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

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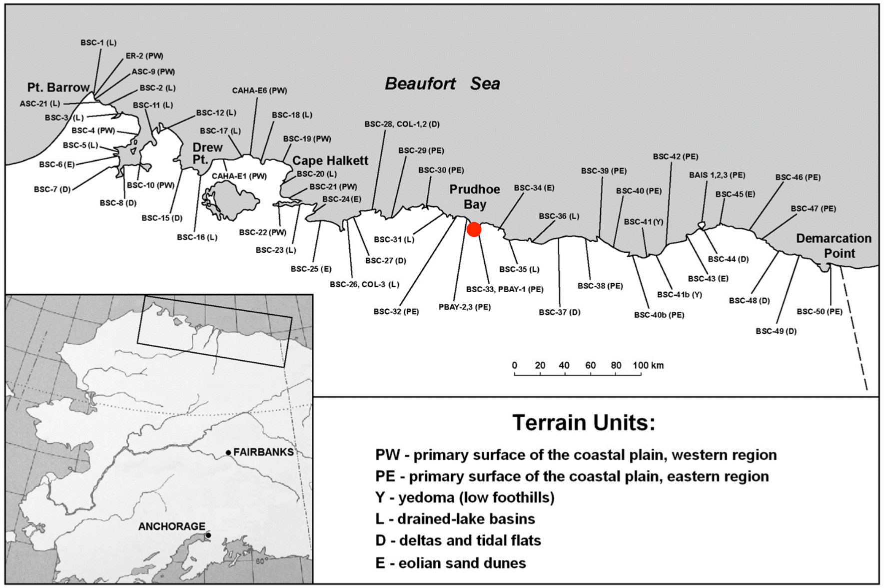
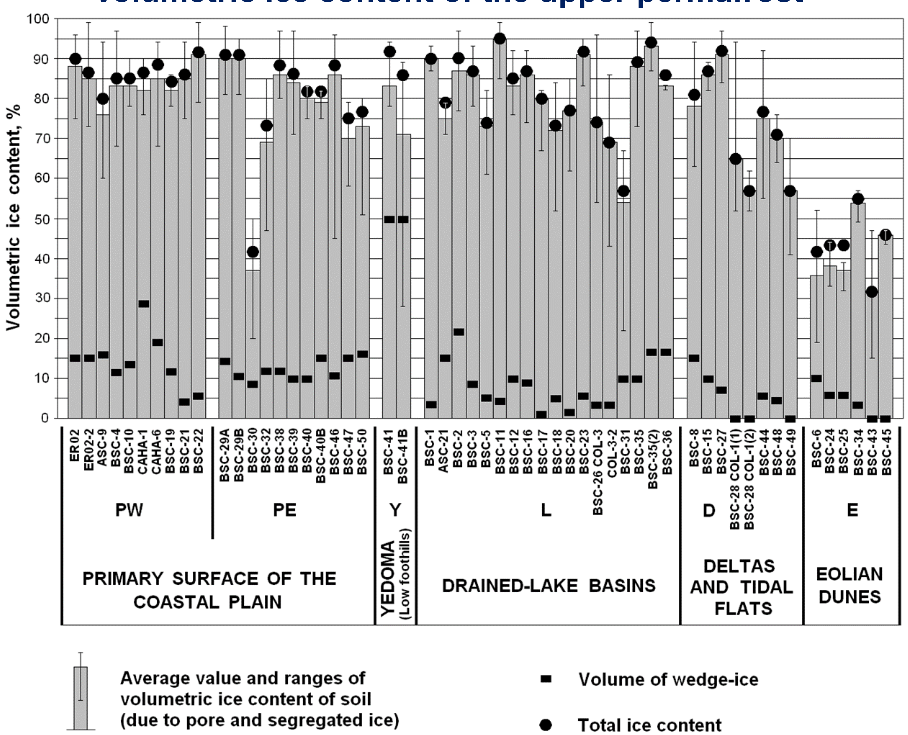
ARCTIC CHANGE 2014, RATIC workshop, December 9

Location of field sites (2005-2008), Beaufort Sea coast



Volumetric ice content of the upper permafrost

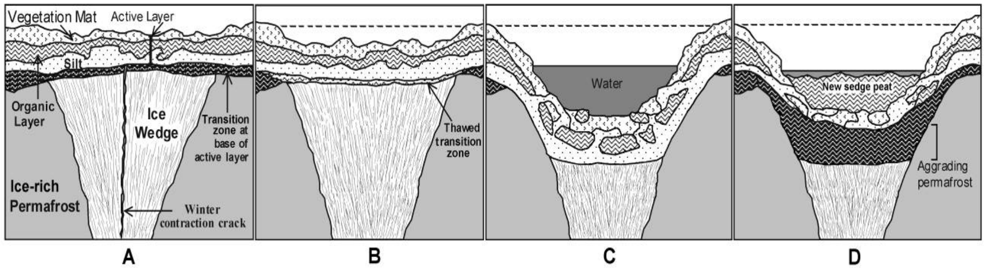


Wedge-ice content varies in different landscapes of the Arctic Coastal Plain from 0-5% (eolian and deltaic landscapes) to 15-30% (primary surface of the Coastal Plain and drained-lake basins), with average value of about 11% for the entire coast. The total average ground-ice content (due to wedge, segregated,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

Kanevskiy, M., Shur, Y., Jorgenson, M.T., Ping, C.-L., Michaelson, G.J., Fortier, D., Stephani, E., Dillon, M., and Tumskoy, V. 2013. Ground ice in the upper permafrost of the Beaufort Sea Coast of Alaska. *Cold Regions Science and Technology* 85, 56-70.

