Degradation and recovery of ice wedges in relation to road infrastructure in the Prudhoe Bay Oilfield, AK

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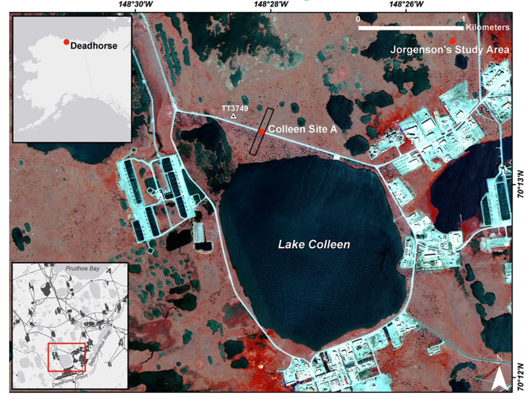
Widespread degradation of ice wedges has been observed in the Arctic Coastal Plain of Alaska during the last decades (Jorgenson et al. 2006; Raynolds et al. 2014). It strongly affects environment and infrastructure of the Prudhoe Bay Oilfield (PBO). The upper permafrost of PBO contains significant amounts of excess ground ice, including segregated ice and large epigenetic ice wedges (width up to 4 m; vertical extent up to 3.5 m). High ice content makes the study area extremely vulnerable to thermokarst and thermal erosion. In most cases, these processes are triggered by climatic changes or human activities.

Lake Colleen study area

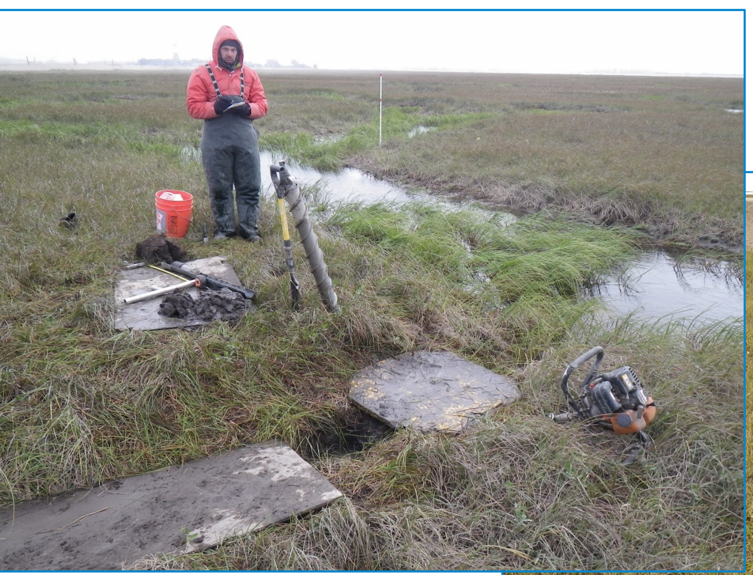


Large ice wedges exposed at the Alaskan Beaufort Sea coast, McLeod Point

Wedge-ice content varies in different landscapes of the Arctic Coastal Plain from 0-5% (eolian and deltaic landscapes) to 15-30% (primary surface of the Coastal Plain and drained-lake basins), with average value of about 11% for the entire coast. The total average ground-ice content (due to wedge, segregated, and pore ice) for the whole area is approximately 77%vol. (Kanevskiy et al. 2013)

Road infrastructure in PBO affects the ice-wedge degradation by an increase in the active-layer thickness (ALT) triggered by flooding of large areas due to construction of road embankments; accumulation of dust, which kills vegetation and changes thermal properties of soil; and additional snow accumulation near the embankment.

