Geophysical and borehole investigations of permafrost conditions associated with compromised infrastructure in Dawson and Ross River, Yukon

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ABSTRACT

The effects of permafrost degradation in Yukon have serious negative implications for the structural integrity of vertical infrastructure. This is especially pertinent for critical buildings such as hospitals, schools, etc., in small communities that are situated on top of warm, ice-rich permafrost. Projections of mean annual air temperature over the next few decades, based on regional climatic models, indicate that air temperature will rise, hastening the thaw of permafrost. The combination of rising of air temperatures and buildings situated on warm permafrost has prompted this investigation into the vulnerability of Yukon Government vertical infrastructure. The application of DC resistivity and ground penetrating radar in conjunction with borehole drilling indicates that in Dawson there is warm ice-rich permafrost beneath the Palace Grand Theatre; the Old Territorial Administration building is underlain by primarily unfrozen sediment; and permafrost under the St. Andrew's Church is characterized by high variability. A deep active layer was observed at Ross River School and geophysical surveys indicate that warm water drainage from the roof is contributing to the thaw of the underlying permafrost.

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INTRODUCTION

Degrading permafrost continues to have devastating impacts on critical community infrastructure including schools and health centres in northern regions. It is anticipated that projected temperature increases and changes in precipitation will accelerate the warming and thawing of permafrost (ACIA, 2004). Regional scale trend analyses generated by the Pacific Climate Impact Consortium (PCIC) indicate a projected mean air temperature increase of 6.2°C per century (Werner *et al.*, 2009).

The projected warming of mean annual air temperature and variations in precipitation patterns will induce further disruptions in the equilibrium of warm permafrost. Permafrost is defined as ground which has remained below zero degrees Celsius for two consecutive years (Harris *et al.*, 1988). Since permafrost is defined as a thermal condition, subtle perturbations to the ground thermal regime, such as increases in ambient air temperature, changes to the micro-hydrologic regime, vegetation clearing, and depth of snow pack may have serious implications for its long-term sustainability. This has important implications for the maintenance of the structural integrity for infrastructure located on permafrost vulnerable to warming-induced degradation.

Yukon is divided into three permafrost zones: continuous (90-100%); extensive discontinuous (50-90%); and sporadic (10-50%) (Heginbottom *et al.*, 1995) (Fig. 1). The extensive and sporadic permafrost zones contain the warmest permafrost within the territory. It is this warm permafrost that is the most susceptible to thaw due to factors such as ambient air temperature increase, disturbance of insulating surface vegetation, and changes to snow cover. The City of Dawson and the community of Ross River are both located within the zone of extensive discontinuous and typically warm permafrost (Fig. 1).

The impacts of permafrost degradation on vertical infrastructure are evident at numerous building locations throughout Yukon. Evidence of this degradation is visible from the historic wooden structures built in the early 20th century within the City of Dawson, and at other locations such as the Ross River School, where the heating of the buildings has contributed to the warming and subsequent thaw and destabilization of the supporting permafrost.

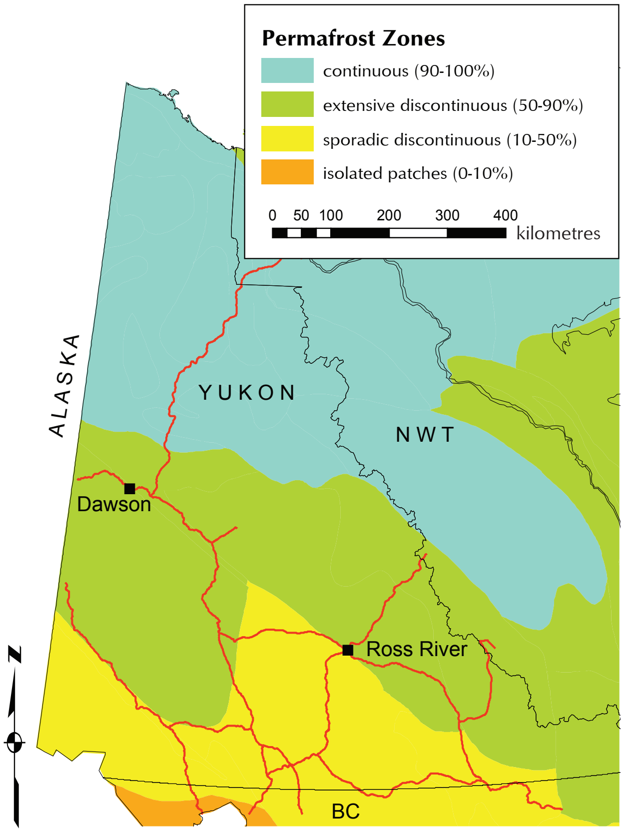

Figure 1. *Location of Dawson and Ross River in the extensive discontinuous permafrost zone.*