Main stages of ice-wedge degradation and stabilization

A – undisturbed terrain with undegraded ice wedge
B – initial degradation
C – advanced degradation
D – advanced stabilization

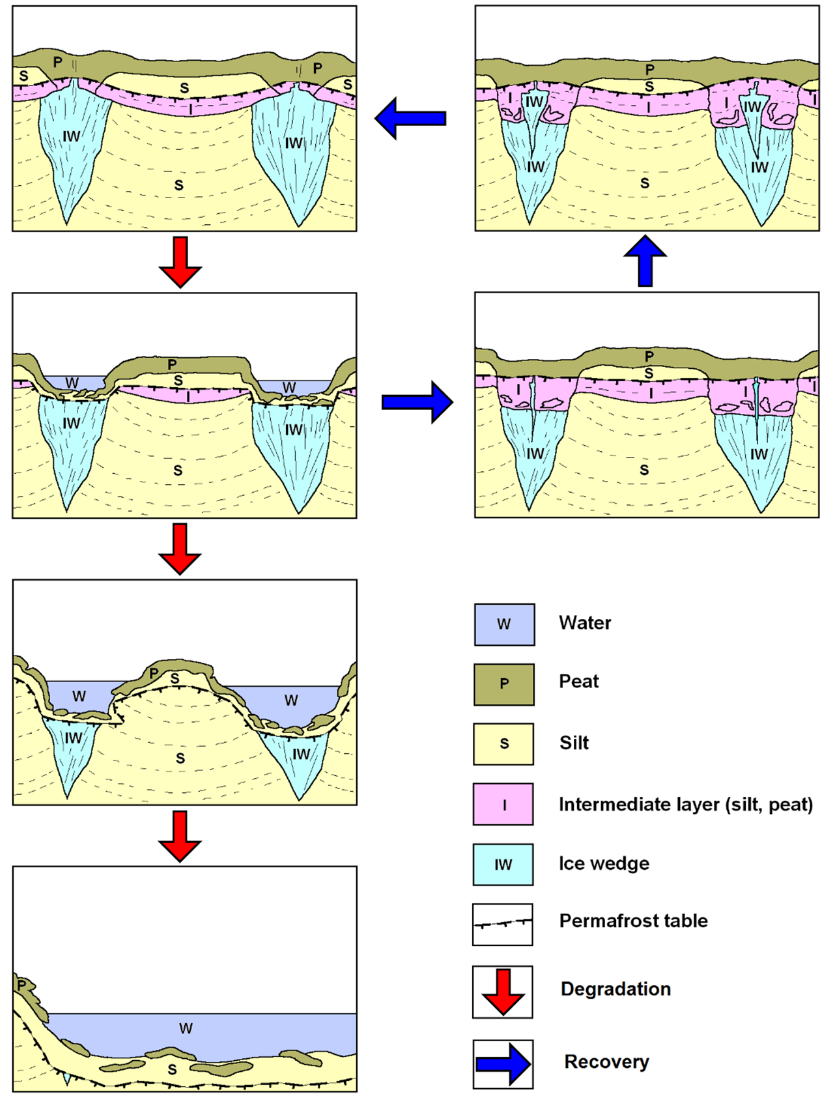


Jorgenson, M.T., Shur, Y.L., and Pullman, E.R. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. *Geophysical Research Letters* 33, L02503, doi:10.1029/2005GL024960.

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. Accumulation of organic matter in the troughs developing on top of degrading wedges eventually leads to decrease in the active-layer thickness and formation of the ice-rich intermediate layer (Shur 1988), protecting ice wedges from further degradation. In the areas with cold climate, new generation of ice wedges start forming after termination of 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.

