Ice-wedge Degradation and Stabilization in the Prudhoe Bay Oilfield, Alaska (2011-2022)

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Previous studies

The Prudhoe Bay Oilfield (PBO) is located on the Arctic Coastal Plain of Alaska, USA, near the Beaufort Sea coast. High ground-ice content and occurrence of large ice wedges make this area vulnerable to thermokarst and thermal erosion. During the last decades, widespread degradation of ice wedges has been observed across the Arctic, including the PBO (Shur et al., 2003; Jorgenson et al., 2006, 2015; Raynolds et al., 2014; Walker et al., 2014, 2015, 2022; Liljedahl et al., 2016; Frost et al., 2018). In 2011-2015, we studied processes of ice-wedge degradation and stabilization in relation to changing climate and infrastructure in the PBO (Jorgenson et al., 2015; Kanevskiy et al., 2017, 2022; Walker et al., 2022). Field work was performed within three study areas: one undisturbed (Jorgenson Site, JS) and two road-affected (Colleen Site, CS, and Airport Site, AS) areas (**Figures 1** and **2**).

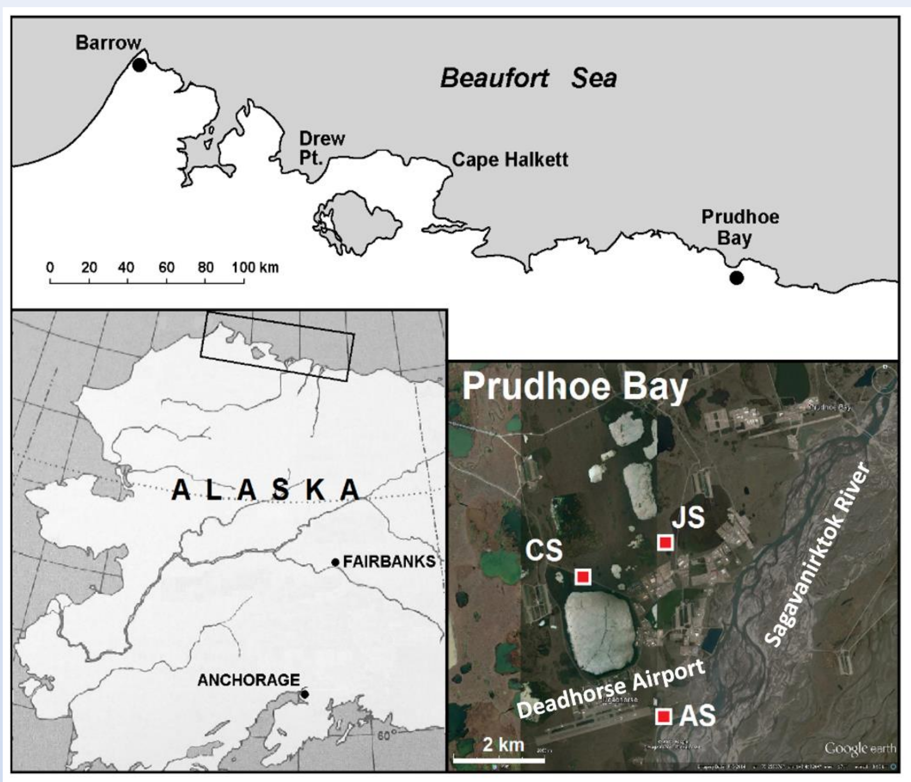

Figure 1. Locations of study sites: JS, Jorgenson Site; CS, Colleen Site; and AS, Airport Site (Kanevskiy et al., 2022).