In order to address the costs associated with the effects of permafrost degradation on infrastructure, initiatives such as the development of the Canadian Standards Association (2010) *Technical guide for infrastructure foundations in permafrost: A practice guide for climate change adaptation for building in permafrost areas;* and *True North: Adapting Infrastructure to Climate Change in Northern Canada* (NRTEE, 2009) have been developed. Yukon Government's *Climate Change Action Plan* (2009) has also identified that the adaptation of infrastructure to climate change is a priority and noted that actions should be taken. The *True North* (NRTEE, 2009) paper noted that ensuring the resiliency of infrastructure throughout its designed lifespan is one of the most critical aspects of climate change adaptation.The findings brought forward by the *True North: Adapting Infrastructure to Climate Change in Northern Canada* (NRTEE, 2009) report highlight some of the past hindrances to addressing the adaptation of building practices to changing climatic conditions. Three of the most applicable findings to this study include:

1. The limited interaction among scientists and data providers, designers and builders of infrastructure, and policy-makers are barriers to problem identification and the application of solutions.

2. Significant gaps exist in the availability and accessibility of data and information that form the basis for infrastructure risk management and loss prevention, including information on current and projected impacts of climate change, as well as data on the stock of, and demand projections for infrastructure.
3. The capacity across and within northern jurisdictions to assess climate risks to infrastructure, and to develop, deploy, and enforce standards and risk reduction measures is uneven and lacking.

This paper aims to: 1) employ a combination of non-destructive geophysical and traditional borehole methods to identify the condition of permafrost adjacent to, and underneath buildings vulnerable to permafrost degradation at case study locations in the City of Dawson and the community of Ross River, Yukon; and 2) establish a baseline of permafrost conditions to monitor and assess the response of buildings to future climatic regimes.

STUDY SITES

To gain a better understanding of how buildings are responding to permafrost degradation within the zone of extensive discontinuous permafrost, the communities of Dawson and Ross River, Yukon were selected. Although these communities are both situated within the Klondike Plateau Ecoregion, a constituent of the larger Boreal Cordillera Ecozone, and within the Central Yukon Basin Yukon climatic zone, they are each characterized by unique geologic and climatic characteristics (Yukon Ecoregions Working Group, 2004a,b; Wahl *et al.*, 1987) (Fig. 1). The selection of buildings at these two locations within the extensive discontinuous permafrost zone enables the comparative analyses of the effects of thawing permafrost on buildings situated in different physiographic conditions.

DAWSON

Dawson City, Yukon, (64°03′34N, 139°25′50W; 320 m a.s.l.) is situated along the banks of the Yukon River and is home to ~1,891 residents (Yukon Bureau of Stats., 2010) (Fig. 2a). The climate of Dawson is characterized by continental conditions with the 1971-2000 climate normals recording an annual daily average temperature of -4.4°C and a yearly precipitation total of 324.3 mm (Fig. 3) (Environment Canada, 2010). Mean annual air temperature measured in 2007-2008 in the townsite was -3.16°C. Projected annual mean temperature trends generated by the Canadian Global Climate Model (CGCM3), following the A2 emissions scenario, indicate a mean annual temperature increase of 2.5 to 3.5°C in Dawson for the 2050s compared with the 1961-1990 baseline (Werner *et al.*, 2009). The surficial geology is characterized by fluvial deposits overlain by muck (frozen organic sediment), and capped in locations by eolian sediments (Duk-Rodkin, 1996; Duk-Rodkin *et al.*, 2000; Froese *et al.*, 2000, 2001).

