

Permafrost patch size in the sporadic discontinuous and isolated patches permafrost zones, southern Yukon and northern B.C.

Olivier Bellehumeur-Génier & Antoni G. Lewkowicz
Department of Geography – University of Ottawa, Ottawa, Ontario,
Canada



Challenges from North to South
Des défis du Nord au Sud

ABSTRACT

Little is known about permafrost patch size, trends and dynamics from the southernmost limit of discontinuous permafrost through to the boundary of continuous permafrost. This research focused on evaluating permafrost patch size and related variables along a 1400 km transect between Fort St. John, BC and Whitehorse, YT. Methods used included electrical resistivity tomography (ERT), climate data collection, active layer measurement, analysis of historic aerial photos, and on-site near-vertical aerial imaging. Field observations indicate that discrete permafrost patches are in the order of 10^1 - 10^3 m² in area and that permafrost boundaries at a given site are influenced by microtopography, slope, drainage, substrate, and antecedent disturbance. Ongoing data analysis is expected to establish whether spatial trends in permafrost patch size and characteristics exist along the transect or whether local factors are the primary controls.

RÉSUMÉ

Il existe très peu de recherche sur les tendances dans la grandeur, la distribution et la dynamique des parcelles du pergélisol, de la limite méridionale du pergélisol discontinu jusqu'à la limite du pergélisol continu. Cette recherche est axée sur l'évaluation des dimensions des parcelles de pergélisol le long d'un transect de 1400 km entre Fort St-John, C-B et Whitehorse, YT. La méthodologie a consisté de tomographie à résistivité électrique (TRE), d'analyses de données climatiques, de mesures de la profondeur de la couche active, d'observations de photographies aériennes historiques et d'analyses de photos aériennes contemporaines. Les observations de terrain suggèrent que les parcelles de pergélisol dans la région ont une superficie de l'ordre de 10^1 - 10^3 m² et que les limites du pergélisol sont influencées par la microtopographie, la pente, le drainage, le substrat et les perturbations passées. L'analyse des données devrait établir si des tendances spatiales dans la taille des parcelles de pergélisol et ses caractéristiques existent le long du transect ou si les facteurs locaux sont les contrôles primaires.

1 INTRODUCTION

Permafrost patch size and spacing in the discontinuous permafrost zones are significant for upscaling from point measurements of ground temperatures and active layer depths, such as those in the Global Terrestrial Network on Permafrost, and hence for the validation of regional or global climate models. Little is known, however, about fine-scale permafrost characteristics from the outer margin of the isolated patches zone through to the boundary between extensive discontinuous and continuous permafrost. This research focused on initiating such measurements along a southeast to northwest oriented transect along the Alaska Highway between Fort St. John, BC and Whitehorse, YT.

In 1964, Roger Brown undertook a survey along the Alaska Highway to identify permafrost bodies and found permafrost at about 55% of the sites examined (Brown, 1967). These sites were generally north-facing, poorly drained, and had a thick organic mat. The survey was repeated in 2007 and 2008 in order to investigate the changes in permafrost along the transect (James et al. 2013). MAAT had increased by 1.5°C to 2.0°C since the mid-1970s, the active layer appeared to be thicker than in 1964 and permafrost degradation had occurred at almost half of the permafrost sites examined by Brown (James et al. 2013). Lewkowicz et al. (2011) measured TTOP temperatures at some of the sites and observed that they

were generally very close to 0°C. They concluded that if temperatures continue to rise, permafrost would actively degrade. It was also suggested that the presence of permafrost might be responsible for the large thermal offsets observed at some sites (Lewkowicz et al. 2011). Miceli (2012) used fixed electrode arrays at 10 of Brown's surveyed sites to examine seasonal variations in electrical resistivity. She found that permafrost thickness was generally less than 15 m thick and rarely exceeded 25 m.

The present study builds on this earlier work but focuses on assessing the dimensions of permafrost bodies along the transect.

2 STUDY AREA

The study area extends along 1400 km of the Alaska Highway corridor, traversing the entire isolated patches zone and much of the sporadic discontinuous permafrost zone (Heginbottom et al. 1995). Mean annual air temperatures vary between 2°C and -4°C (Wahl et al. 1987; James et al. 2013) and the entire study route is forested with the exception of poorly drained sites, alluvial fans and sites altered by human activity. Most of the 10 field sites distributed along the transect have a cover of black spruce (*Picea mariana*), typically stunted (James et al. 2013; Brown 1967). Other species found in the study area are white spruce (*Picea glauca*), tamarack (*Larix*

laricina), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), paper birch (*Betula papyrifera*), dwarf birch (*Betula nana*) and willow. Mosses, lichens, sedges and labrador tea (*Rhododendron groenlandicum*) form ground covers (James et al. 2013; Miceli 2012).