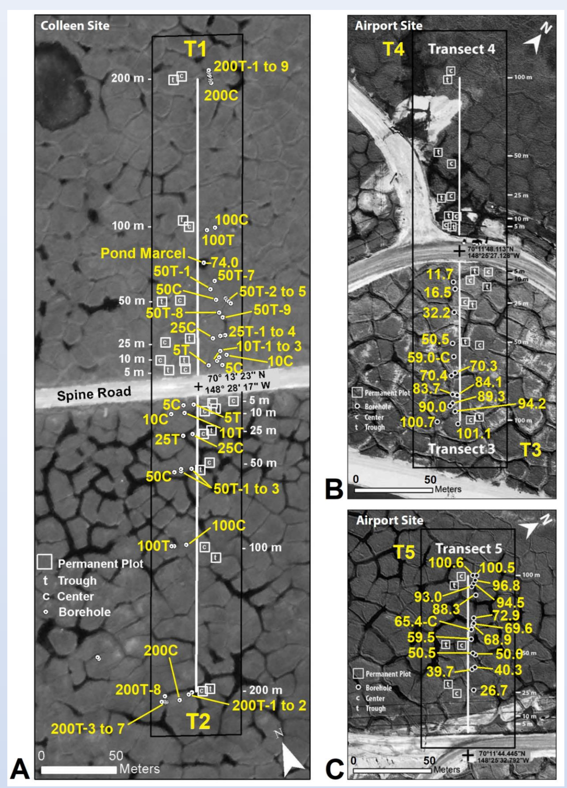

Figure 2. Locations of boreholes at (A) Colleen Site, (B and C) Airport Site (Kanevskiy et al., 2022).

Our previous studies (Jorgenson et al., 2006, 2015; Kanevskiy et al., 2017, 2022) showed that ice-wedge dynamics are driven by a quasi-cyclic process, which includes five main stages: Undegraded wedges (UD) – Degradation-initial (DI) – Degradation-advanced (DA) – Stabilization-initial (SI) – Stabilization-advanced (SA) (**Figure 3**). Initial degradation is caused by extreme weather conditions (e.g., exceptionally warm and wet summers) or physical disturbance, which leads to increase in the active-layer thickness (ALT) and partial thawing of ice wedges with formation of shallow troughs. Water impoundment and additional snow accumulation in troughs leads to further thawing of ice wedges and deepening of troughs. However, accumulation of organic matter in the troughs developing on top of degrading wedges eventually leads to a decrease in the ALT and formation of the ice-rich intermediate layer (IL), protecting ice wedges from further degradation. Stabilized ice wedges have thicker intermediate layer on top of them and, therefore, are less vulnerable to thermokarst than undegraded wedges.