ROSS RIVER

Ross River, Yukon, (61°58′47N, 132°27′03W; 650 m a.s.l.) is situated along the banks of the Pelly River and is home to ~361 residents (Yukon Bureau of Stats., 2010) (Fig. 2b). Located in the Tintina Trench rain shadow, Ross River experiences drier continental conditions with more variation between winter and summer temperatures than regions further to the west where the climatic conditions are moderated by the close proximity to the Pacific Ocean. The greatest amount of precipitation occurs during

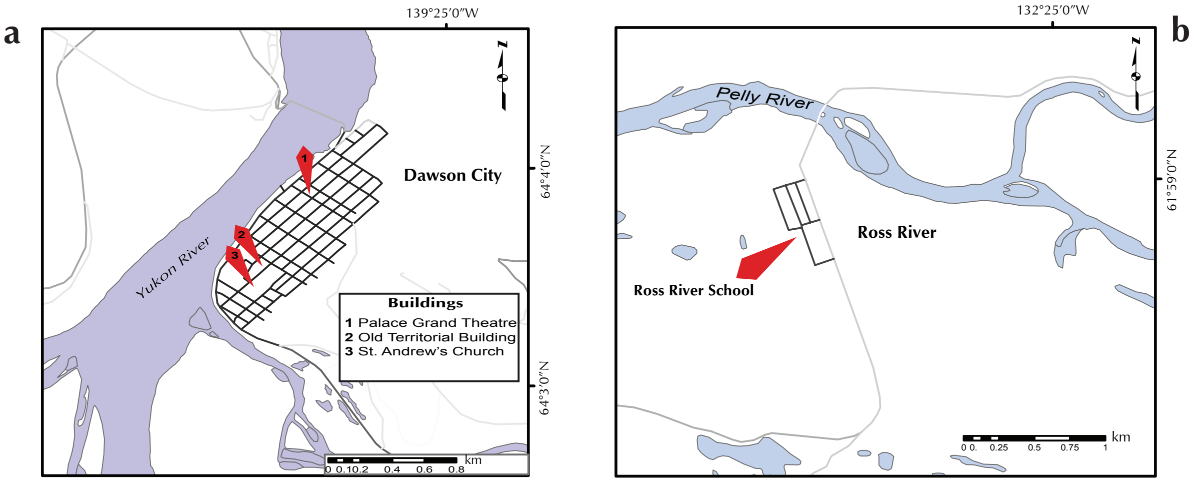

Figure 2. *Locations of the study sites in* ***(a)*** *Dawson and* ***(b)*** *Ross River, Yukon.*

the summer months of July and August (Fig. 3). The 1967-1994 climate averages are an annual daily average temperature of -4.6°C and yearly precipitation total of 258.7 mm (Fig. 3) (Environment Canada, 2010). The mean annual air temperature for 2008 was -3.7°C. The average annual ground surface temperature for 2008 was 0.4°C and the average annual temperature recorded at 19 m below surface was -0.14°C (Fig. 4), both temperatures were recorded from the Ross River School borehole. The surficial geology of the area is characterized by hill slopes and low-valleys blanketed in silt-rich till and coarse-grained glaciofluvial sediments that have been deposited in main valley meltwater channels and outwash plains (Lipovsky and Huscroft, 2007).

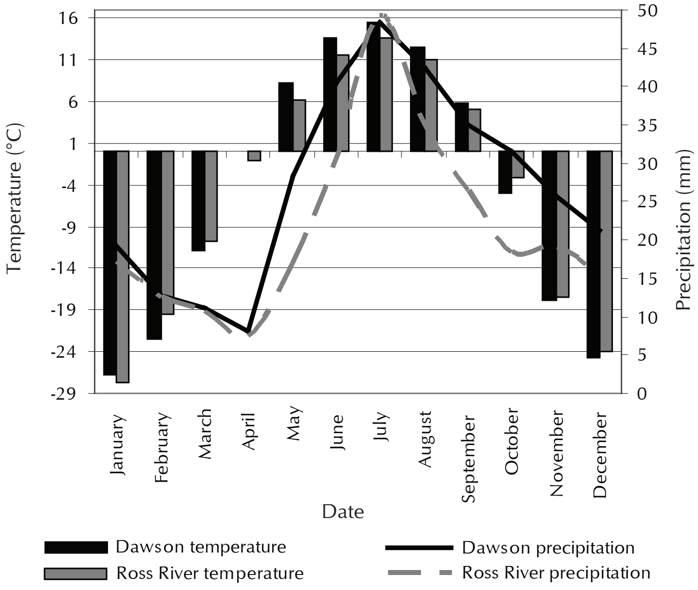

__Figure 3.__ Climatic data for Dawson City and Ross River, Yukon.

METHODS

The subsurface adjacent to the buildings was investigated using a combination of geophysical and physical techniques. The Dawson sites were sampled July 19-23, 2010, and the Ross River site was sampled on August 26, 2010.