3 METHODS

Permafrost was present at all ten sites in 1964 (Brown 1967) and has persisted through to the present (James 2010). Each site is set up with three monitoring stations located 20-40 m apart, equipped with data loggers recording surface temperature and ground temperatures within the active layer at two hour intervals. The main station is also equipped with an air temperature logger, and all three stations record snow depths using stakes with stacked iButtons (Lewkowicz 2008). Some sites also have a shallow borehole (up to 5 m deep) in which ground temperatures are continuously measured. Climate records presented cover three years from October 1, 2010 to September 30, 2013, but logger malfunction or damage by animals resulted in loss of data at some sites. In these cases, correlations for daily air temperature were undertaken between site data and nearby sites or Environment Canada stations. In all cases, r^2 values for the correlations were greater than 0.97. Snow cover records include a fourth year of data and run from 2010-2011 to 2013-2014.

A 120 cm long frost probe was used to measure the depth to the frost table and confirm the presence of permafrost. Extensive probing was done along the ERT transect at 1 m intervals, to verify the geophysical interpretations. Probing was undertaken elsewhere at each site where the environmental settings were judged most likely to produce permafrost.

An Unmanned Aerial Vehicle (UAV) was used to obtain aerial images of the sites. The UAV was the DJI Phantom 2 Vision+ quadcopter, equipped with a 14 megapixel camera, with a resolution of 4384 x 3288, two selectable fields of view (85°/100°) and a maximum gimbal tilt of 90° (DJI 2014). Each image was obtained at an altitude of approximately 100 m above the ground and at a gimbal angle of 90°. Reference points with known GPS coordinates were placed on the ground to help in geo-referencing the images. The 2014 images were compared to historic air photos from the National Air Photo Library in Ottawa to determine if visible change has occurred at the sites.

The main technique used to define permafrost patch boundaries was electrical resistivity tomography (ERT), which is a geophysical technique that measures subsurface resistance to a DC electrical current (Hauck and Kneisel 2008). During ERT measurements, electrical current is transmitted into the ground using two current electrodes and two potential electrodes measure the output voltage which is recorded (Loke 1999; Hilbich et al. 2008). An ABEM Terrameter LS profiling system was used with a Wenner electrode array and 1 or 2 m spacing of the electrodes. The range of penetration depths

depends on the spacing and length of the array and varied from approximately 6 to 25 m. The field measurements were inverted using RES2DINV software (Loke et al. 2003) using the robust inversion model which copes best with the rapid changes that occur at the boundaries of frozen and unfrozen materials. Model iterations were stopped after the RMS error fell below 5%, or at the 5th iteration, whichever came first. The images presented use a uniform resistivity scale with cold (blue) colours to represent high resistivities and warm (red) colours to represent low resistivities. The typical threshold between frozen and unfrozen soils in the region is 300 to 800 Ω m but the actual value varies from site to site.

The various datasets were combined in order to estimate the boundaries of the permafrost patches identified at each site. Permafrost patch area was calculated assuming the patches to be elliptical in shape.

4 RESULTS

Here we present the results from three of the sites that represent the southern part (MP 286), the middle (MP 681) and the northwest end (MP 825) of the transect.

4.1 MP 286

MP 286 (Figure 1) is located 14 km south of Fort Nelson, BC and an elevation of 417 m above sea level (asl). The site is in open forest with variable tree cover. One part of the site has hummocky microtopography where vegetation is mainly moss (including sphagnum), lichens and labrador tea with scattered trees and shrubs. Spruce and tamarack are the dominant species in the forested area (James 2010).

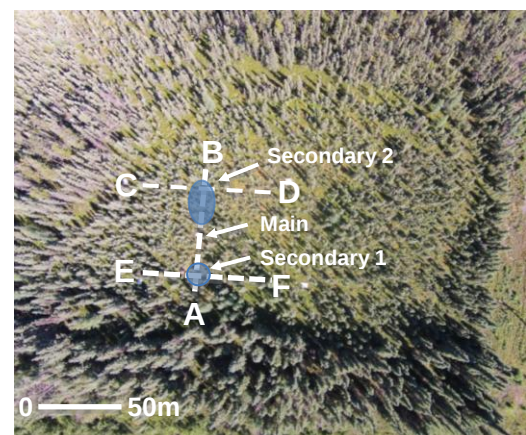


Figure 1. Aerial image of MP 286 in August 2014 showing the three ERT transects: Permanent array (A-B), ERT 2 cross-section (C-D,) and ERT 3 cross-section (E-F). The shaded area represents the interpreted permafrost patch. The main and secondary climate stations are marked. Scale is approximate.