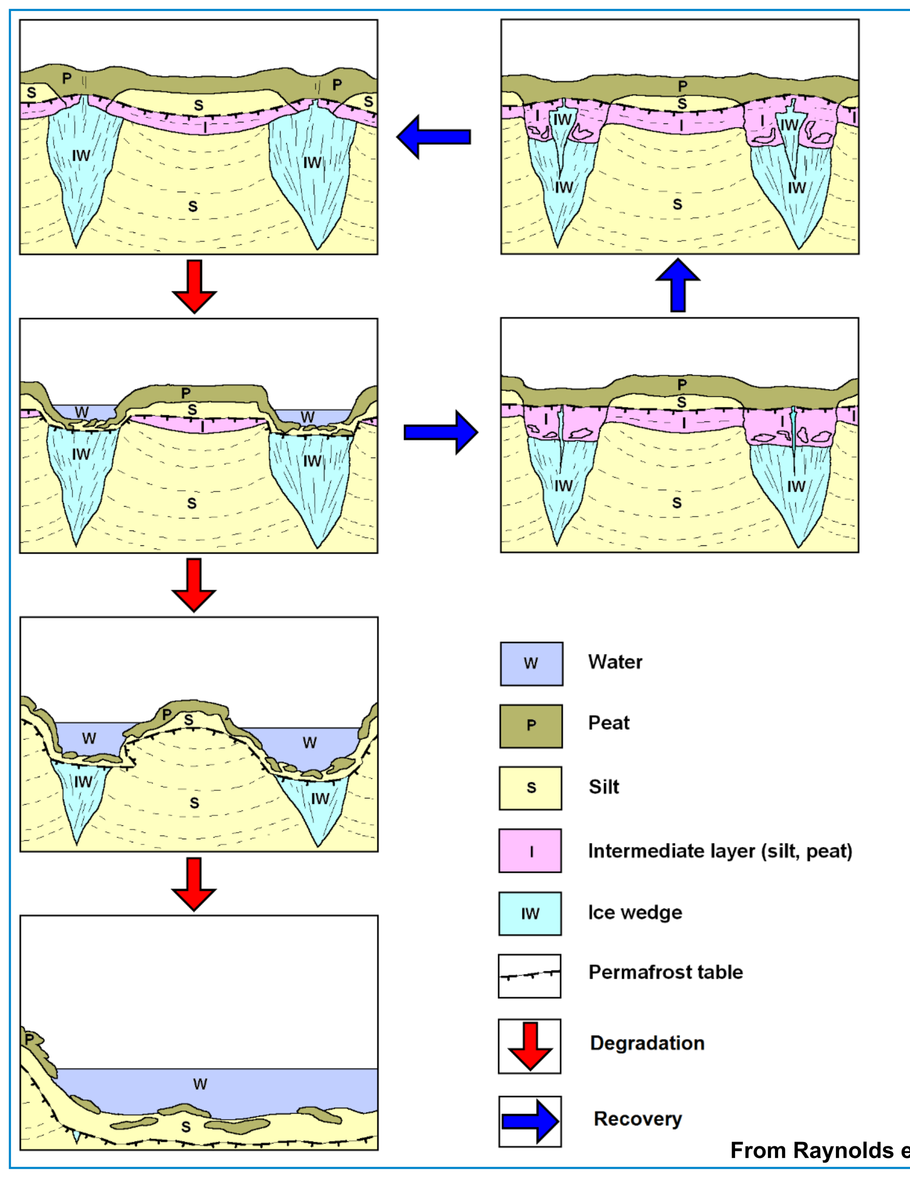
During 2-14 August 2014, we examined thermokarst features within the Lake Colleen area. The main objectives of this field study were to document the extent and effects of road dust and road-related flooding to the topography, landforms, permafrost, soils, and vegetation. We were particularly interested in changes to the permafrost and ice wedges. We chose an intensive study site along the Spine Road, the oldest most heavily traveled road in the PBO region.



Permafrost drilling

Degradation of ice wedges is a cyclic process, which includes five main stages: Undegraded wedges – Degradation-initial – Degradation-advanced – Stabilization-initial – Stabilization-advanced. The processes of ice-wedge degradation and recovery are determined by interactions between the active layer and the underlying transition zone of the upper permafrost (Shur 1988, French and Shur 2010, Kanevskiy et al. 2013), which includes transient layer (TL) and intermediate layer (IL). Accumulation of organic matter in the troughs developing on top of degrading wedges eventually leads to decrease in ALT and formation of the ice-rich IL, protecting ice wedges from further degradation (Jorgenson et al. 2006; Raynolds et al. 2014).