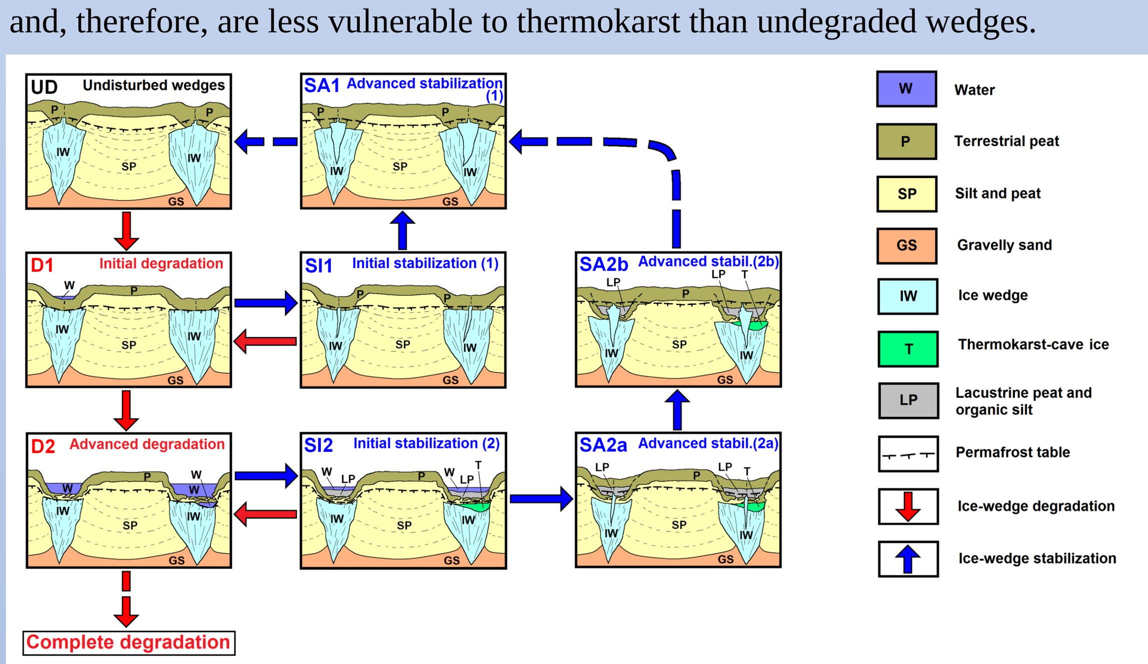

Figure 3. Stages of the ice-wedge degradation and stabilization (part of the conceptual model; modified from Kanevskiy et al., 2017, 2022).

We found that vulnerability of ice wedges to thermokarst strongly depends on the structure and thickness of soil layers above ice wedges, including the active, transient, and intermediate layers. For estimation of vulnerability, we consider the three protective layers (PL) of frozen soils (**Figure 4A**). Our system of evaluation of vulnerability of ice wedges to thermokarst (**Figure 4B**) is based on measured thicknesses of these protective layers.