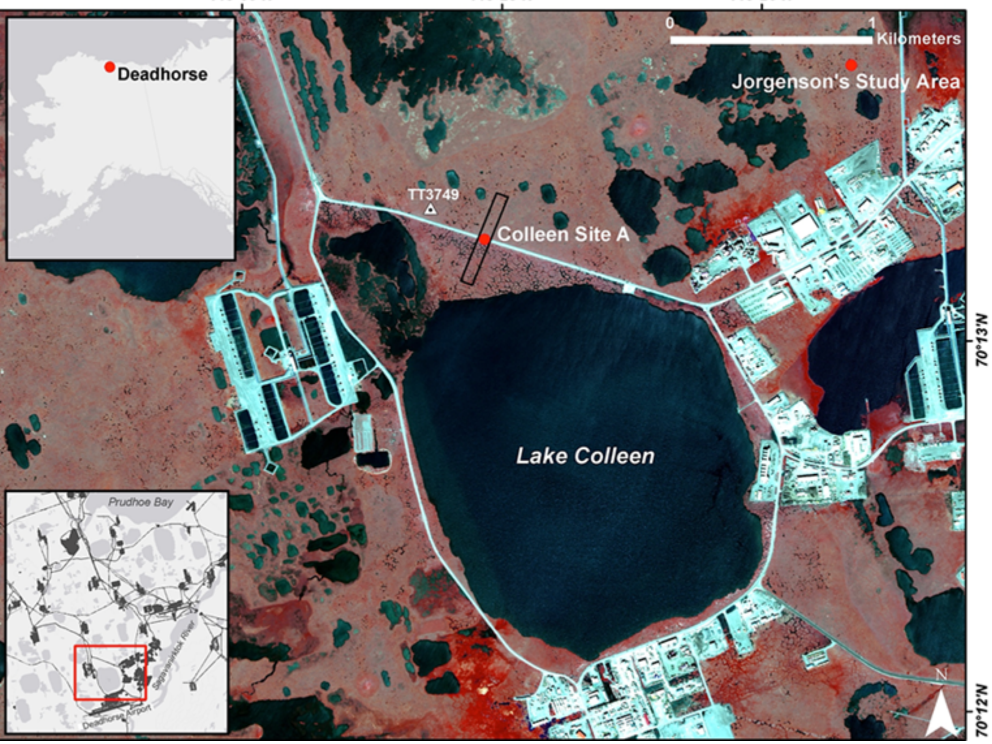
The second (irreversible) scenario (red arrows) usually occurs when the central parts of the ice-wedge polygons are also affected by thermokarst as a result of the loss of the protective organic layer. A further thermokarst development results in the continuing ground subsidence, ponding of surface with 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.

Conceptual model of the ice-wedge degradation and stabilization



Raynolds, M.K., Walker, D.A., Ambrosius, K.J., Brown, J., Everett, K.R., Kanevskiy, M., Kofinas, G.P., Romanovsky, V.E., Shur, Y., and Webber, P.J. 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. Global Change Biology 20 (4), 1211-1224, doi: 10.1111/gcd.12500.

Lake Colleen study area



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 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);

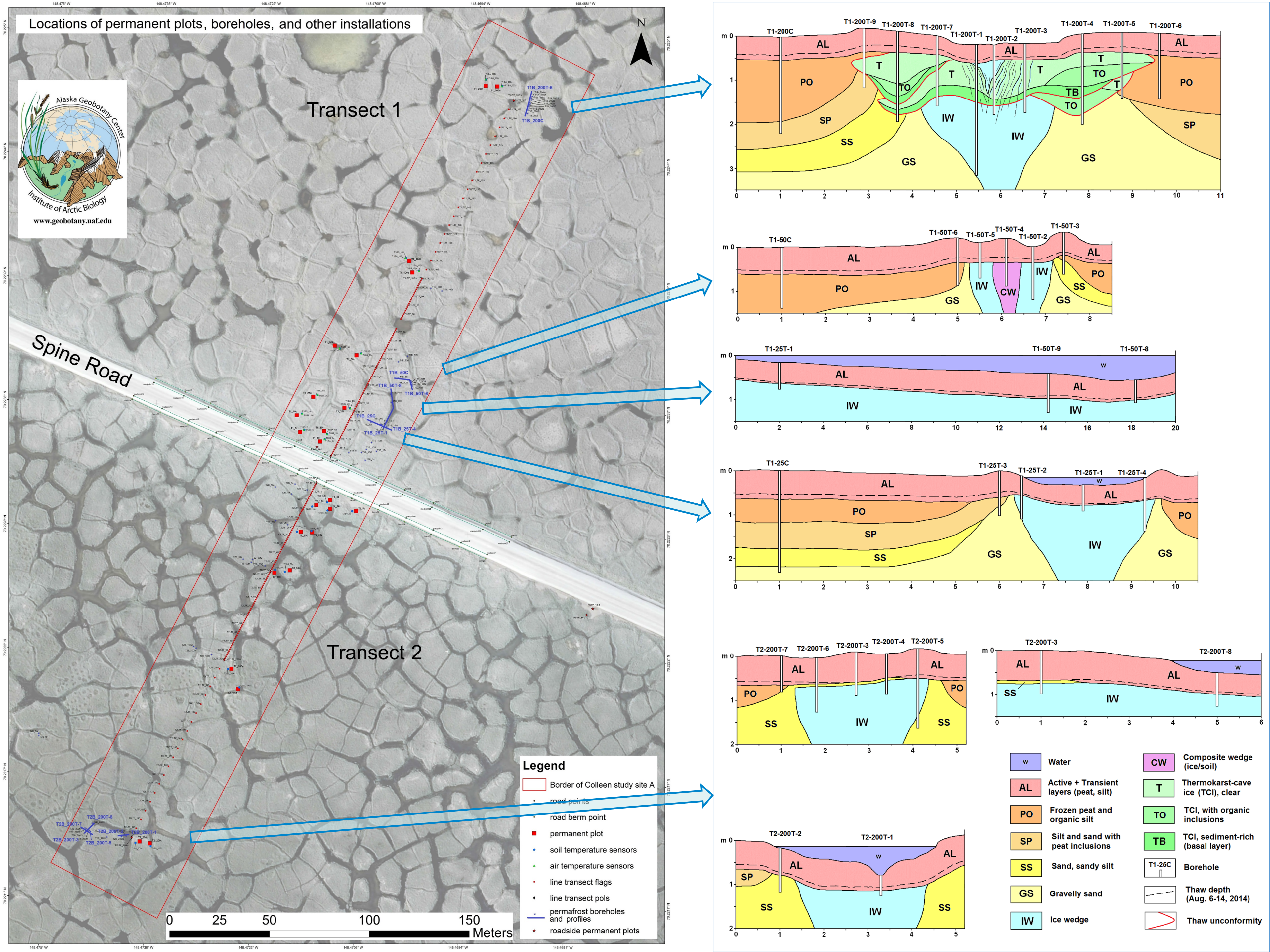
(2) Transient layer and the frozen part of the active layer (peat, organic silt, silt, relatively ice-poor), including, 6-12 cm thick, 8.3 cm average, GMC=130±77% (n=9);