Conceptual model of the ice-wedge degradation and stabilization in the continuous permafrost zone



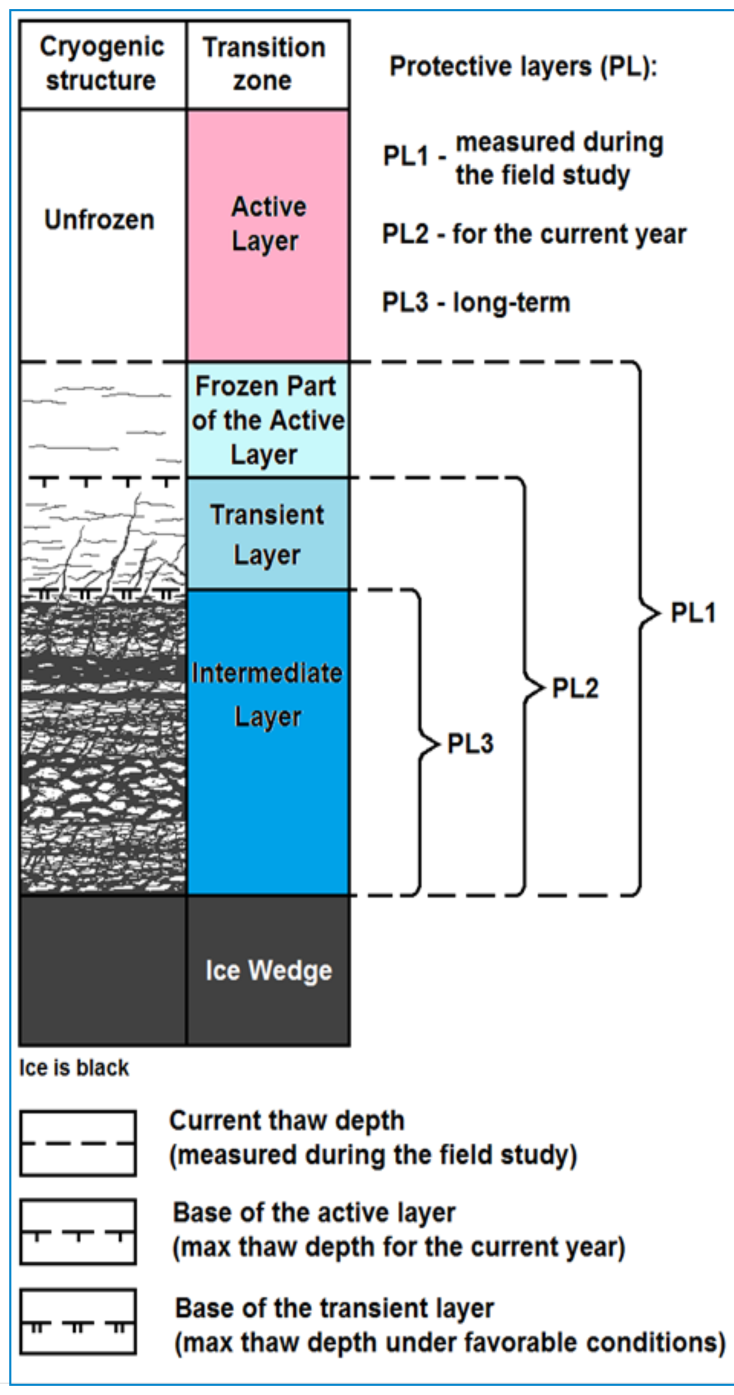
From Raynolds et al. (2014), based on Jorgenson et al. (2006)

The first (reversible) scenario (blue arrows) is possible when only the ice wedges are affected by thermokarst, while central parts of polygons remain relatively stable. In the areas with cold climate, new generation of ice wedges start forming after termination of thermokarst. These wedges penetrate through the intermediate layer into the wedges of previous generation, truncated by thermokarst. When these new ice wedges reach a significant size, they can be affected by a new cycle of thermokarst, and a reversible scenario will repeat itself again.

The second (irreversible) scenario (red arrows) usually occurs when the central parts of the ice-wedge polygons are also affected by thermokarst as a result of the loss of the protective organic layer. A further thermokarst development results in the continuing ground subsidence, ponding of surface with melt-water, and formation of a shallow initial thermokarst lake above polygons. Eventually the deepening and enlarging of thermokarst lake leads to acceleration of thermokarst and relatively fast degradation of ice-rich soils under the lake.

