Evaluation of Risk of Ice-Wedge Degradation, Prudhoe Bay Oilfield, Alaska

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Ice-wedge degradation

Widespread degradation of large ice wedges (Fig. 1) has been observed in the Arctic Coastal Plain of Alaska during the last decades, including the area of the Prudhoe Bay Oilfield (PBO), where it strongly affects environment and infrastructure (Raynolds et al., 2014; Jorgenson et al., 2015). 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. 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.

Figure 1. 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) of the upper permafrost of the Arctic Coastal Plain is approximately 77%vol. (Kanevskiy et al. 2013)

Prudhoe Bay study area

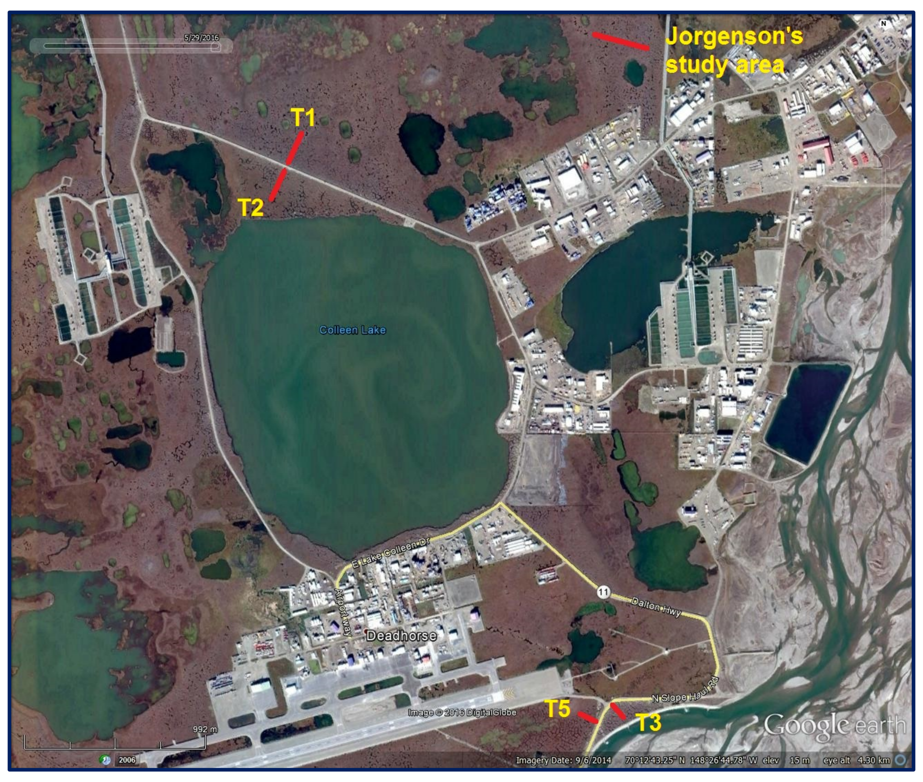


Figure 2. Location of transects T1, T2, T3, and T5.

During 2-14 August 2014, 57 boreholes were drilled in ice-wedge polygon centers and troughs (Figs. 2, 5 to 8) at the Colleen Site A (Lake Coleen area) along two 200-m-long transects (T1 and T2) established at the both sides of the Spine Road; 35 boreholes encountered 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 intermediate layer (IL, equal to PL3) up to 19-cm thick, which indicates relative stability of ice wedges, was encountered in 13 boreholes (Fig. 6). Two ice wedges experienced thawing at the time of drilling, but calculations indicate that by the end of the thawing season six more wedges would be affected by thermokarst, and during exceptionally warm summers (the summer of 2014 was very cold) up to two thirds of wedges may experience partial melting.

During 18-23 September 2015, when ALT reached its maximum values (PL1=PL2), 28 boreholes were drilled in ice-wedge polygon centers and troughs at the Airport Study Site along two 100-m-long transects (T3 and T5) established at the both sides of the Dalton Highway; 23 boreholes encountered ice wedges at various stages of degradation and recovery. At the time of drilling, a protective layer of frozen soil 0.5 to 15 cm thick (PL2, which includes TL and/or IL) was observed above the majority of ice wedges. The ice-rich IL up to 14 cm thick was encountered in 10 boreholes. Seven ice wedges of 23 experienced thawing at the time of drilling.