(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).

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).



Locations of permanent plots, boreholes, and other installations
Transect 1
Transect 2
Spine Road
Alaska Geobotany Center
Institute of Arctic Biology
www.geobotany.uaf.edu
N
Legend
Border of Colleen study site A
road points
road berm point
permanent plot
soil temperature sensors
air temperature sensors
line transect flags
line transect pols
permafrost boreholes and profiles
roadside permanent plots
0 25 50 100 150 Meters
T1B_200T-6
T1B_200C
T1B_50C
T1B_50T-6
T1B_25C
T1B_25T-4
T1B_25T-1
T2B_200T-7
T2B_200T-6
T2B_200T-3
T2B_200T-5
T2B_200T-1
T1-200C
T1-200T-9
T1-200T-8
T1-200T-7
T1-200T-1
T1-200T-2
T1-200T-3
T1-200T-4
T1-200T-5
T1-200T-6
T1-50C
T1-50T-6
T1-50T-5
T1-50T-4
T1-50T-2
T1-50T-3
T1-25T-1
T1-50T-9
T1-50T-8
T1-25C
T1-25T-3
T1-25T-2
T1-25T-4
T2-200T-7
T2-200T-6
T2-200T-3
T2-200T-4
T2-200T-5
T2-200T-8
T2-200T-2
T2-200T-1
m 0
W
Water
AL
Active + Transient layers (peat, silt)
PO
Frozen peat and organic silt
SP
Silt and sand with peat inclusions
SS
Sand, sandy silt
GS
Gravelly sand
IW
Ice wedge
CW
Composite wedge (ice/soil)
T
Thermokarst-cave ice (TCI), clear
TO
TCI, with organic inclusions
TB
TCI, sediment-rich (basal layer)
T1-25C
Borehole
Thaw depth (Aug. 6-14, 2014)
Thaw unconformity

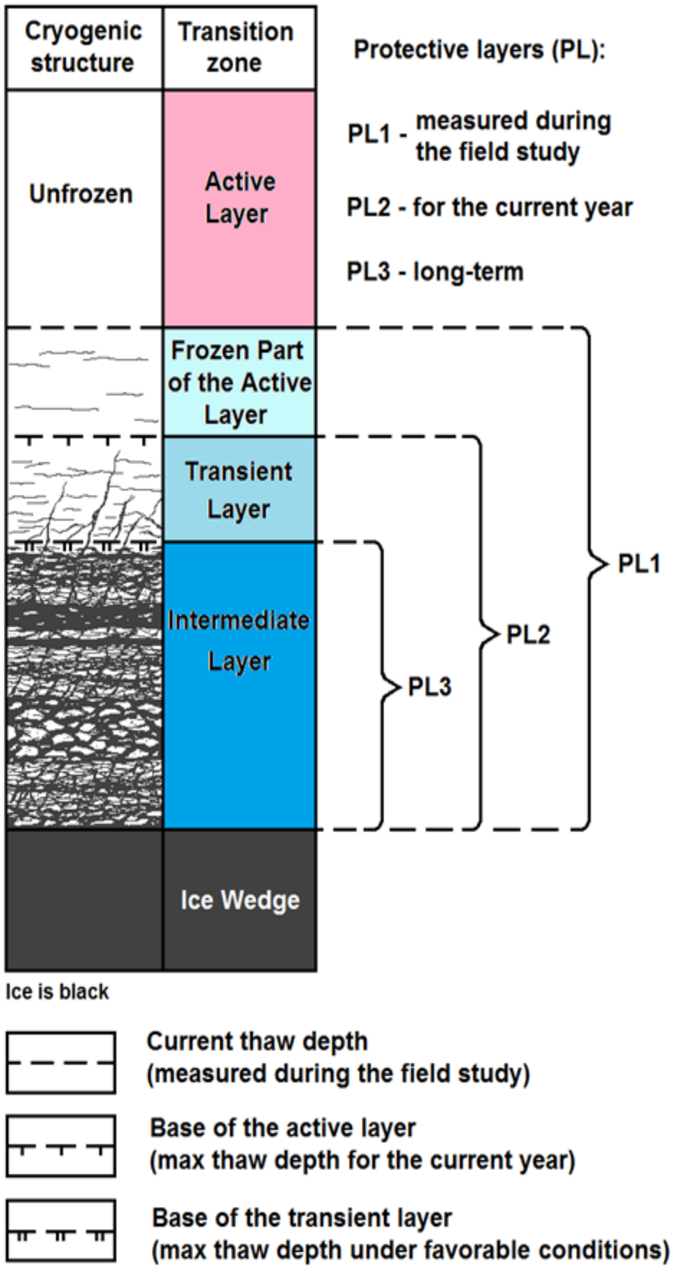
Boreholes drilled in ice-wedge troughs, intermediate layer above wedges