During 2-14 August 2014, 57 boreholes were drilled in ice-wedge polygon centers and troughs at 5, 10, 25, 100, and 200 m from the Spine Road in the Lake Colleen area along two transects established at the different sides of the road. Boreholes drilled in ice-wedge polygon centers (totally 12 boreholes up to 2.5-m deep) revealed five main cryostratigraphic units (both transects have a similar structure): (1) Unfrozen part of the active layer (peat, organic silt, silt), 41-75 cm thick, 58 cm average, gravimetric moisture content (GMC) 96±60% (n=36); (2) Transient layer and the frozen part of the active layer (peat, organic silt, silt, relatively ice-poor), including, 6-12 cm thick, 8.3 cm average, GMC=130±77% (n=9); (3) Frozen organic soil, including intermediate layer (organic silt, peat, organic silt/peat, ice-rich), 30-150 cm, 73 cm average, GMC=187±71% (n=30); (4) Clean mineral soil with peat inclusions (20 to 70 vol%, usually forming sub-vertical structure), ice-rich, 20-100 cm, 49 cm average (only 9 boreholes of 12 could reach this layer), GMC=220±95% (n=16); (5) Clean mineral soil (sandy silt, sand, gravelly sand), mostly ice-rich; from the depth 130-200 cm (only 6 boreholes of 12 could reach this layer), GMC=98±52% (n=8).

Estimation of risk of the ice-wedge degradation in the study area, based on the thickness of protective layers



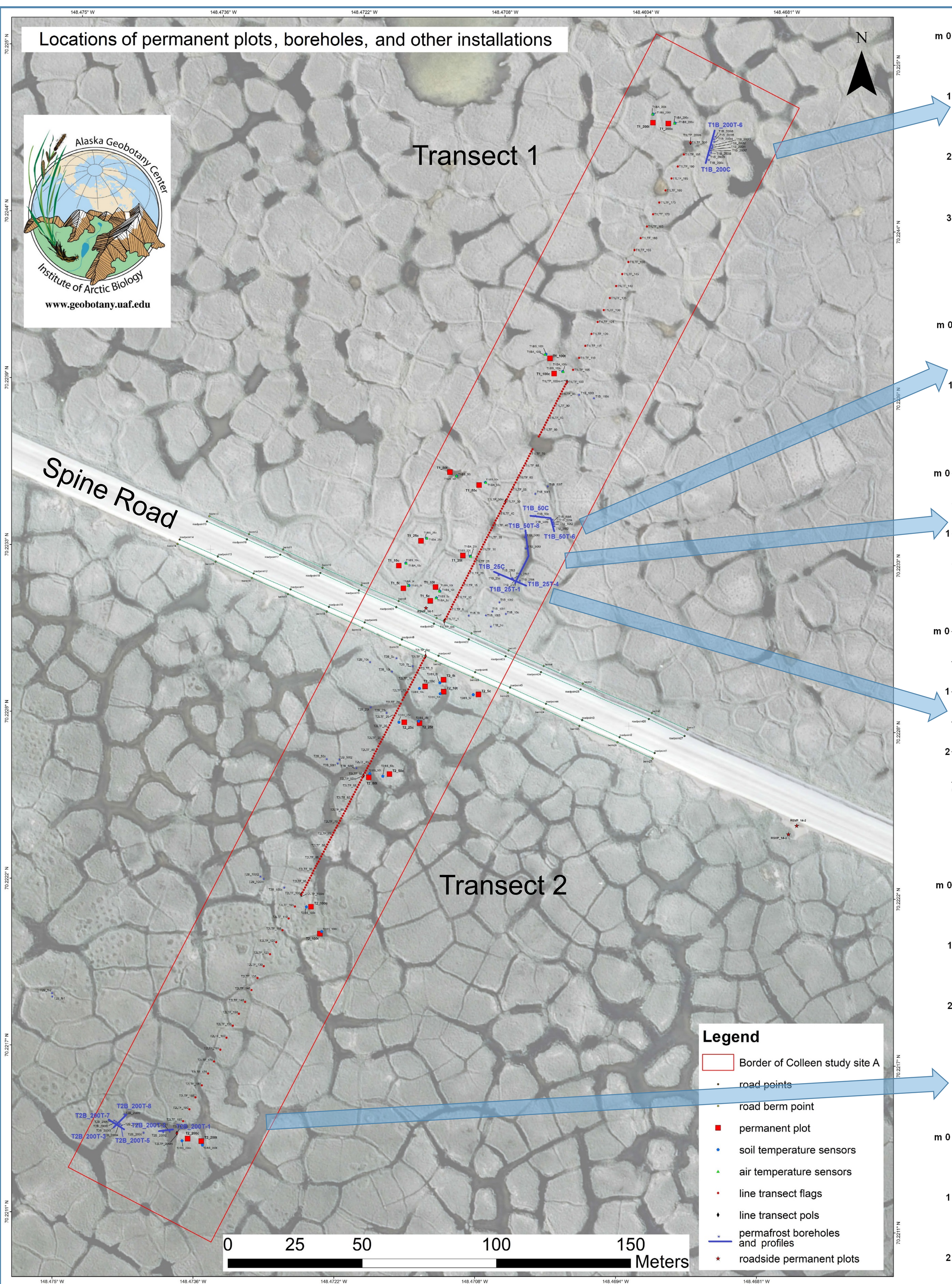
Risk level	Thickness of protective layers, cm			Notes
	PL1*	PL2	PL3	
1. Active degradation	0	0	0	No protective layers; the top part of the ice wedge is currently degrading
