean is our garden.... That's where we get our meat, and we get our produce from the land, eggs and berries. I wish this climate change would just change and [for it] to be normal, back how it was. It's just moving so quick.... It hurts for me to see my kids, if in the future, if this weather keeps being like this, and my kids can't continue our subsistence life.... [8]*

- **To future generations in Point Lay**
    - *This is where I built my home. It's where I raised my family. We want our kids to grow up here. I just really want them to be able to know where we lived, how we lived, how we survived and the things we do here that might not be here in a few years. So when I go out, I try to take as many videos and pictures as I can. And I try to go to the same spot every year, because I want them to see what it was like. [1]*
    - *I would like them to know that of course adaptation is a must. They cannot be stationary, because every year is different. [2]*
    - *I want them to know that I did what I can to make sure they don't have to fight like we did. They will have their fight to come, but I would like them to know that I did the best I can. [2]*
    - *You show them by example. So we're not contaminating our land, we're trying to clean the land. We're not abusive with our hunting rights. We become stewards of a lot of our animals. We have a lot of respect for the environment. The ocean is our garden.... We understand that our ocean can be shared with a shipping lane. I think internationally we have to work together to make it so it's not detrimental to one group of people to advance another group's rights. [4]*
    - *One day we'll have so much knowledge about adapting to permafrost loss, we'll be able to teach our kids about it. So that if it ever happens in their lifetime, if it even gets worse, they'll have a bunch of information on how to attack this and know what we did during my time to stop it. It might not be possible to stop it, but I could teach my children when they're older and when I'm an elder that this is what we did, this is how we had to adapt to it. This is going to be their home. [6]*
    - *Point Lay is going to change, and the kids need to know where they came from and accept what is before them and be part of it. They need a good education and a community that's inviting and comfortable. Getting fiber optics is going to be a big deal here, because the kids want to know more. I've seen our kids huddled up next to the school on a cold wintry day. They're all huddled together under a blanket trying to catch the school Internet signal. [4]*
    - *It takes teamwork and cooperation from everybody to make something really happen on a grand scale. [4]*
    - *I want them to know first that there's more than just Point Lay. There's a whole world out there. When I first moved here, a lot of people didn't know what sidewalks were. They didn't know what meridians were. They didn't know what black olives tasted like. [4]*

APPENDIX 4 House Foundation Photos

Photographs of Point Lay house foundations, 25-29 June 2022. (Credits: B.G. Connor, J.L. Peirce)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202 (IMG 1102.jpg)


205 (IMG 1097.jpg)


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