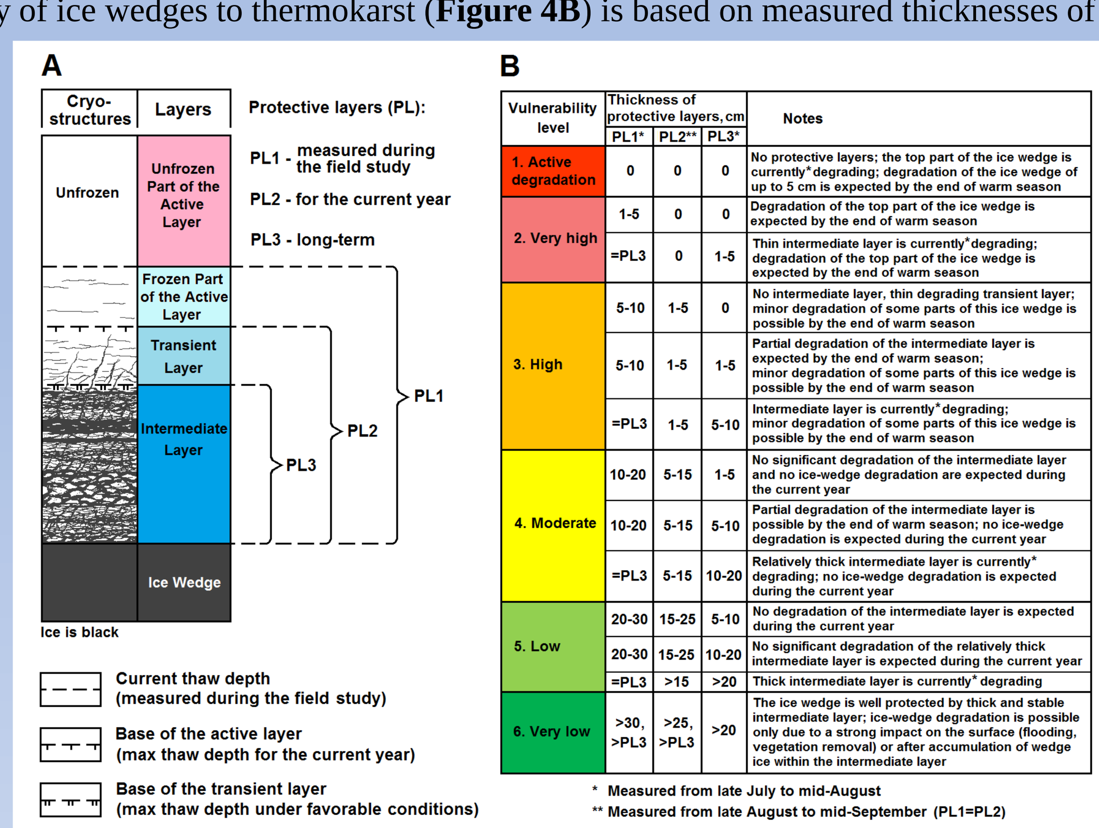

Figure 4. Estimation of vulnerability of ice wedges to thermokarst. (**A**) Protective layers of frozen soils preventing wedge ice from thawing; (**B**) evaluation of vulnerability of ice wedges to thermokarst for northern Alaska based on measurements of thicknesses of protective layers during field studies performed after late July (Kanevskiy et al., 2022).

Redrilling of 2011-2015 boreholes

In 2011-2015, more than 140 boreholes were drilled in ice-wedge troughs within all Prudhoe Bay study areas. Several years after initial studies, we reexamined our sites to detect changes in status of ice wedges (**Table 1**). In 2019, we redrilled 21 boreholes at the undisturbed JS at the same locations where ice wedges had been either degrading or stabilizing during our initial studies in 2011 and 2012. In 2020, nine boreholes were redrilled at the CS (Transect T1) to study changes that had occurred since 2014. In 2021, we redrilled 13 boreholes at the AS (Transects T3 and T5) at the same locations where we had already performed coring in 2015. In 2022, nine boreholes were redrilled at the CS (Transect T2).

Table 1. Results of redrilling of 2011-2015 boreholes within the Prudhoe Bay study areas.

Site	Years	Depth to massive ice, cm	Water depth, cm	Intermediate layer (PL3), cm	Frozen protective layer, cm	Thaw depth, cm	Changes in ice-wedge status*
JS	June 2011, July 2012	46.9	31.7 (n=5)	2.6			NC=2 D=5 S=7 DS=7
	July 2019	56.0	27.4 (n=16)	5.2			
	Change	+9.1	+17.5 (n=16)	+2.6			
	n	21	5/16	21	N/A	N/A	21
T1	August 2014	50.2	19.3 (n=4)	0.6	4.6	45.7	NC=5 D=1 S=2 DS=1
	August 2020	57.8	21.0 (n=6)	3.7	10.0	47.8	
	Change	+7.6	+8.2 (n=6)	+3.1	+5.4	+2.1	
	n	9	4/6	9	9	9	9
T2	August 2014	57.8	29.2 (n=6)	5.0	10.0	47.8	NC=2 D=0 S=5 DS=2
	August 2022	63.6	31.0 (n=7)	8.4	14.3	49.1	
	Change	+5.8	+6.0 (n=7)	+3.4	+4.3	+1.3	
	n	9	6/7	9	9	9	9
T3	September 2015	53.7	27.0	0.0	0.2	53.5	NC=2 D=1 S=5 DS=0
	September 2021	59.4	26.0	1.0	4.6	54.8	
	Change	+5.7	-1.0	+1.0	+4.4	+1.3	
	n	8	1	8	8	8	8
T5	September 2015	52.5	14.6 (n=5)	1.4	3.9	48.6	NC=0 D=0 S=5 DS=0
	September 2021	59.6	6.8 (n=4)	1.8	11.4	48.2	
	Change	+7.1	-9.2 (n=5)	+0.4	+7.5	-0.4	
	n	5	4/5	5	5	5	5
Total	2011-2015	50.9	14.6	2.2	4.9	48.8	NC=11 D=7 S=24 DS=10
	2019-2022	58.5	23.9	4.5	10.1	50.0	
	Change	+7.5	+9.3	+2.4	+5.2	+1.3	
	n	52	35	52	31	31	52

* NC – No significant changes; D – Degradation; S – Stabilization; DS – Degradation and then stabilization.