2. Very high	≤5	≤5	0	Degradation of the top part of the ice wedge is expected by the end of warm season
	=PL3	=PL3	≤5	Thin intermediate layer is currently degrading; degradation of the top part of the ice wedge is expected by the end of warm season
3. High	5-10	5-10	0	Degradation of the top part of the ice wedge is possible
	5-10	5-10	≤5	Partial degradation of the intermediate layer is expected by the end of warm season; degradation of the top part of the ice wedge is possible
	=PL3	=PL3	5-10	Intermediate layer is currently degrading; degradation of the top part of the ice wedge is possible
4. Moderate	10-20	10-15	≤5	No significant degradation of the intermediate layer and no ice-wedge degradation are expected during the current year
	10-15	10-15	5-10	Partial degradation of the intermediate layer is possible by the end of warm season; no ice-wedge degradation is expected during the current year
	=PL3	=PL3	10-15	Relatively thick intermediate layer is currently degrading; no ice-wedge degradation is expected during the current year
5. Low	20-30	15-20	5-10	No degradation of the intermediate layer is expected during the current year
	15-30	15-25	10-15	No significant degradation of the relatively thick intermediate layer is expected during the current year
	=PL3	=PL3	≥15	Thick intermediate layer is currently degrading
6. Very low	≥30, >PL3	≥25, >PL3	≥15	The ice wedge is well protected by thick and stable intermediate layer; ice-wedge degradation is possible only due to a strong impact on the surface (large-scale flooding, vegetation removal) or after accumulation of wedge ice within the intermediate layer