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

Our studies show that degradation of ice wedges is a cyclic process, which includes five main stages: Undegraded wedges (UD) – Degradation-initial (DI) – Degradation-advanced (DA) – Stabilization-initial (SI) – Stabilization-advanced (SA) (Jorgenson et al., 2006, 2015). The processes of ice-wedge degradation, stabilization 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), which includes transient layer (TL) and intermediate layer (IL). Accumulation of organic matter in the troughs developing on top of degrading ice wedges eventually leads to decrease in the active-layer thickness (ALT) and formation of the ice-rich IL, protecting ice wedges from further degradation (Jorgenson et al., 2006, 2015). Conceptual model of the ice-wedge thermokarst development is shown in Fig. 3.

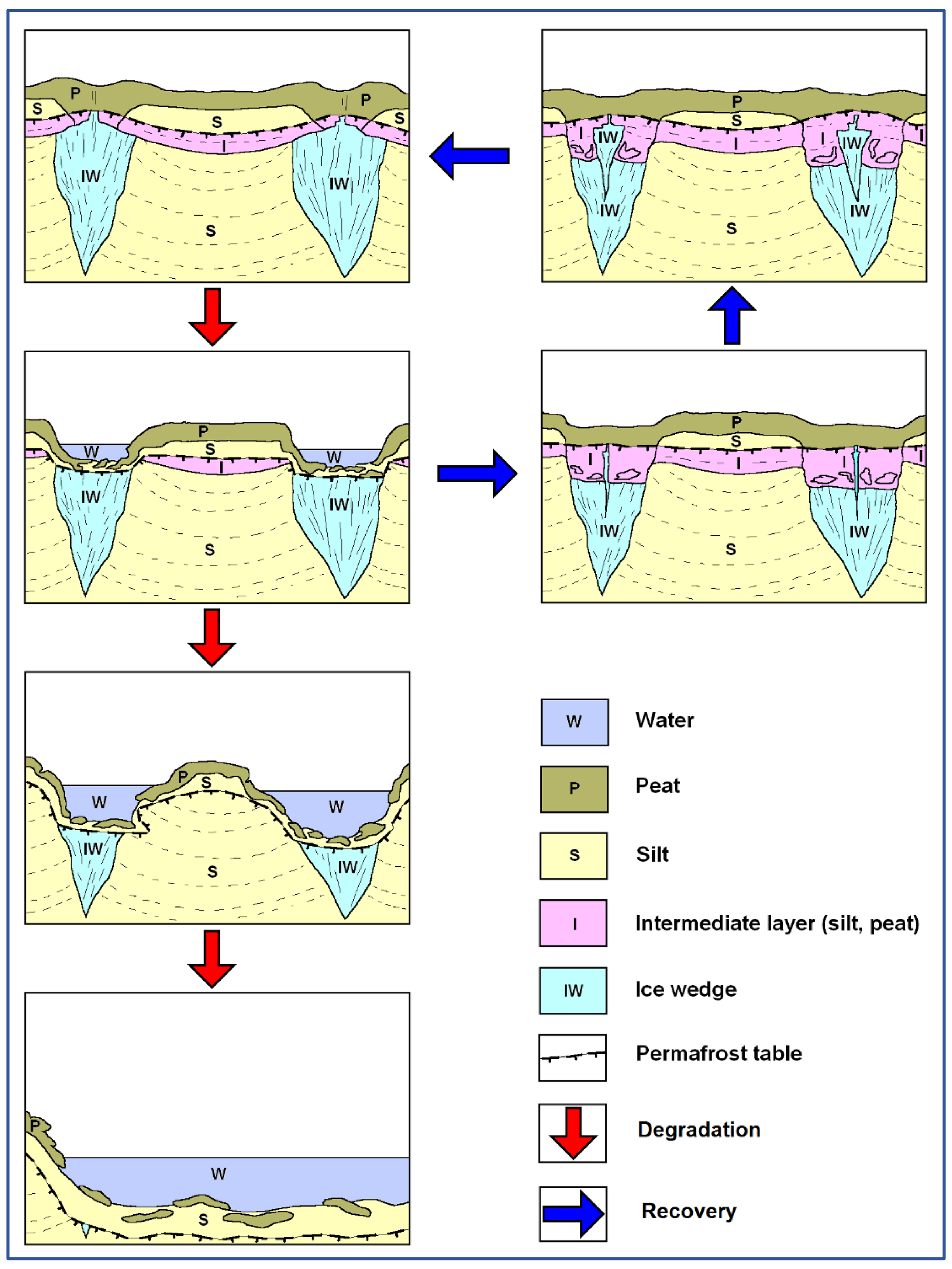


Figure 3. Two possible scenarios of ice-wedge thermokarst. From Raynolds et al. (2014), based on Jorgenson et al. (2006).

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) is not very common. It 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 thawing of ice-rich soils under the lake.

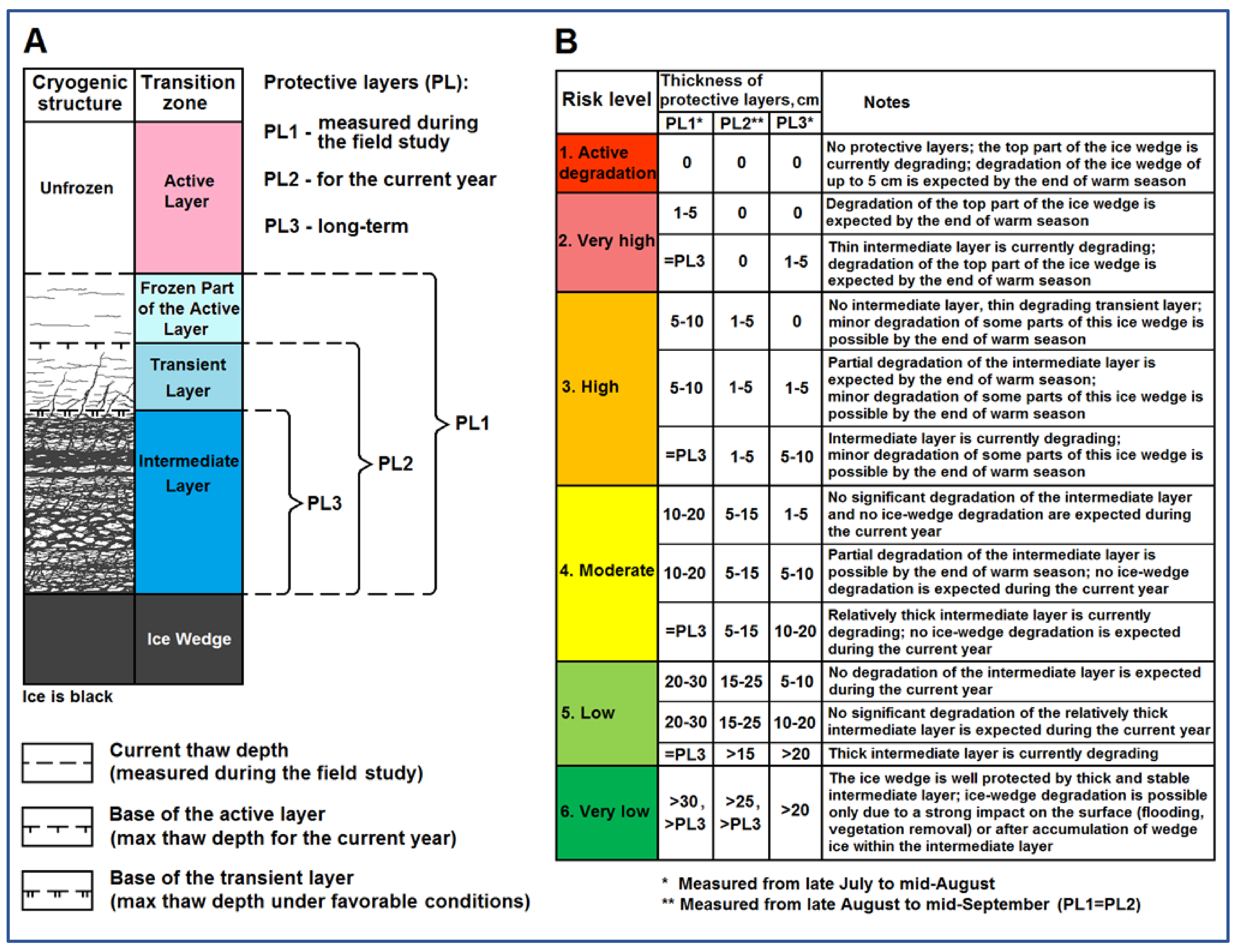
Figure 5. Permafrost drilling with the SIPRE-corer.