T1-50T-1, IL=8 cm

T2-5T-1, IL=12 cm

T2-100T-1, IL=6 cm

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	15-25	5-10	No degradation of the intermediate layer is expected during the current year
	20-30	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

Thicknesses of protective layers, Transects 1 and 2, Jorgenson's study area

Borehole(s)	Date	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	8/7/2014	-	51	60	60 WI	9	0	0
T1-10T-1	8/7/2014	1	58	58	58 WI	0	0	2.5
T1-10T-2	8/7/2014	-	56	56	61 WI	5	5	0.5
T1-25T-1, 2, 4 average	8/6/2014	0-15	44.3	46.3	46.3 WI	2.0	0	1.6
T1-50T-1	8/7/2014	-	55	65	73 WI	18	8	0
T1-50T-2, 4, 5 average	8/13/2014	-	35.3	45.7	45.7 WI	10.3	0	0
T1-50T-7	8/14/2014	30	43	43	43 WI	0	0	3.0
T1-50T-8	8/14/2014	49	41	44	44 WI	3	0	0.7
T1-50T-9	8/14/2014	31	51	56	56 WI	5	0	0.3
T1-100T-1	8/7/2014	-	44	45	45 WI	1	0	2
T1-200T-1, 2, 3, 7 ave.	8/8/2014	-	30.8	39.0	39.0 WI,TCI	8.3	0	0
Average for T1 (all boreholes)			42.1 (n=27)	48.0 (n=27)	49.0 (n=22)	8.1 (n=22)	1.2 (n=22)	
Average for T1 (all wedges, n=11)			**46.3**	**50.7**	**51.9**	**5.6**	**1.2**	
Transect T2								
T2-5T-1	8/10/2014	12	43	58	70 WI	27	12	0
T2-10T-1	8/10/2014	0	53	59	66 WI	13	7	0
T2-25T-1	8/10/2014	35	45	45	64 WI	19	19	0
T2-50T-1	8/11/2014	-	48	58	59 WI	11	1	0
T2-50T-3	8/11/2014	35	46	54	56 WI	10	2	0
T2-100T-1, 2 average	8/11/2014	0-8	46.5	54.5	59.0 WI	13.0	4.5	0
T2-200T-1	8/12/2014	70	28	36	36 WI	8	0	0
T2-200T-3, 4, 5, 6 ave.	8/12/2014	-	59.8	62.5	66.3 WI	6.5	3.8	0.3
T2-200T-8	8/13/2014	27	44	49	49 WI	5	0	0
Average for T2 (all boreholes)			49.2 (n=16)	55.2 (n=16)	60.2 (n=13)	11.1 (n=13)	5.0 (n=13)	
Average for T2 (all wedges, n=9)			**45.9**	**52.9**	**58.4**	**12.4**	**5.5**	
Average for Jorgenson's study area (undisturbed)	June 2011, July 2012		**42.2** (n=39, July 2012)	**47.5** (n=83)	**56.0** (n=83)	**17.7** (n=39)	**8.6** (n=83)	

CONCLUSIONS

- ❖ At the time of drilling (first half of August), a protective layer of frozen soil (PL1) 1- to 27-cm thick was observed above the majority of ice wedges.
- ❖ The ice-rich intermediate layer (PL3) up to 19-cm thick, which indicates relative stability of ice wedges, was detected in 13 of 35 boreholes which encountered massive-ice bodies.
- ❖ Only two ice wedges (Transect 1) experienced thawing at the time of drilling, but calculations indicate that by the end of the thawing season 6 more wedges will be affected by thermokarst (five of them are located along Transect 1).
- ❖ Ice-wedge degradation in most cases was triggered by increase in the active-layer thickness 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,
- ❖ Despite a strong influence of the road construction and heavy traffic on the upper permafrost stability, ice-wedge degradation is a reversible process.
- ❖ At present time the wedges along Transect 2 (even the wedges under the deep troughs filled with water) are more stable than the wedges along Transect 1, although thermokarst here was much more active just several years ago. This may be explained by very high rates of accumulation of dust and organic matter in the ice-wedge troughs.