GROUND PENETRATING RADAR

Ground-penetrating radar (GPR) was used to gain a two dimensional image below ground surface. A TerraSIRch Subsurface Interface Radar (SIR) System 3000® with a 200-MHz antenna (Geophysical Survey Systems, Inc. (GSSI)) was employed for the field investigation. The SIR-3000 control unit was set to record at 64 scans per second, which translates to 10 scans per metre, and a dielectric constant set at 13. Post collection processing was conducted using RADAN™ (version 6.6, GSSI) software.

BOREHOLE DRILLING

Drilling was conducted at selected sites using a combination of two drilling systems. A truck-mounted J.K. Smit rotary rig was used in areas where coarse gravel were encountered near the surface. This drill uses 2.5″ solid-stem augers and carbide-tipped fishtail or offset-tooth bits. A Bosch rotary percussion electric drill was used to retrieve core from ice-rich permafrost. This uses a 1″ or 3″ diamond-tipped high-speed coring barrel. Intact core samples were retrieved from ice-rich fine-grained permafrost with this tool. However, the coring is ineffective in gravel and sandy soils with poor core recovery and can cause damage to the equipment. The Bosch electric drill was used indoors to recover core within the St. Andrew's Church to a depth below ground surface of 3.8 m.

__Figure 4.__ Ground Surface temperature data from Ross River School borehole 2007-2010.

ELECTRICAL RESISTIVITY TOMOGRAPHY

Electrical resistivity is an effective method for determining the presence of frozen ground (Hauck *et al.,* 2003). Resistivity is a measure of the degree of conductivity of soil materials and their inverse, which is measured as resistance or resistivity. The resistivity varies according to the material type, composition and moisture content. Temperature and the state of water have an exponential effect on resistivity; liquid water has an exponentially lower resistivity than frozen ice. Resistivity works by injecting a current into the ground at one location, then measuring the voltage in the ground at another location. Using a large number of electrodes and multi-core cables, many combinations of transmitting and receiving electrodes are activated and voltages measured. These measurements are then inverted and processed using well-defined geometric factors to produce a tomogram, which is a one, two, or three dimensional image of the subsurface resistivity patterns.

Mapping of the horizontal extent of permafrost has been reliably established using galvanically and capacitivally coupled resistivity (Hauck *et al*., 2003; Kneisel, 2004; Fortier *et al*., 2008). The system used for these investigations is the Advanced Geosciences SuperSting R1/IP. This equipment uses 28 electrodes, an automatic switchbox and processor, and can conduct a survey in less than 20 minutes. Array lengths of 120 and 60 m were used, giving a depth of penetration from 10 to 20 m.

Wenner arrays were used for near-surface resolution as well as speed of survey. Results were processed using AGI EarthImager2D software.

RESULTS

DAWSON CITY

Palace Grand Theatre

Building history

The Palace Grand is a flagship building of the Klondike Gold Rush Historical Complex and as such has great cultural, historical and civic value (Fig. 2a). The Palace Grand is built on a flat, level site, with one building adjacent on the east and a large graveled parking lot on the west. The Palace Grand is a wood-framed, three-storey building which was built in 1899 and heavily refurbished in 1962 (Coutts, 1984). The structure is supported on wooden piles. These piles have concrete pads poured around their uppers. Wooden beams are placed on top of the piles. Beneath the building, and extending 0.5 m out from the building's sides, is a 1.2 m ventilated crawlspace.

Surficial geology, ice content

The area behind the building, on the north side, is disturbed but re-vegetated with grass and 3 to 4 m-high willows. The areas immediately adjacent to the building on the north and west sides are covered with White Channel gravel fill brough in from the Klondike River Valley southeast of the town site. Drilling, GPR and resistivity surveys were conducted on the White Channel gravel adjacent to the building.