Within the undisturbed JS, 14 of 21 ice wedges were vulnerable in 2011-12, and only 5 of them were vulnerable in 2019. At the same time, the number of water-filled ice-wedge troughs had increased from five in 2011-12 to 16 in 2019; 12 ice wedges of 21 had experienced some degradation but seven of them had already stabilized. Within the disturbed CS and AS areas (transects T1 to T5), 21 of 31 ice wedges were vulnerable in 2014-15, and only 6 of them were vulnerable in 2020-22. Five of 31 ice wedges within the disturbed areas had experienced some degradation (three of them had already stabilized), and changes in water depths in these areas were less significant than in the JS.

Examples of changes in ice-wedge status

Our studies at the PBO revealed significant changes in ice-wedge status that had occurred from 2011-2015 to 2019-2022 at some of our coring sites. For example, T1-100T-1 site (CS) in 2014 had a shallow dry trough, and in 2019 at this site we could observe a deep water-filled trough, and this ice wedge was still degrading (**Figure 5**). On the contrary, significant stabilization had occurred at T1-10T-1 (**Figure 6**) and T5-26.7 (**Figure 7**) coring locations.

Figure 5. Ice-wedge degradation at T1-100T-1 site (CS, Transect T1, see **Figure 2A** for location). On August 7, 2014, ice wedge was protected by a very thin layer of frozen soil (PL1 = 1 cm) (**Left**), and on August 18, 2020, this wedge was degrading (PL2 = 0 cm) (**Center**). Total depth to wedge ice from the soil surface had increased from 45 cm in 2014 to 50 cm in 2020, and a shallow dry trough that was observed in 2014 had transformed by 2020 into a deep trough above degrading ice wedge with water depth of 32 cm (**Right**).

Figure 6. Ice-wedge stabilization at T1-10T-1 site (CS, Transect T1, see **Figure 2A** for location). Actively degrading wedge (PL1=0 cm), August 6, 2014 (**Left**) had stabilized (PL2=15 cm) by August 18, 2020 (**Right**). Total depth to wedge ice from the soil surface had increased from 58 cm in 2014 to 63 cm in 2020.

Figure 7. Ice-wedge stabilization at T5-26.7 site (CS, Transect T5, see **Figure 2C** for location). Extremely vulnerable ice wedge (PL2=2 cm), September 20, 2015 (**Left**), had stabilized (PL2=13 cm) by September 5, 2021 (**Right**). Total depth to wedge ice from the soil surface had increased from 55 cm in 2015 to 58 cm in 2021.

Main results of 2019-2022 studies

Totally, 52 boreholes were redrilled in 2019-2022 (**Table 1**). Overall, the depth to massive ice had increased by 7.5 cm, and PL2 thickness had increased by 5.3 cm. Only 4 of 52 locations had some decrease in a depth to wedge ice, and 5 of 31 (excluding JS locations that were sampled in June and July) had some decrease in a thickness of PL2. Changes that had occurred within the study areas are illustrated by graphs in **Figure 8**. Based on the results of coring and visual assessment of coring sites (e.g., depth of troughs and water depths), we divided all studied ice wedges into four classes that reflect changes in their initial status (degradation/stabilization): (1) ice wedges that have not experienced any significant changes; (2) ice wedges that have experienced degradation, detected by deeper troughs and thinner protective layers; (3) ice wedges that have experienced stabilization, detected by thicker protective layers; and (4) ice wedges that have experienced degradation and subsequent stabilization, detected by deeper troughs and thicker protective layers. Most of studied ice wedges have experienced stabilization (**Figure 9**). It should be noted, however, that we redrilled mainly the ice wedges that had been either degrading (PL2 = 0 cm) or rather vulnerable (PL2 <5 cm) in 2011-15. Thus, we presume that many other ice wedges that were well protected in 2011-15 haven't experienced any significant changes since that time. These results correspond to remote-sensing data (**Figure 10**), which show that after rapid ice-wedge degradation that started in 1990s, the rates of this process became much lower during the recent years, mainly because of formation of protective layer of frozen soil above many partially degraded ice wedges.