Figure 6. Ice-rich intermediate layer above ice wedges.
Left: T2-25T-1; Right: T2-100T-1

Estimation of risk of the ice-wedge degradation

The model of the active layer/upper permafrost system (Fig. 4A) suggests that in order to estimate a risk of ice-wedge thermokarst we should obtain information on thickness and properties of protective soil layers overlying ice wedges, including active, transient, and intermediate layers. A thickness of the protective layer PL1 (or a total thickness of frozen soil above the ice wedge, including the frozen part of active layer, transient layer, and intermediate layer) is measured during the field study. PL2 is protective layer for the current year; its thickness is measured at the end of warm season. PL3 includes the intermediate layer, which can be distinguished by its specific cryogenic structure: this layer is extremely ice-rich with predominantly ataxitic (suspended) and reticulate cryostructures and numerous thick ice layers (belts) (Fig. 6). Degradation of the ice wedge begins when the thawed and subsided PL1 layer joins the active layer and a part of thermal resources during the remaining part of the warm season can be spent on thawing of massive ice. Especially important is the information on thickness of the intermediate layer (PL3), which provides a long-term stability of ice wedges.

The color-coded system of evaluation of the risk of ice-wedge degradation as a function of thickness of protective layers of frozen soil above wedges (PL1, PL2, and PL3) includes six risk levels from bright red (risk level 1, the highest) to dark green (risk level 6, the lowest) (Fig. 4B). Two highest risk levels are related to currently degrading wedges. The difference between them is determined by the activity of degradation: while the first risk level refers to active degradation with significant thawing of ice wedges, the second only is related to slow degradation, when the depth of seasonal thawing can reach the tops of ice wedges only at the end of warm season. The third risk level is related to ice wedges which are not currently degrading, but the protective layer is so thin that degradation can start very easily, and some parts of studied wedges may already experience degradation by the time of study. Levels of risk strongly depend on stages of ice-wedge degradation / stabilization: while ice wedges at UD and SA stages are relatively well protected by the intermediate layer (P3), most of wedges at DI and DA stages have no protection.



Risk level	Thickness of protective layers, cm PL1*	PL2**	PL3*	Notes
1. Active degradation	0	0	0	No protective layers; the top part of the ice wedge is currently degrading; degradation of the ice wedge of up to 5 cm is expected by the end of warm season
2. Very high	1-5	0	0	Degradation of the top part of the ice wedge is expected by the end of warm season
	=PL3	0	1-5	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	1-5	0	No intermediate layer, thin degrading transient layer; minor degradation of some parts of this ice wedge is possible by the end of warm season
	5-10	1-5	1-5	Partial degradation of the intermediate layer is expected by the end of warm season; minor degradation of some parts of this ice wedge is possible by the end of warm season
	=PL3	1-5	5-10	Intermediate layer is currently degrading; minor degradation of some parts of this ice wedge is possible by the end of warm season
4. Moderate	10-20	5-15	1-5	No significant degradation of the intermediate layer and no ice-wedge degradation are expected during the current year
	10-20	5-15	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	5-15	10-20	Relatively thick intermediate layer is currently degrading; no ice-wedge degradation is expected during the current year
5. Low	20-30	15-25	5-10	No degradation of the intermediate layer is expected during the current year
	20-30	15-25	10-20	No significant degradation of the relatively thick intermediate layer is expected during the current year
	=PL3	>15	>20	Thick intermediate layer is currently degrading
6. Very low	>30, >PL3	>25, >PL3	>20	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 (flooding, vegetation removal) or after accumulation of wedge ice within the intermediate layer