This work was funded by the National Science Foundation (NSF grants ArcSEES 1233854 and ARC 1023623) with partial support from Bureau of Ocean Energy Management (BOEM) and Department of Interior (DOI) and NASA Land Cover Land Use Change (LCLUC) Program, Grant No. NNX14AD906.

Boreholes drilled in ice-wedge troughs, Transect 1

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)**	Inter-mediate layer (PL3)	Ice-wedge thawing, expected in 2014***, cm
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
T1-50T-1	8/7/14	118	trough	-	55	65	73 WI	18	8	0
T1-50T-2	8/13/14	86	trough	-	28	36	36 WI	8	0	0
T1-50T-3	8/13/14	95	rim	-	45	?	-	-	-	-
T1-50T-4	8/13/14	108	trough	-	43	55	55 CW	12	0	0
T1-50T-5	8/13/14	81	trough	-	35	46	46 WI	11	0	0
T1-50T-6	8/14/14	98	rim	-	45	56	-	-	-	-
T1-50T-7	8/14/14	81	trough	30	43	43	43 WI	0	0	3.0
T1-50T-8	8/14/14	51	trough	49	41	44	44 WI	3	0	0.7
T1-50T-9	8/14/14	88	trough	31	51	56	56 WI	5	0	0.3
T1-100T-1	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)	

* Top of the intermediate layer (based on analysis of cryostructures)

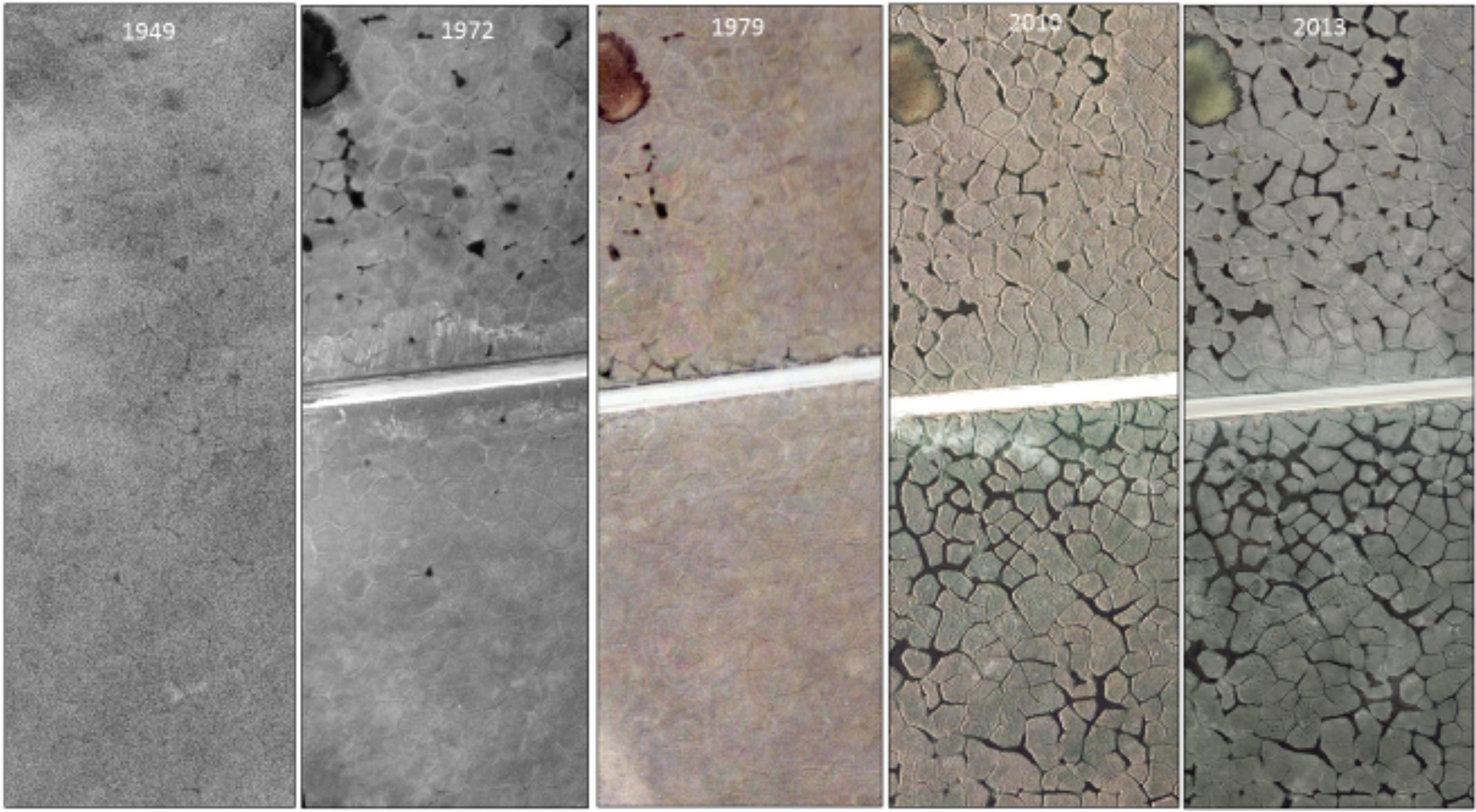
**Thickness of frozen soil layer on top of massive ice bodies on the day of drilling (includes the frozen part of the active layer, transient layer, and intermediate layer)