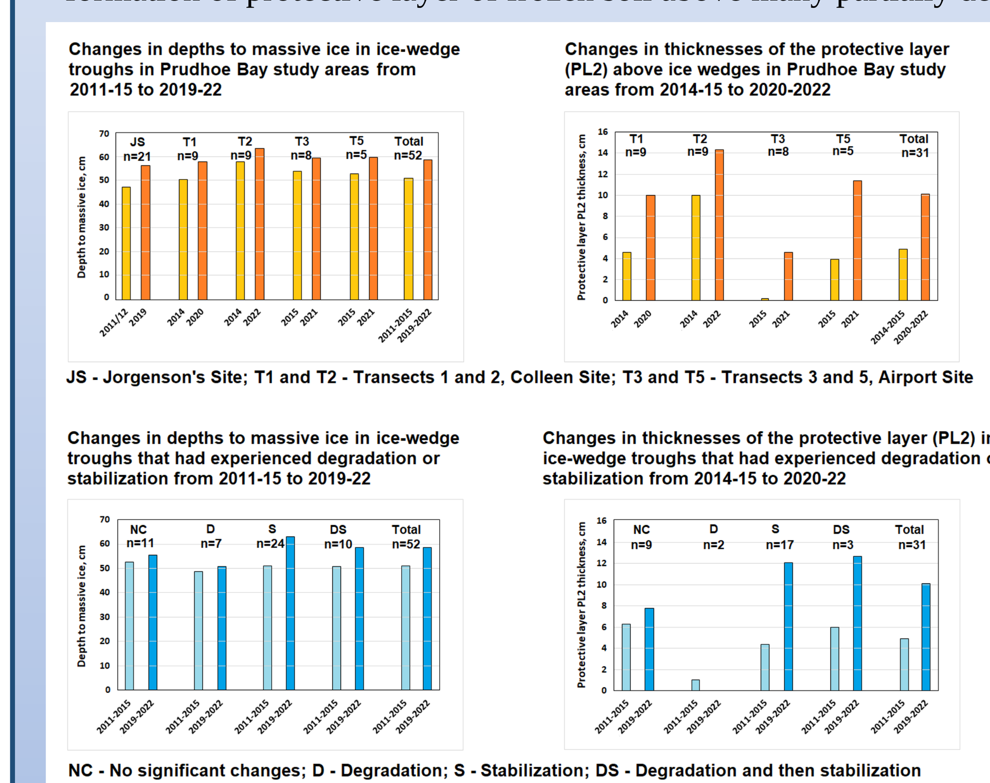

Figure 8. Changes in depths to massive ice (**Left**) and thicknesses of the frozen protective layer (PL2, see **Figure 4**) above ice wedges (**Right**) from 2011-2015 to 2019-2022.

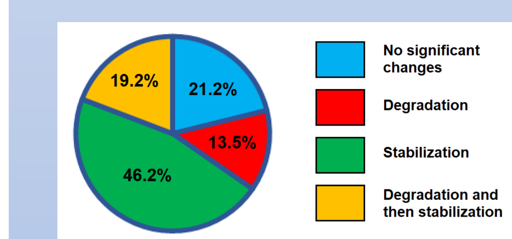

Figure 9. Changes in status of ice wedges in the Prudhoe Bay study areas from 2011-2015 to 2019-2022, n=52.