* Measured from late July to mid-August
** Measured from late August to mid-September (PL1=PL2)

Figure 4. Estimation of risk of the ice-wedge degradation. **A – Protective layers of frozen soils preventing wedge ice from thawing; B – Evaluation of risk of the ice-wedge degradation for northern Alaska.**

Average thicknesses of frozen protective layers above massive-ice bodies in boreholes drilled in ice-wedge troughs, Prudhoe Bay transects

Average thicknesses of protective layers for T1 were 8.1 cm (PL1) and 1.2 cm (PL3), which correspond to high level of risk of ice-wedge degradation (see the table below). For T2, average thicknesses were 11.1 cm (PL1) and 5.0 cm (PL3), which correspond to moderate level of risk of ice-wedge degradation. For comparison, at the adjacent Jorgenson's study area which was not affected by the road construction and heavy traffic (Jorgenson et al., 2015), the risk of ice-wedge degradation was also moderate but protective layers were thicker: PL1=17.7 cm and PL3=8.6 cm. Average thicknesses of protective layers for T3 were 2.3 cm (PL2) and 2.0 cm (PL3), while for T5 they were 4.2 cm (PL2) and 2.6 cm (PL3). Such values correspond to high level of risk of ice-wedge degradation for both transects, though the risk of degradation is much higher at T3: along this transect, protective layers (of any thickness) were encountered only in 50% of ice wedges (which means that a half of wedges were degrading by the end of summer), while at T5 more than 90% of wedges had this layer, and most of them were protected by a thin intermediate layer.

Transect	Thaw depth, cm	Perma-frost table*, cm	Depth to massive ice, cm	Frozen protective layer (PL1/PL2)**, cm	Intermediate layer (PL3), cm	Actively degrading ice wedges***, %
T1, August 7-14, 2014	42.1 (n=27)	48.0 (n=27)	49.0 (n=22)	8.1 (PL1) (n=22)	1.2 (n=22)	9.1% (n=22)
T2, August 10-13, 2104	49.2 (n=16)	55.2 (n=16)	60.2 (n=13)	11.1 (PL1) (n=13)	5.0 (n=13)	0% (n=13)
T3, September 18-22, 2015 (PL1=PL2)	54.7 (n=12)	54.9 (n=12)	56.9 (n=12)	2.3 (PL2) (n=12)	2.0 (n=12)	50.0% (n=12)
T5, September 20-21, 2015 (PL1=PL2)	54.5 (n=13)	56.9 (n=13)	56.2 (n=11)	4.2 (PL2) (n=11)	2.6 (n=11)	9.1% (n=11)
Jorgenson's study area (~undisturbed), June 9-14, 2011; July 22-27, 2012	42.2 (n=39)	47.5 (n=83)	56.0 (n=83)	17.7 (PL1) (n=39)	8.6 (n=83)	0% (n=39)

* 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)
*** Percent of boreholes drilled between late July and mid-September, which encountered ice wedges actively degrading on the day of drilling (PL1=0)