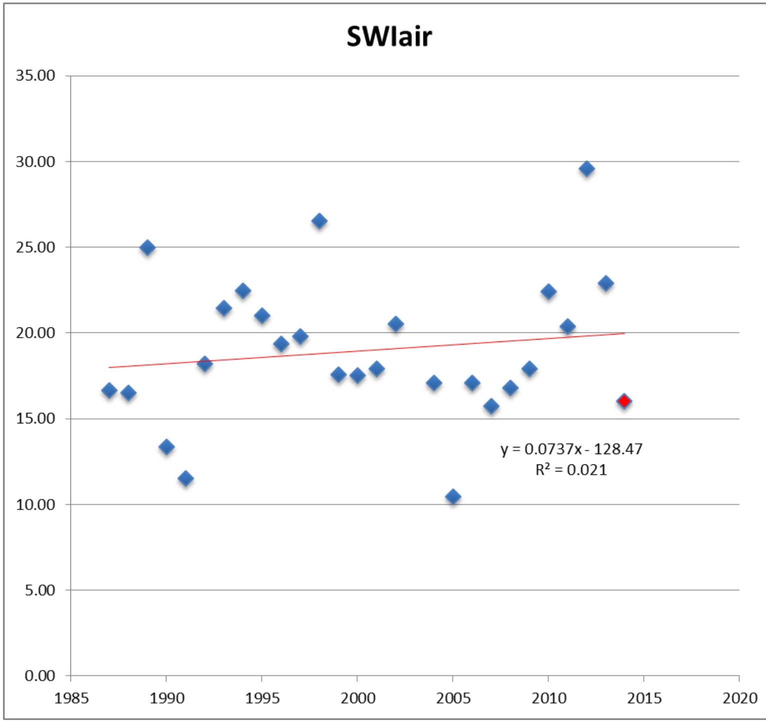
***Based on the Stefan equation

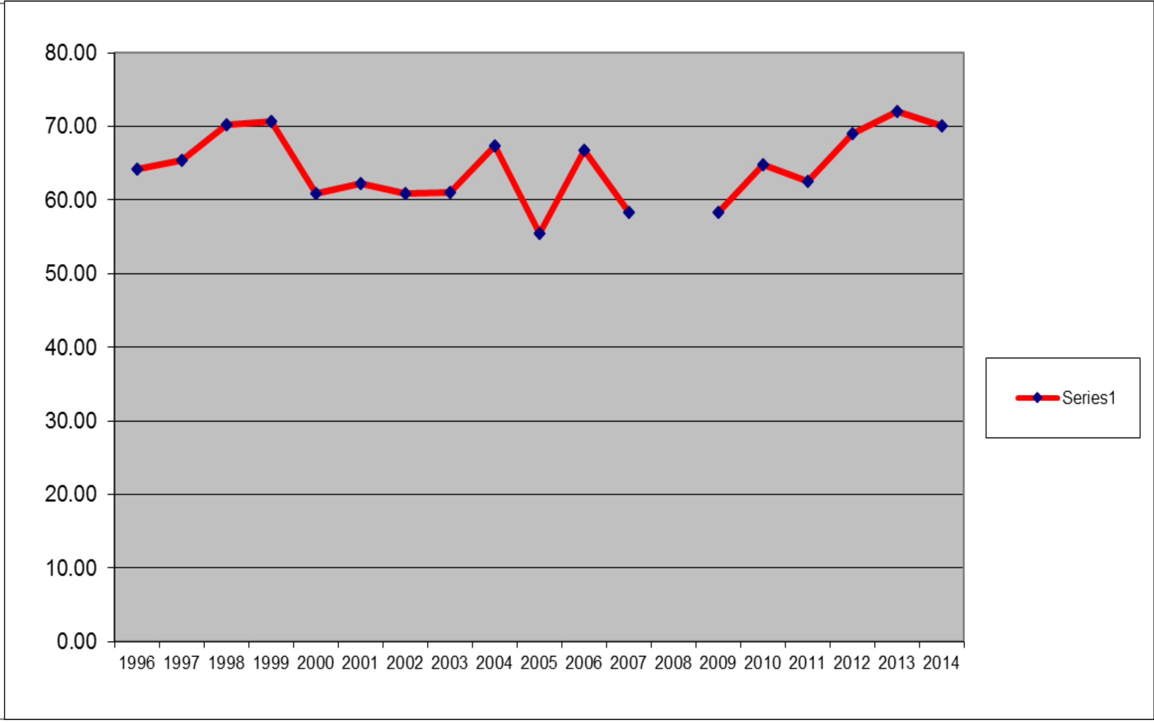
Boreholes drilled in ice-wedge troughs, Transect 2