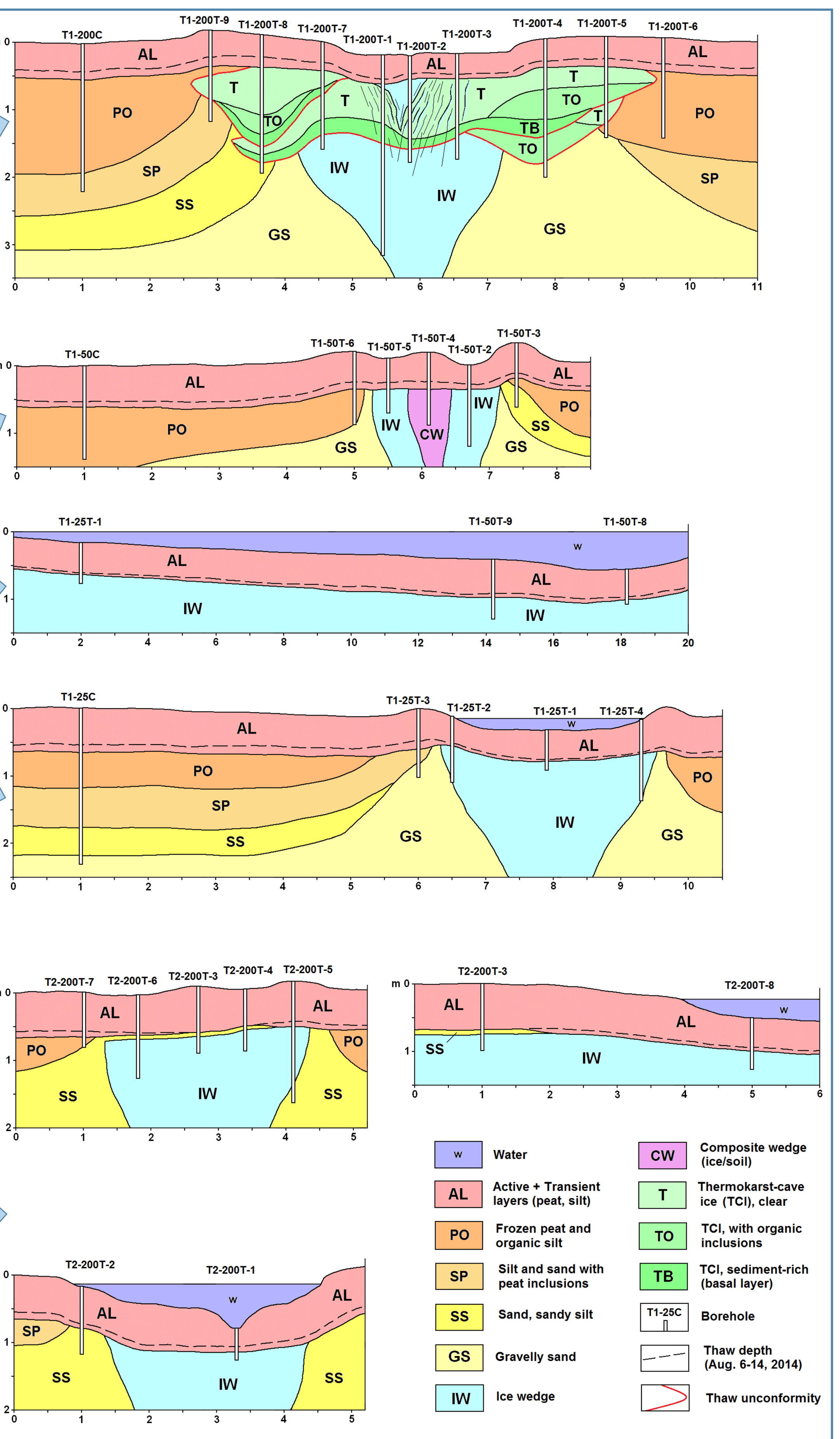
* Measured in the first half of August

Our study showed that 35 of 43 boreholes drilled in ice-wedge troughs and surrounding rims encountered massive-ice bodies (mostly ice wedges at various stages of degradation and recovery). At the time of drilling, a protective layer of frozen soil 1 to 27-cm thick (PL1) was observed above the majority of ice wedges. The ice-rich IL up to 19-cm thick (PL3), which indicates relative stability of ice wedges, was detected in 13 boreholes. Two ice wedges experienced thawing at the time of drilling, but calculations indicate that by the end of the thawing season 5 more wedges will be affected by thermokarst.

Despite a strong influence of the road construction and heavy traffic on the upper permafrost stability, ice-wedge degradation is a reversible process. Its activation in most cases was triggered by increase in the ALT during exceptionally warm and wet summers. Initial degradation of ice wedges along Transect 2 was probably related to the flooding of the southwest side of the Spine Road triggered by the road construction, but at present time the wedges along this transect (even the wedges under the deep troughs filled with water) are more stable than the wedges along Transect 1, which have not been affected by flooding.