At the time of inspection on July 20, 2010, the crawlspace had 5 to10 cm of water in a depressed area near the centre of the building (Fig. 5). The floor of the crawlspace appears to have subsided almost 40 cm since the piles were poured, as evidenced by suspended concrete slabs which originally rested on grade. The piles do not appear to be settling and the building appears to have remained level.

Figure 5. *Water in crawl space beneath Palace Grand Theatre, July 25, 2010; note the exposed piling below concrete pad indicating the presence of ground surface subsidence.*

Drilling at the rear of the building, on the north side, revealed 1.6 m of gravel, silt and debris fill over almost 1 m of nearly pure ice. Ice contents decreased in silt and sand until alluvial gravel were encountered at a depth of 3.4 m. The transition from silt to sand was gradational, and coarse-grained particles were found lower in the borehole. DC resistivity geophysics were then used to reveal a large region of ice-rich permafrost extending for several metres (Fig. 6). GPR was used to survey the subsurface site stratigraphy and to detect areas of massive ice and groundwater seepage (Fig. 7).

Geophysics

Drilling and resistivity showed a relatively consistent active layer approximately 1.5 m thick (Fig. 6). Deeper thaw was observed beneath a drainage ditch in a parking lot to the west of the structure (Fig. 6). Several ice-rich or pure ice lenses were detected by the resistivity and drilling at depths from 1.4 to 5.0 m. These were characterized by high resistivities of 800-1200 Ωm. This roughly corresponds with the depth of the silt unit. Frozen gravel layers beneath the ice-rich silt have lower resistivities due to lower ice contents (200-300 Ωm). The thawed active layer, which is largely composed of White Channel gravel fill, has a very low resistivity (40-50 Ωm). This indicates high groundwater content between the highly resistive quartz cobbles. Standing water was observed in the crawlspace below the building. The source of this water is likely groundwater moving through the permeable active layer.

The GPR output indicates an active layer which is approximately 2 m thick (Fig. 7). Above this level, the signal is attenuated and blurry, indicating groundwater presence. Several regions of chaotic GPR signals may indicate massive ice or very ice-rich conditions.

Old Territorial Building

Building history

The Old Territorial Administration Building is located near the permafrost boundary south of Church Street (Fig. 2a). It is a wood-framed three story building that currently houses the museum and several government offices. It was built in 1901 and has been in continuous service to present day. The building is supported on posts with a ventilated crawlspace. Evidence of subsidence is indicated by the presence of 0.5 m-deep depressions in the lawn surrounding the building, and damage to various porches and boardwalks has also occurred.