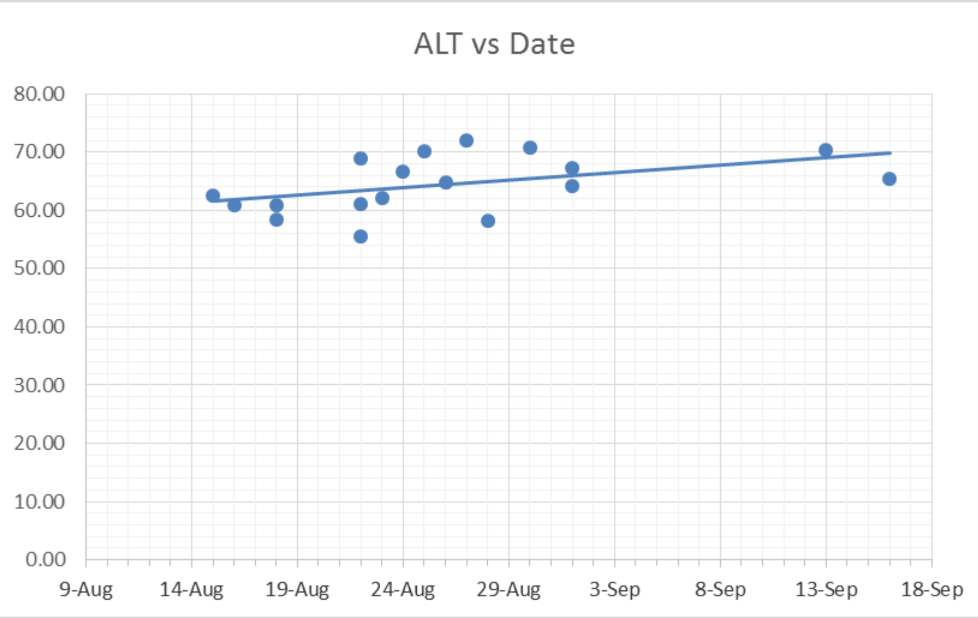
Borehole	Date	Bore-hole depth, cm	Location	Water depth, cm	Thaw depth, cm	Perma-frost table*, cm	Depth to massive ice, cm	Frozen protective layer (PL1)**, cm	Inter-mediate layer (PL3), cm	Ice-wedge thawing, expected in 2014***, cm
T2-5T-1	8/10/14	90	trough	12	43	58	70 WI	27	12	0
T2-10T-1	8/10/14	89	trough	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)	5.0 (n=13)	

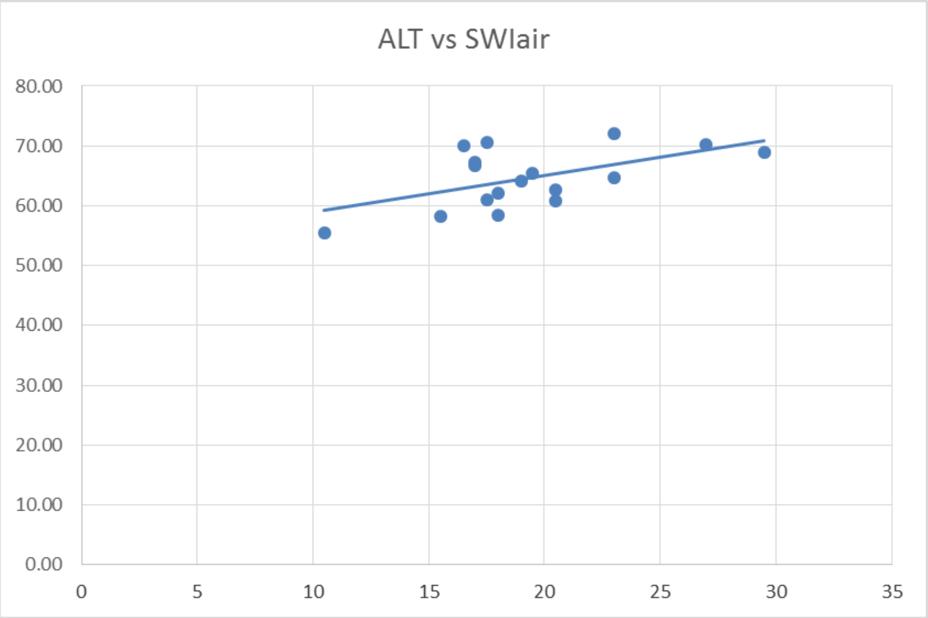
* Top of the intermediate layer (based on analysis of cryostructures)
** Thickness of frozen soil layer on top of massive ice bodies on the day of drilling (includes the frozen part of the active layer, transient layer, and intermediate layer)
*** Based on the Stefan equation


1949
1972
1979
2010
2013


SWIair
y = 0.0737x - 128.47
R² = 0.021


Series1


ALT vs Date


ALT vs SWIair