The mean annual air temperature (MAAT) averaged -0.9°C and varied between a maximum of 0.3°C and a

minimum of -2.0°C (Table 1). The Mean Annual Ground Surface Temperatures (MAGST) at all three stations were above 0°C . The Mean Annual Ground Temperature (MAGT) within the active layer was slightly above 0°C at secondary station 1 (but within the range of error of 0°C) and slightly below 0°C at secondary station 2. Surface offsets averaged 2.3°C at secondary 1 and 3.3°C at secondary 2 while average thermal offsets were -1.3°C and -2.6°C , respectively. Snow cover at the site (see Table 2 for snow depth day data) varied from a minimum of 7400 snow depth days (SDD) to a maximum of 13445 SDD between 2010-2011 and 2013-2014. The winter with the highest snow cover was 2012-2013 with an average 11143 SDD and the main station had the most snow with an average 8857 SDD.

The ERT survey along the 40 m permanent array at MP 286 (Figure 2.1) shows considerable variability in the near surface and two bodies of resistivities exceeding 300

$\Omega\text{ m}$ are present. The layer of lower resistivities immediately below the surface is thin and represents the active layer. The high resistivity bodies are shallow, small and relatively well defined and correspond to where probing identified a frost table at a depth of less than 120 cm. The two cross-sections ERT 1 (Figure 2.2) and ERT 2 (Figure 2.3) show similar results, with a single shallow body of higher resistivity. The high resistivities just below the surface at the west end of ERT 2 are interpreted as seasonal frost due to their thin and shallow nature.

4.2 MP 681

MP 681 (Figure 3) is located 65 km west of Watson Lake, YT at an elevation of about 850 m asl. The site has an uneven topography with a ground cover of mosses, lichens, and labrador tea, willow and birch shrubs, with black spruce and tamarack. The soil is a moderately