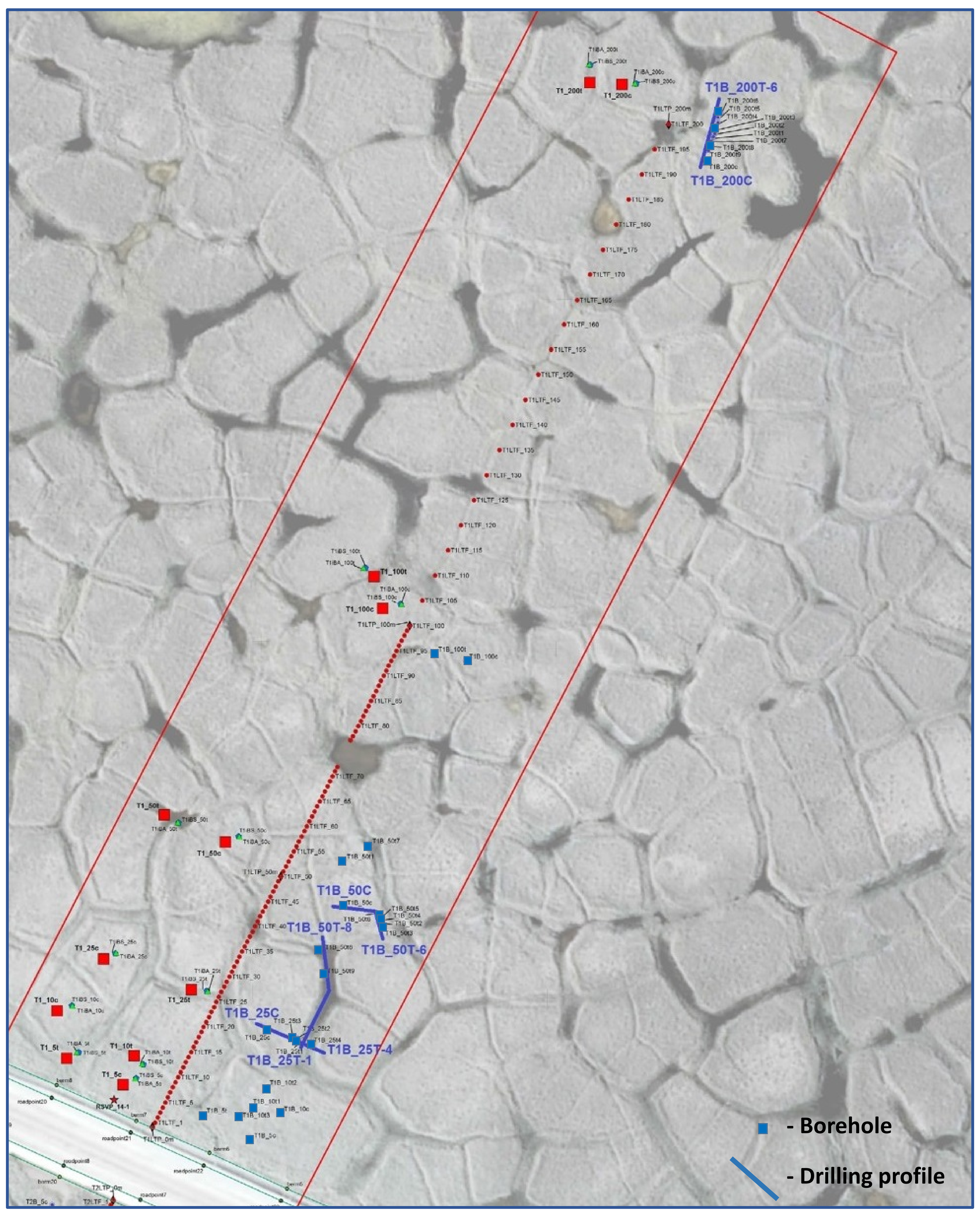


Figure 7. Location of boreholes and drilling profiles, Colleen Site A, transect T1.