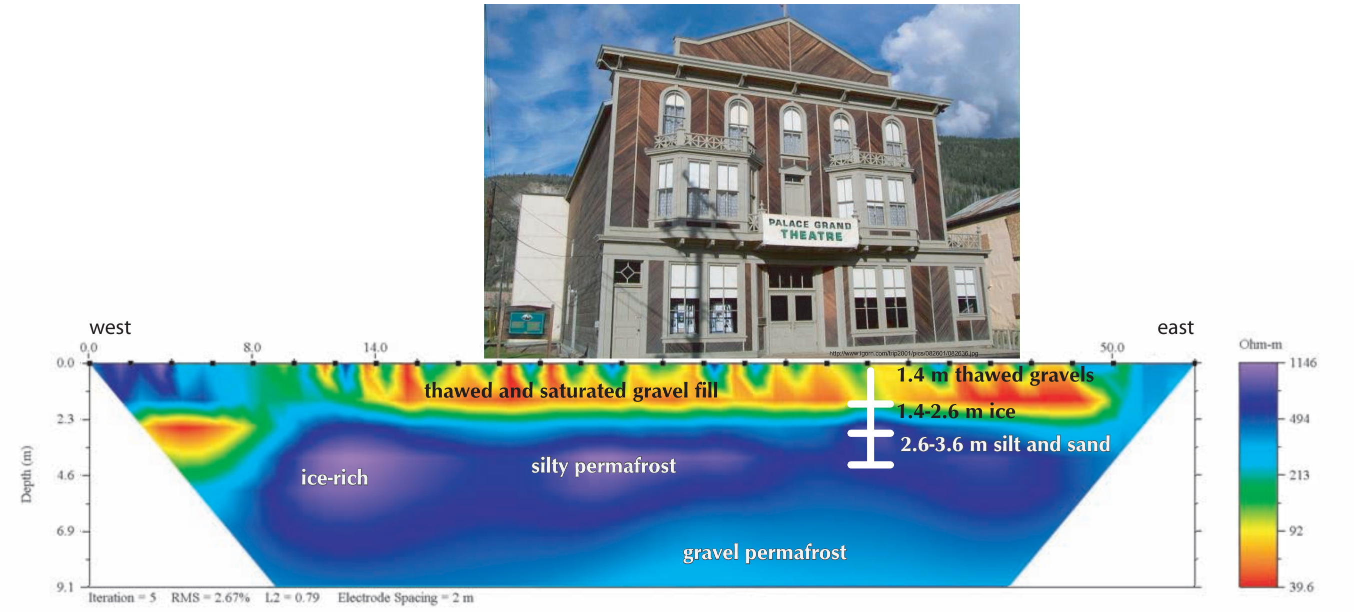

Figure 6. *The Palace Grand Theatre resistivity tomogram run on the north side of the building, and borehole data.*

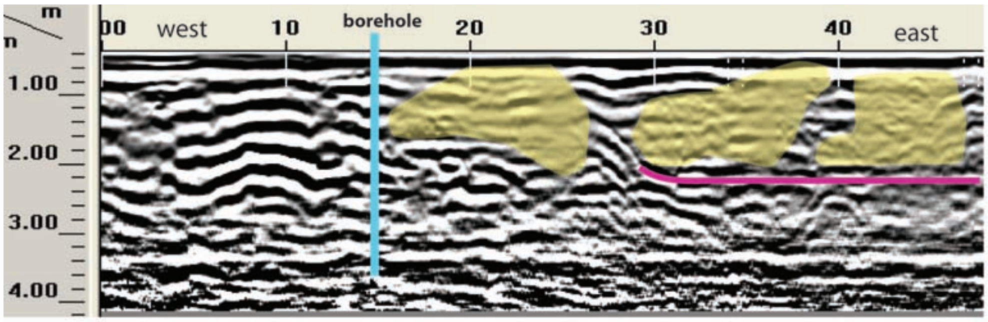

Figure 7. *GPR image along same path as resistivity transect located on the north side of the Palace Grand Theatre. Yellow areas demark zones with higher ground water content; the blue line indicates the location of the borehole; and the pink line is the interpreted upper contact of the silty sand unit.*

Geophysics

Resistivity transects were performed on the south, north and east-facing sides of the building. Excavation for the new hospital, on the east side of the building, allowed for ground-truthing of the results, as did one shallow borehole to a depth of 1.6 m on the south side of the building.

No permafrost was detected within the top 10 m of the subsurface on the south side of the building (Fig. 8a). While higher resistivities were present near the base of the image, there is no sharp boundary which is generally found at the top of the permafrost table. Thawed silt were encountered in the upper 2 to 5 m (100-200 Ωm). Gravel is likely found below 5 m. Low resistivities within the gravel indicate that they are probably thawed (200-350 Ωm). Borehole BH01 was drilled to a depth of 1.3 m; sticky unfrozen clay bound the Bosch drill auger stem and prevented further drilling.

The transect on the east side of the building was run along the east side of the parking lot adjacent to the foundation excavation for the new hospital construction site (Fig. 8b). Possible permafrost was encountered at the north end of the transect within local alluvial gravel (300-500 Ωm). The hospital foundation excavation allowed for observation of materials to a depth of 4 m, which consisted of 2 to 3 m of silt (50-200 Ωm) overlaying gravel. No permafrost was found by equipment operators during excavation for the new hospital's foundation; however, the resistivity showed a strong contrast between high and low resistance materials. This is likely ice-poor gravel permafrost which equipment operators may not have recognized. As the ice content in the sediments are low, thaw and subsidence are not expected at this site.