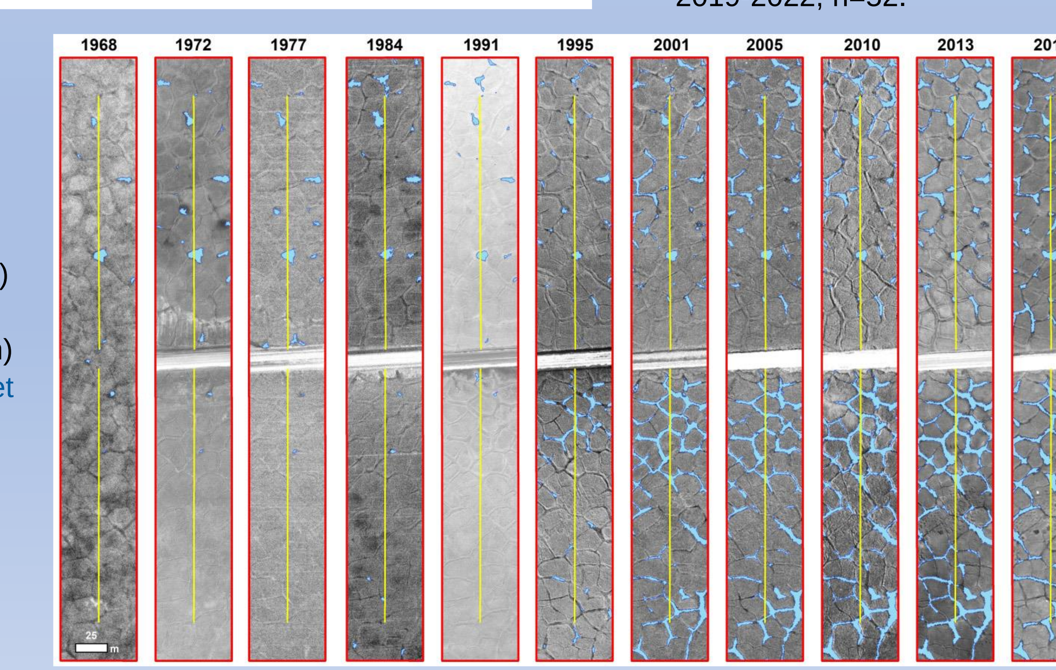

Figure 10. Changes in waterbody distribution (blue) from 1968 to 2018, Colleen Site, Transects T1 (northern) and T2 (southern) (Walker et al., 2022).

Conclusions

Obtained data show that degradation and stabilization of ice wedges may occur within the same areas simultaneously. While many ice wedges have not experienced significant changes (or have experienced some minor stabilization), some formerly stable ice wedges have experienced degradation with formation of new thermokarst ponds. Some of these wedges are still degrading, while others have already stabilized.

Most of the ice wedges that were actively degrading in 2011-2015 have experienced stabilization detected by thicker intermediate and transient layers. For example, seven ice wedges of 13, which were redrilled at the AS, had been degrading in September 2015 but only one of 13 was degrading in September 2021. The most significant stabilization has occurred in deep thermokarst ponds, where fast development of aquatic vegetation has resulted in a decrease in the active-layer thickness and formation of a thick protective intermediate layer above partially degraded ice wedges.

Our studies show that ice-wedge degradation in the continuous permafrost zone is a reversible process not only in undisturbed areas but in the areas affected by infrastructure. Despite the strong influence of the road infrastructure on the active layer and the upper permafrost stability through changes in hydrology and surface conditions, numerous ice wedges at the CS and AS have already experienced stabilization. We presume that in some cases stabilization was accelerated by accumulation of road dust.

Processes of ice-wedge degradation/stabilization are highly dynamic, and formation of protective layers of frozen soils may occur very fast, which is indicated by rapid increase in depth to wedge ice from the soil surface (average rate ~1 cm/year). Such increase is caused by accumulation of organic matter and mineral material (including road dust) in ice-wedge troughs, and formation of segregated ice in PL2. Only 4 of 52 locations (<8%) showed some decrease in a depth to massive ice by 2019-2022.

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