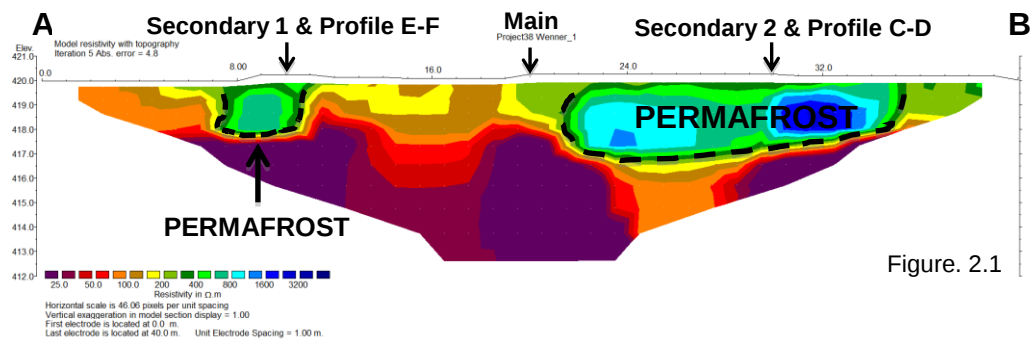


Figure. 2.1

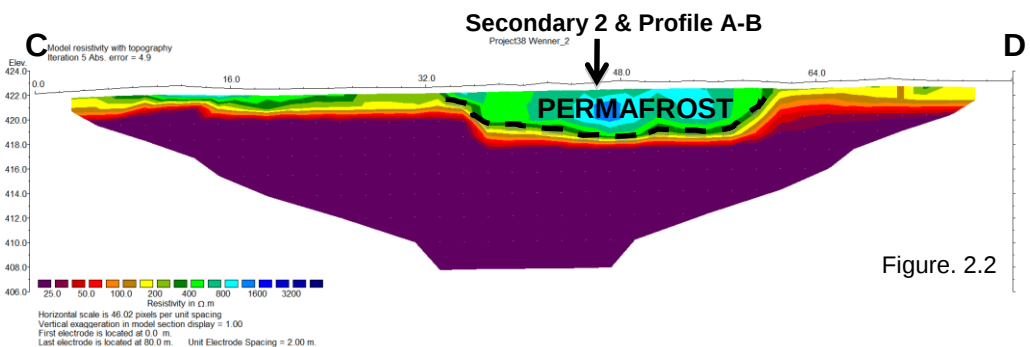


Figure. 2.2

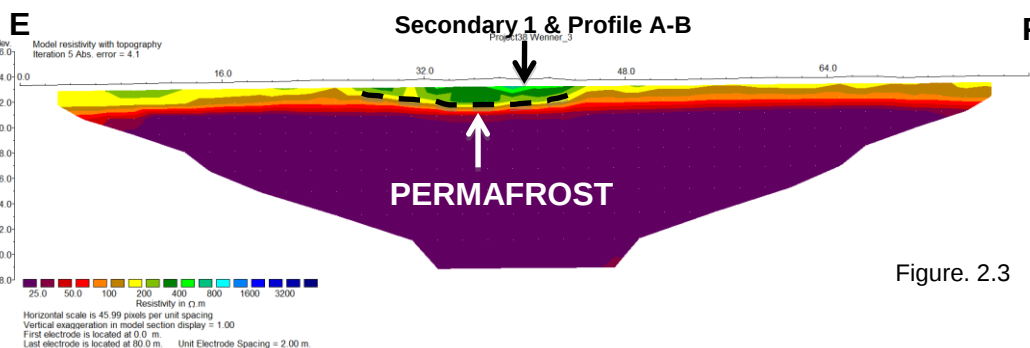


Figure. 2.3

Figure 2. Modelled ERT inversion profiles at MP 286 with dashed lines representing inferred permafrost boundaries: 2.1-permanent array; 2.2-ERT 2; 2.3-ERT 3. The frozen/unfrozen boundary is taken to be 300 $\Omega\text{ m}$ at this site.

Table 1: Climate data for the three study sites along the Alaska Highway corridor (2010-2011 to 2012-2013). Annual averages are for October 1 to September 30 of the years shown. Empty cells represent missing data.

Site	Years	Secondary Station 1		Main Station			Secondary Station 2	
		MAGST (°C)	MAGT (°C)	MAGST (°C)	MAGT (°C)	MAAT (°C)	MAGST (°C)	MAGT (°C)
MP 286	2010-11	1.0	-0.1	1.7		-1.2	1.8	-0.2
	2011-12	2.0	0.3	2.5		0.3		
	2012-13	1.2	0.1			-2.0 ^a	3.0	-0.2
	Average	1.4	0.1	2.1		-0.9	2.4	-0.2
MP 681	2010-11	1.0	-0.3	0.5	-0.5	-3.3 ^b	1.4	0.9
	2011-12	1.2	0.4	0.4	-0.3	-3.0 ^c	1.4	0.4
	2012-13	2.6			0.0	-3.7 ^c	2.3	1.1
	Average	1.6	0.0	0.5	-0.3	-3.3	1.7	0.8
MP 825	2010-11			1.4		-1.5 ^d	1.0	0.0
	2011-12	2.9	1.8	1.9		-0.2		
	2012-13	2.9	1.4	1.3		-1.3	1.6	0.1
	Average	2.9	1.6	1.5		-1.0	1.3	0.1

^aMissing data from June 5 to Sept. 30, 2013 estimated by correlation with Fort Nelson Environment Canada station.

^bMissing data in 2010-2011 estimated through correlation with Watson Lake Environment Canada station and blended with reliable data from MP 681.

^cMissing data in 2011-2012 and 2012-2013 estimated through correlation with MP 597 station (neighbouring site) and blended with reliable data from MP 681.

^dMissing data from August 1 to August 18, 2011 estimated by correlation with Fort Nelson Environment Canada station.

Table 2: Snow covers at three sites along the transect (2010-2011 to 2013-2014). Values were derived from iButton stakes (Lewkowicz 2008) and are expressed in Snow Depth Days (SDD) (cm d).

Site	Year	Secondary Station 1 (SDD)	Main Station (SDD)	Secondary Station 2 (SDD)	Average
MP 286	2010-2011	7400	8680	7932	8004
	2011-2012	2915	6610	5090	4872
	2012-2013	9355	10630	13445	11143
	2013-2014	6705	9508	8788	8333
	Average	6594	8857	8814	8088
MP 681	2010-2011	8476	8159	8892	8509
	2011-2012	7723	7740	9690	8384
	2012-2013	9565	11195	10453	10404
	2013-2014	7603	11670	9880	9718
	Average	8342	9691	9729	9254
MP 825	2010-2011	5504	5931	5786	5740
	2011-2012	5075	4965	4645	4895
	2012-2013	5320	3560	4738	4539
	2013-2014	7553	5663	4970	6062
	Average	5863	5030	5035	5309

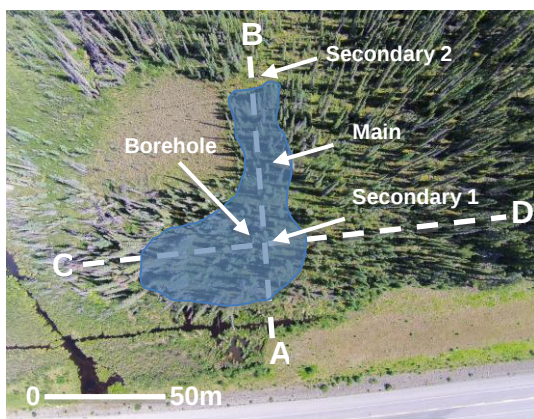


Figure 3. Aerial image of MP 681 in August 2014 showing the two ERT transects: the permanent array with extension (A-B) and ERT 2 cross-section (C-D). The shaded area represents the interpreted permafrost patch. The main and secondary climatic stations and the borehole are marked. Scale is approximate.

cohesive silt, with a thick organic layer (James 2010).