The transect on the north side of the building ran parallel to the structure at the edge of the Fifth Ave. entrance boardwalk (Fig. 8c). Several regions of very low resistivity may be groundwater channels, rotting wooden pilings or buried metallic debris (10-30 Ωm). Low resistivities near the surface are likely thawed silt (25-200 Ωm). A high resistance buried object (2000-8000 Ωm) was found beneath the centre of the porch. Permafrost appears to be present at depths below 7 m with high resistivities (1000-3000 Ωm), likely in alluvial gravel. This area may have been subject to permafrost thaw and surface subsidence in the past; however, with such a deep active layer and ice-poor gravel, further subsidence is unlikely.

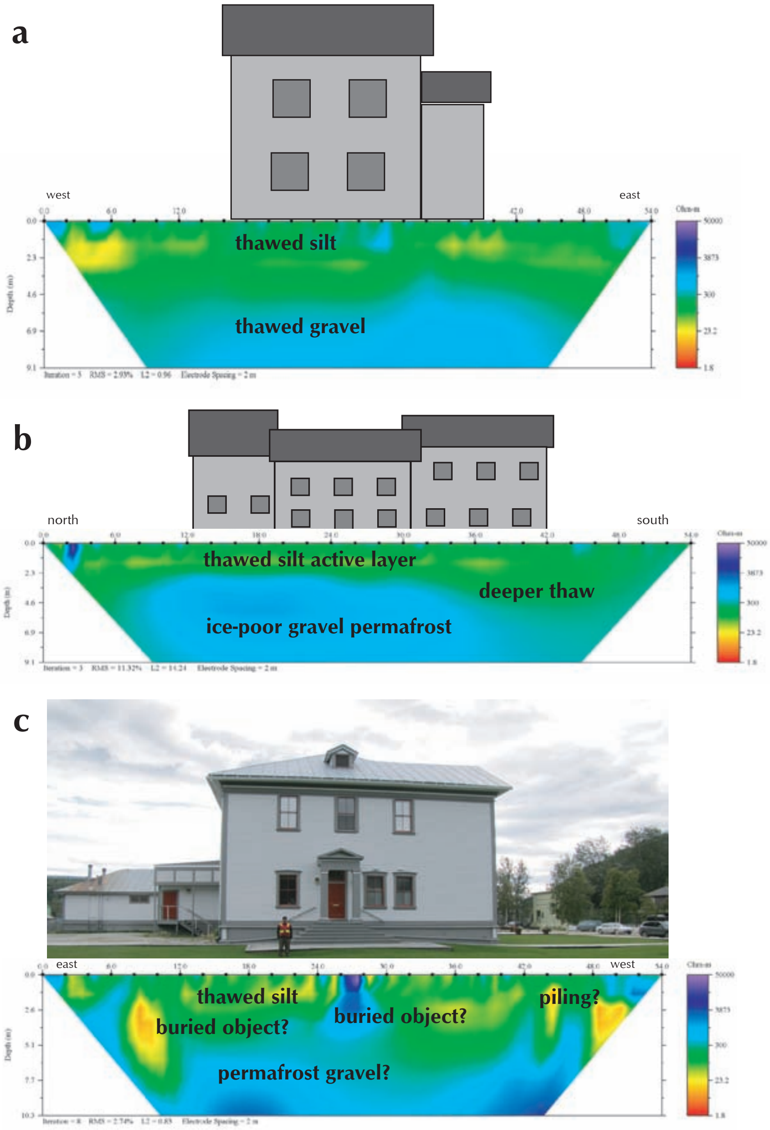

Figure 8. *Resistivity tomograms at the Old Territorial building:* ***(a)*** *run on the south side;* ***(b)*** *run on the east side; and* ***(c)*** *run on the north side.*

St. Andrew's Church

Building history

St. Andrew's Church is one of the best examples in the area of a historical building which has been rendered unusable due to permafrost degradation (Fig. 2a). The building was constructed in 1901 and abandoned in 1932 due to permafrost thaw and subsequent structural collapse (Commonwealth, 1984). This collapse may have been caused by the installation of a furnace in a cellar excavated in permafrost. The inside of the structure was shored using large timbers during the mid-1980s. There is currently no floor in the structure, and large gaps in the foundation allow for air and water flow into the interior.