Drilling profiles, Transects 1 and 2





Intermediate layer above ice wedges

Boreholes drilled in ice-wedge troughs, August 2014

Borehole	Date	Bore-hole depth, cm	Location	Water depth, cm	Thaw depth, cm	Perma-frost table*, cm	Depth to massive ice, cm	Frozen protective layer (PL1)**, cm	Inter-mediate layer (PL3), cm	Ice-wedge thawing, expected in 2014***, cm
Transect T1										
T1-5T-1	8/7/14	98	trough	-	51	60	60 WI	9	0	0
T1-10T-1	8/7/14	90	trough	1	58	58	58 WI	0	0	2.5
T1-10T-2	8/7/14	95	trough	-	56	56	61 WI	5	5	0.5
T1-10T-3	8/7/14	151	trough	-	59	66	-	-	-	-
T1-25T-1	8/6/14	75	trough	15	45	47	47 WI	2	0	2
T1-25T-2	8/13/14	97	trough	-	40	43	43 WI	3	0	0.7
T1-25T-3	8/13/14	102	rim	-	48	?	-	-	-	-
T1-25T-4	8/13/14	120	trough	-	48	49	49 WI	1	0	2
T1-50-T1	8/7/14	118	trough	-	55	65	73 WI	18	8	0
T1-50-T2	8/13/14	86	trough	-	28	36	36 WI	8	0	0
T1-50-T3	8/13/14	95	rim	-	45	?	-	-	-	-
T1-50-T4	8/13/14	108	trough	-	43	55	55 CW	12	0	0
T1-50-T5	8/13/14	81	trough	-	35	46	46 WI	11	0	0
T1-50-T6	8/14/14	98	rim	-	45	56	-	-	-	-
T1-50-T7	8/14/14	81	trough	30	43	43	43 WI	0	0	3.0
T1-50-T8	8/14/14	51	trough	49	41	44	44 WI	3	0	0.7
T1-50-T9	8/14/14	88	trough	31	51	56	56 WI	5	0	0.3
T1-100-T1	8/7/14	75	trough	-	44	45	45 WI	1	0	2
T1-200T-1	8/8/14	298	trough	-	35	42	42 WI	7	0	0
T1-200T-2	8/9/14	158	trough	-	27	34	34 WI	7	0	0
T1-200T-3	8/9/14	155	trough	-	30	37	37 TCI	7	0	0
T1-200T-4	8/9/14	205	rim	-	33	44	44 TCI	11	0	0
T1-200T-5	8/9/14	150	rim	-	33	46	46 TCI	13	0	0
T1-200T-6	8/9/14	150	rim	-	40	52	-	-	-	-
T1-200T-7	8/9/14	160	rim	-	31	43	43 TCI	12	0	0
T1-200T-8	8/9/14	204	rim	-	33	49	49 TCI	16	0	0
T1-200T-9	8/9/14	135	rim	-	40	54	67 TCI	27	13	0
Average					42.1 (n=27)	48.0 (n=27)	49.0 (n=22)	8.1 (n=22)	1.2 (n=22)	
Transect T2										
T2-5T-1	8/10/14	90	trough	12	43	58	70 WI	27	12	0
T2-10T-1	8/10/14	89	trough	0	53	59	66 WI	13	7	0
T2-25T-1	8/10/14	102	trough	35	45	45	64 WI	19	19	0
T2-50T-1	8/11/14	77	trough	-	48	58	59 WI	11	1	0
T2-50T-2	8/11/14	178	trough	-	62	70	-	-	-	-
T2-50T-3	8/11/14	68	trough	35	46	54	56 WI	10	2	0
T2-100T-1	8/11/14	65	trough	8	43	51	57 WI	14	6	0
T2-100T-2	8/11/14	107	trough	0	50	58	61 WI	11	3	0
T2-200T-1	8/12/14	49	trough	70	28	36	36 WI	8	0	0
T2-200T-2	8/12/14	100	trough	3	55	62	-	-	-	-
T2-200T-3	8/12/14	98	trough	-	68	68	73 WI	5	5	0.6
T2-200T-4	8/12/14	92	trough	-	55	55	60 WI	5	5	0.6
T2-200T-5	8/12/14	179	trough	-	59	67	67 WI	8	0	0
T2-200T-6	8/12/14	124	trough	-	57	60	65 WI	8	5	0
T2-200T-7	8/12/14	82	rim	-	58	65	-	-	-	-
T2-200T-8	8/13/14	75	trough	27	44	49	49 WI	5	0	0
Average					49.2 (n=16)	55.2 (n=16)	60.2 (n=13)	11.1 (n=13)	4.4 (n=13)	

* Top of the intermediate layer (based on analysis of cryostructures)
** Thickness of frozen soil layer on top of massive ice bodies on the day of drilling (includes the frozen part of the active layer, transient layer, and intermediate layer)
***Based on the Stefan equation

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