MP 681 is amongst the coldest sites along the transect with a MAAT of -3.3°C and relatively little inter-annual variation (Table 1). The MAGST values at the three stations are above 0°C in all years with the two secondary stations averaging about 1°C warmer than the main station. MAGT values average slightly below 0°C at the main station, 0°C at secondary station 1, and well above 0°C at secondary station 2. The temperature envelope at the borehole (Figure 4) shows an active layer less than 1 m deep with a very shallow depth of zero annual amplitude (~ 2 m) where the temperature is -0.1°C . The main station at MP 681 had the greatest snow cover with an average of 9728 SDD while secondary station 2 had the least with an average of 8341 SDD (see Table 2). The year with the greatest snow cover was 2012-2013 while 2010-2011 had the least.

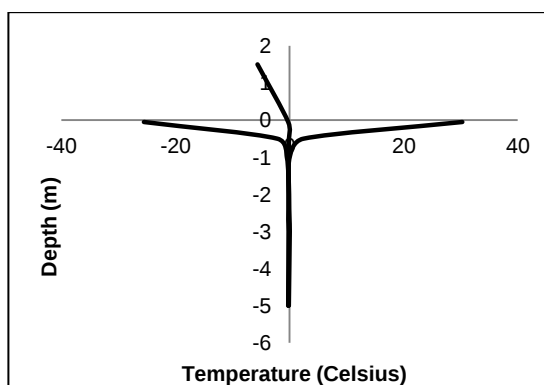


Figure 4. Temperature envelope for the borehole at MP 681 (2013-2014). The temperature at the base of the borehole at 5 m is -0.2°C .

The permanent ERT array with extension (Figure 5.1) shows low resistivities at both ends of the profile where it intersects shallow standing water. A high resistivity body with values exceeding $800 \Omega \text{ m}$ is present in the middle extending to a depth of about 8 m and is overlain by a thin discontinuous layer with lower resistivities. The ERT 2 cross-profile exhibits low resistivities in a bog near its start (C in Figure 5.2). There is a high resistivity body, with values above $800 \Omega \text{ m}$ in the middle of the profile extending to a maximum depth of about 12 m. This terminates at a small depression and resistivities further along the profile are much lower as the terrain gradually rises. The high resistivity bodies correspond to locations where a frost table was probed within 120 cm of the surface. The ground temperature at 5 m depth in the borehole is constant at -0.2°C .

4.3 MP 825

MP 825 (Figure 6) is located approximately 120 km east of Whitehorse, YT at an elevation of 720 m asl. The terrain rises gradually along the fixed array and superimposed on this gradient is an undulating surface within a dense forest cover that includes numerous fallen trees. The vegetation comprises black spruce, labrador tea, mosses and shrubs. The soil is cohesive and consists of silt and sand with some gravel (James 2010).

The MAAT at MP 825 averages -1.0°C , with a maximum of -0.2°C recorded in 2011-2012 (Table 1). The MAGST at the main station averages 1.5°C and is almost the same at secondary station 2 (1.3°C) which gives average surface offsets of 2.5°C and 2.3°C respectively. Secondary station 1 is more than a degree warmer at the ground surface, averaging 1.9°C . The MAGT at 1 m depth at the main station is 0.1°C giving a thermal offset of -1.4°C . The temperature envelope from MP 825 borehole (Figure 7) shows values of just above 0°C to $+0.1^{\circ}\text{C}$ year-round between depths of 1 m and 1.75 m, while the ground freezes and thaws annually to at least 0.5 m and remains continuously cryotic at depths of 2 to 4 m (the base of the borehole). Secondary station 1 has the greatest snow cover with an average 5863 SDD (see Table 2) while the main station and secondary station 2 average about 15% fewer SDD. The year with the greatest snow cover was 2013-2014 with 6062 SDD while the previous year was the least, averaging 4539 SDD.

The three ERT profiles show discrete bodies of higher resistivity ($>300 \Omega \text{ m}$) extending from 1 m to 5-10 m deep (Figure 8). A quasi-continuous low resistivity layer occurs just beneath the surface and lower resistivities also occur at depth. Probing encountered a frost table at depths of less than 120 cm at locations where the surface low resistivity layer was thin or absent, but not at all locations where the high resistivity layer was apparent at depth.