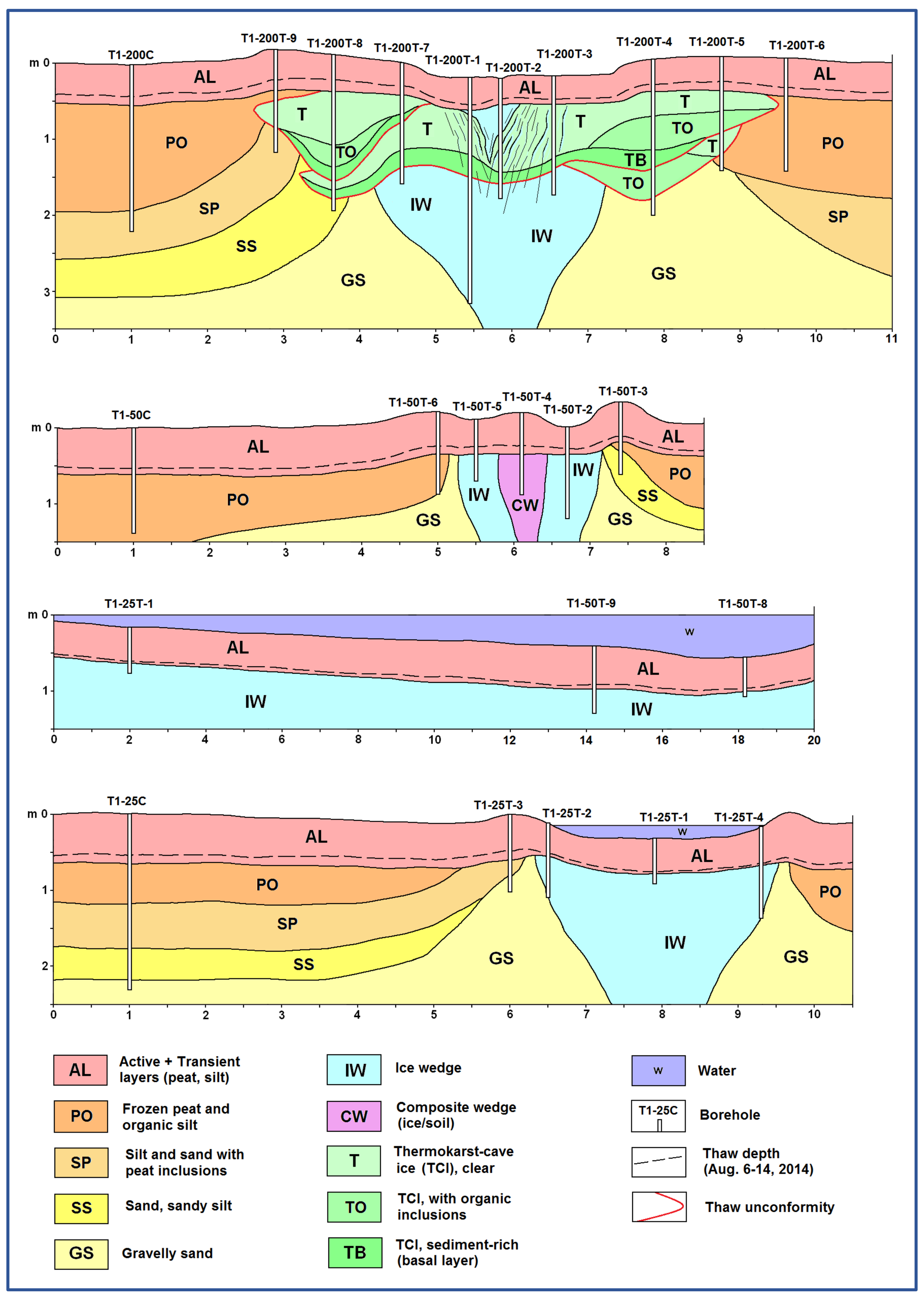


Figure 8. Drilling profiles, Colleen Site A, transect T1.

Conclusions

❑ The processes of ice-wedge degradation and stabilization are regulated by structure, properties, and thicknesses of soil layers above ice wedges, which include the active, transient, and intermediate layers. Occurrence of the intermediate layer indicates permafrost aggradation above ice wedges, which provides their long-term stability.

❑ Despite a strong influence of the infrastructure on the active layer and the upper permafrost stability through changes in hydrology and surface conditions, ice-wedge degradation in the study area is a reversible process, which was confirmed by our studies.

❑ Although thermokarst is usually more severe in flooded areas, higher plant productivity, more litter, and mineral material (e,g, road dust) accumulating in the troughs lead to formation of the intermediate layer, which protects ice wedges from further thawing. As a result, ice wedges under the deep water-filled troughs along T2 transect (initial degradation of ice wedges in this area was probably related to the flooding of the southwest side of the Spine Road triggered by the road construction) are more stable at the present time than the wedges along T1 transect, which had not been affected by flooding.

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