5 DISCUSSION

Two discrete permafrost patches are present at MP 286, varying from 2 to 4 m thick. Secondary station 1 had the lowest

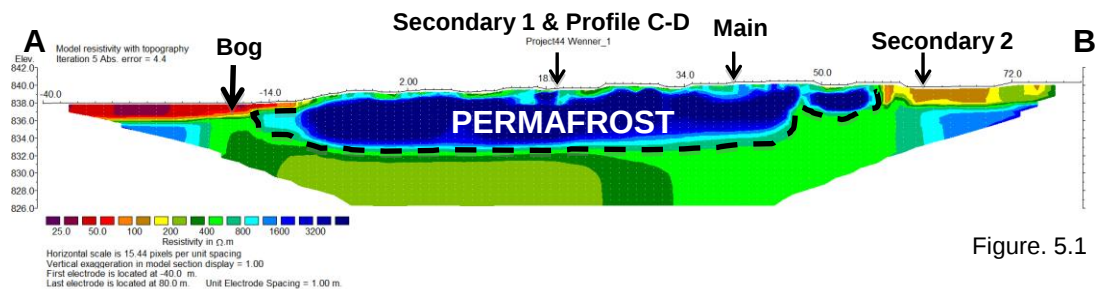


Figure 5.1

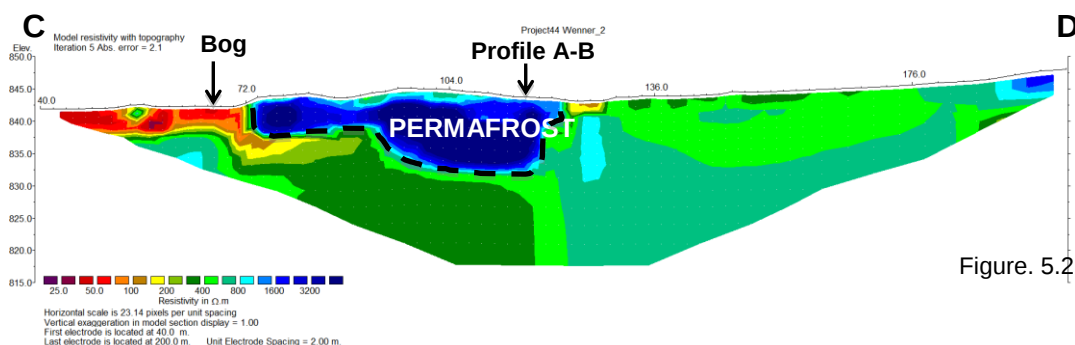


Figure 5.2

Figure 5. Modelled ERT inversion profile at MP 681 with dashed lines representing inferred permafrost boundaries: 5.1-permanent array; 5.2-ERT 2. The frozen/unfrozen boundary is taken to be 800 Ω m at this site.

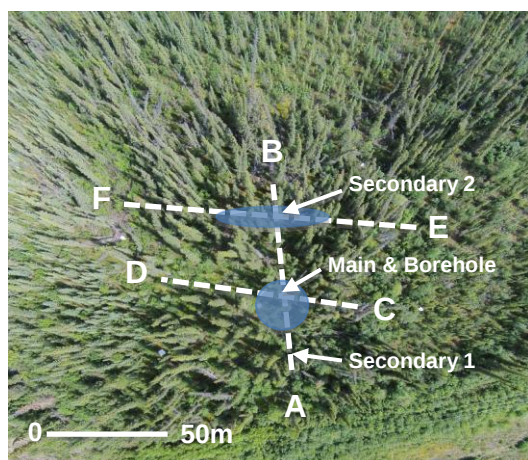


Figure 6. Aerial image of MP 825 in August 2014 showing the three ERT transects: the permanent array (A-B), ERT 2 cross-section (C-D,) and ERT 3 cross-section (E-F). The shaded area represents the interpreted permafrost patch. The main and secondary climatic stations and the borehole are marked. Scale is approximate.

average snow cover and the coldest MAGST, but not the coldest ground temperature (Tables 1 and 2). Soil moisture appears as the most probable control for the permafrost distribution at this site where surface rises of a few cm are correlated with the appearance of permafrost and vegetation changes between dense and open forest. The large offsets at secondary station 1 and 2 and the high MAAT suggest that the site is presently out of equilibrium with the climate and that the permafrost

patches are no longer ecosystem-protected (Shur and Jorgenson 2007). Permafrost may have occupied all of the open forest at the site in the past (see Figure 1), but if so, it has contracted in area and is now degrading.

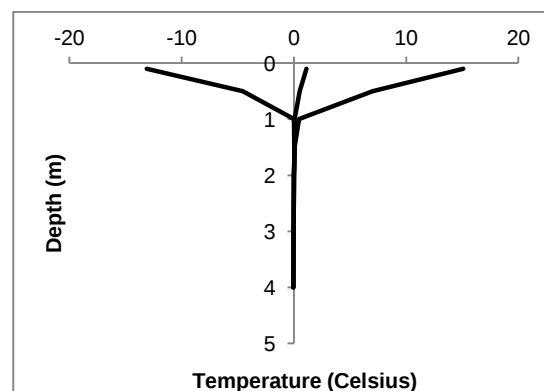


Figure 7. Temperature envelope for the borehole at MP 825 (2010-2014). A supra-permafrost talik is present between 1 m and 1.75 m where the ground is perennially thawed. The temperature at the base of the borehole at 4 m is -0.05°C.

Only one patch of permafrost was found at MP 681 and it has an irregular shape and a maximum thickness of 12 m. The permafrost boundaries are primarily controlled by drainage. Standing or running water delimits three sides of the permafrost body while the fourth is marked by

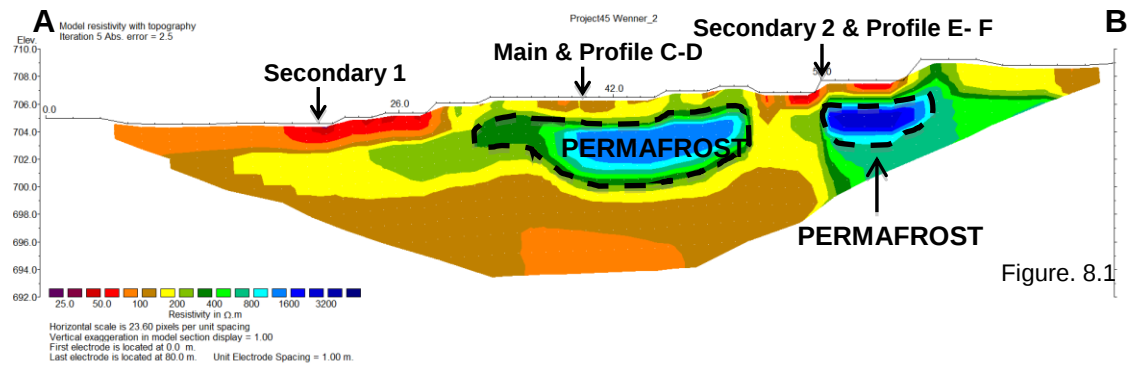


Figure. 8.1

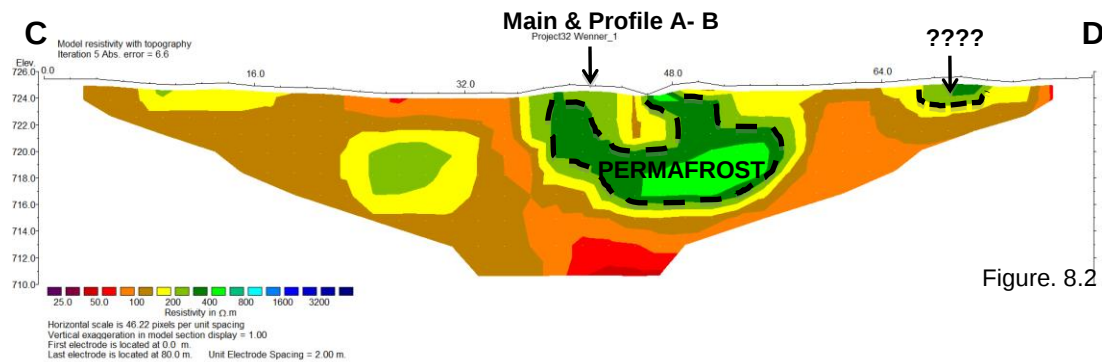


Figure. 8.2

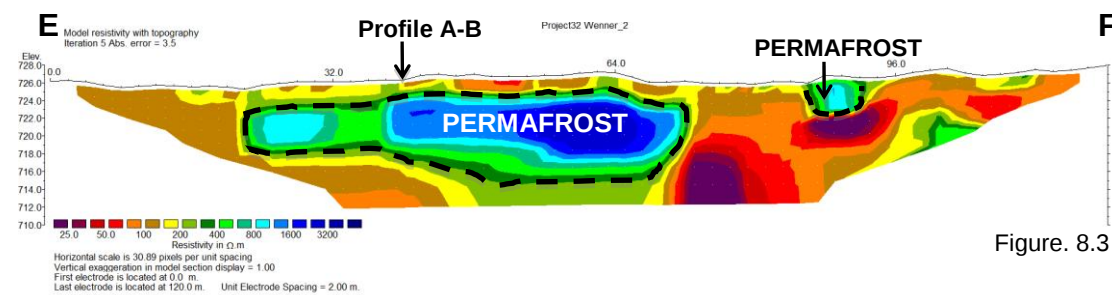


Figure. 8.3

Figure 8. Modelled ERT inversion profile at MP 825 with dashed lines representing inferred permafrost boundaries: 8.1-permanent array; 8.2-ERT 2; 8.3-ERT 3. The frozen/unfrozen boundary is taken to be 300 $\Omega \text{ m}$ at this site.

a surface depression. The latter change is also observable in the vegetation, which becomes more open with lichens and shrubs dominant. The snowpack was greatest at secondary station 2 where permafrost is absent and the ground surface temperature was also slightly higher. The temperature in the ground is about 1°C warmer than at the secondary 1 and main monitoring sites. Comparison of the 2014 aerial images with photos taken in 1964 revealed no significant difference in the local setting. MP 681 therefore appears to be stable and is presumed to be ecosystem-protected with a MAAT below -3°C and ground temperatures at the depth of zero annual amplitude of -0.2°C.

Two bodies of permafrost were found at MP 825 with maximum thicknesses of 9 m and 10 m. The snowpack varies relatively little at the site but is almost always greatest at secondary station 1 where permafrost is absent. The vegetation is a good indicator of permafrost distribution at the site as the areas where permafrost is present have older trees, often tilted, a thick organic mat

and low slope gradients. The neighbouring sites where permafrost is absent are generally drier with a thin organic mat or much wetter with standing or running water. It therefore appears that the permafrost distribution is controlled by local drainage conditions and topography.

There are several indications that the permafrost at MP 825 is degrading, producing a localized thermokarst landscape. First, the surface undulates and a large number of recently fallen trees are present on the slopes of the hummocky mounds. Second, there is a supra-permafrost talik at the borehole. Third, some parts of the permafrost bodies in the ERT profiles are irregular in form (e.g. Figure 8.2), with low resistivity layers corresponding to surface depressions, suggesting that thaw settlement has occurred. It is therefore probable that permafrost was previously more widespread at MP 825 and is undergoing degradation, presumably because as at MP 286, MAAT has risen to values (-1°C over the last 3 years) at which point the ecosystem can no longer protect the permafrost.

Estimated permafrost patch size and maximum thickness at the three study sites are shown in Table 3. The data are extremely limited, but a positive correlation may be present between permafrost thickness and patch area. In turn, as might be expected, there appears to be a negative correlation between MAAT and permafrost thickness. If the remaining seven monitoring sites along the Alaska Highway evince similar relationships, it may be possible to develop a relatively simple means to upscale from point ground temperatures to a real temperature averages in the discontinuous zone.

Table 3. Permafrost patch characteristics

Site	Patch 1 area ^a (m ²)	Patch 1 maximum thickness (m)	Patch 2 area ^a (m ²)	Patch 2 maximum thickness (m)
MP 286	20	2	370	4
MP 681	2500	12	-	-
MP 825	360	9	225	10

^a Approximate area based on elliptical shape

6 CONCLUSIONS

Permafrost patch boundaries at three field sites were identified using a combination of traditional and novel techniques. Observations suggest that strong relationships exist between permafrost boundaries and topography, drainage, soils, and antecedent disturbance. Two of the three sites were likely ecosystem-protected in the past but climatic warming may now have surpassed the possibility of preserving permafrost. One of these sites shows the development of a supra-permafrost talik and hummocky thermokarst topography while the loss of permafrost at the other appears to be occurring with no visible landscape change. The largest and thickest permafrost patch found during field investigations appears to still be ecosystem-protected with no changes apparent in the surface over the past 50 years. MAAT at this site averages -3°C which is much colder than the -1°C measured at the other two sites. Ongoing data analysis is expected to establish whether spatial trends in permafrost patch size and characteristics exist along the Alaska Highway transect or whether local factors are the primary controls.

ACKNOWLEDGEMENTS

Financial support from NSERC, Yukon Research Centre, the University of Ottawa and the Northern Scientific Training Program (NSTP) is gratefully acknowledged. Sharon Smith (Geological Survey of Canada) supplied the loggers and cables for the boreholes. Special thanks are owed to Benoit Faucher for help in the field in 2014 and to

many other field assistants and graduate students for help in earlier years. The comments of the anonymous reviewer are appreciated.

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