Geophysics

Resistivity and GPR were run on four transects around the perimeter of the building. Boreholes were drilled on the west side, north side and within the structure itself. PVC plastic casings (25 mm) were placed in the 75 mm boreholes to facilitate thermistor installation. Boreholes were drilled to refusal on frozen gravel, which varied from 3.0 to 4.5 m depth. This is consistent with other boreholes around the Dawson town site.

The west side of the church appears to be underlain by permafrost within alluvial silt (300-4000 Ωm; Fig. 9a). Permafrost degradation has taken place, as evidenced by tilting of the structure. The permafrost on this side of the church has the lowest resistivity in the building area, indicating low ice contents or high unfrozen water content. Several isolated bodies of high-resistivity material (4000-30000 Ωm) were surrounded by low-resistivities (300-500 Ωm), suggesting that there are relict patches of ice-rich silt surrounded by ice-poor degraded permafrost. Deep thaw depths of >6 m beneath the south face of the bell tower may account for some of the lean evident in the structure. This side of the church may experience more thaw due to its westerly aspect, which receives increased summer evening insolation.

A large region of ice-rich silt underlies the west end of the transect, beneath the bell tower (~30 000 Ωm) (Fig. 9b). Degraded permafrost is found towards the east end of the structure, where surface subsidence is visible (100-200 Ωm). Regions of low resistivity found in the thaw depression at the left end of the image are likely due to saturated silt (<20 Ωm). However, they may also be interpreted as buried metallic debris. Borehole STA02 was drilled to a depth of 4.5 m through ice-rich silt before refusal was encountered on frozen gravel.

Along the east side of the structure, permafrost has a relatively consistent depth of thaw to 2.5 m along the south end of the transect (<300 Ωm; Fig. 9c). Towards the thaw depression at the north side of the building, the active layer becomes much deeper as indicated by the area of increased thaw (<200 Ωm; Fig. 9c). This is an area where surface water pools. This will trap heat and transfer it to the underlying permafrost causing continued thaw. Much of the damage to the structure appears to be as a result of the building 'leaning' into this thaw depression. Permafrost appears to be colder and/or more ice-rich than at other locations beneath the structure as is evidenced by the high resistivities (80 000 to 100 000 Ωm).

The permafrost table is deep and uneven across the south side of the structure; it ranges in depth from 2 m in an adjacent lawn area to 4.0 m directly in front of the structure on 4th Ave. (Fig. 9d). Deep thaw in front of the building (30-100 Ωm) is likely due to the south-facing wall absorbing solar energy and re-emitting that energy into the ground. Ice-rich permafrost is present in the shaded area to the east (3000-30 000 Ωm) of the church, but ice-poor or high water content permafrost with an uneven active layer surface and low resistivities (300-400 Ωm) was found on the west side.

GPR was run along the same path as the resistivity array on the north side of the church. Results from the GPR survey yielded data which support the resistivity results that suggest the presence of a thawed active layer (Figs. 9b,e). Zones with a higher ground water content are identified by a decrease in the GPR signal strength and are highlighted by the yellow areas in Figure 9e. The active layer is also visible on the GPR image as a strong horizontal linear layer at a depth of ~ 2 m below the ground surface.

Active layer depths near the shaded sides of the buildings ranged from 0.9 to 1.4 m. Within St. Andrew's Church, the permafrost table had rebounded to 0.56 m. An area of very ice-rich soil was found at a depth of 1.2 m, which may have been the historical maximum depth of thaw beneath the church. The silt below this region is visually interpreted as containing 50-80% ice, while the silt above had lower ice contents with wood and metal debris.

The thickness of ice-rich silt was remarkably consistent between the Palace Grand and St. Andrew's Church sites, ranging from 3.0-3.6 m in depth. If this soil was to thaw by the projected 1 m depth due to climatic warming surface, subsidence of up to 0.5 m could be reasonably expected.

Dawson Downtown Street Survey

GPR transects were run over many of the main streets of downtown Dawson. The transects revealed a strong reflector at a depth of 2.6 m, which was consistent across the town. It is likely that this is the top of the active layer. This was similar to active layer depths detected by drilling (Table 1) and resistivity around St. Andrew's Church, Front Street and the Palace Grand Theatre. The suspected active layer reflector was observed beneath many streets and all alleyways, but almost never beneath intersections.

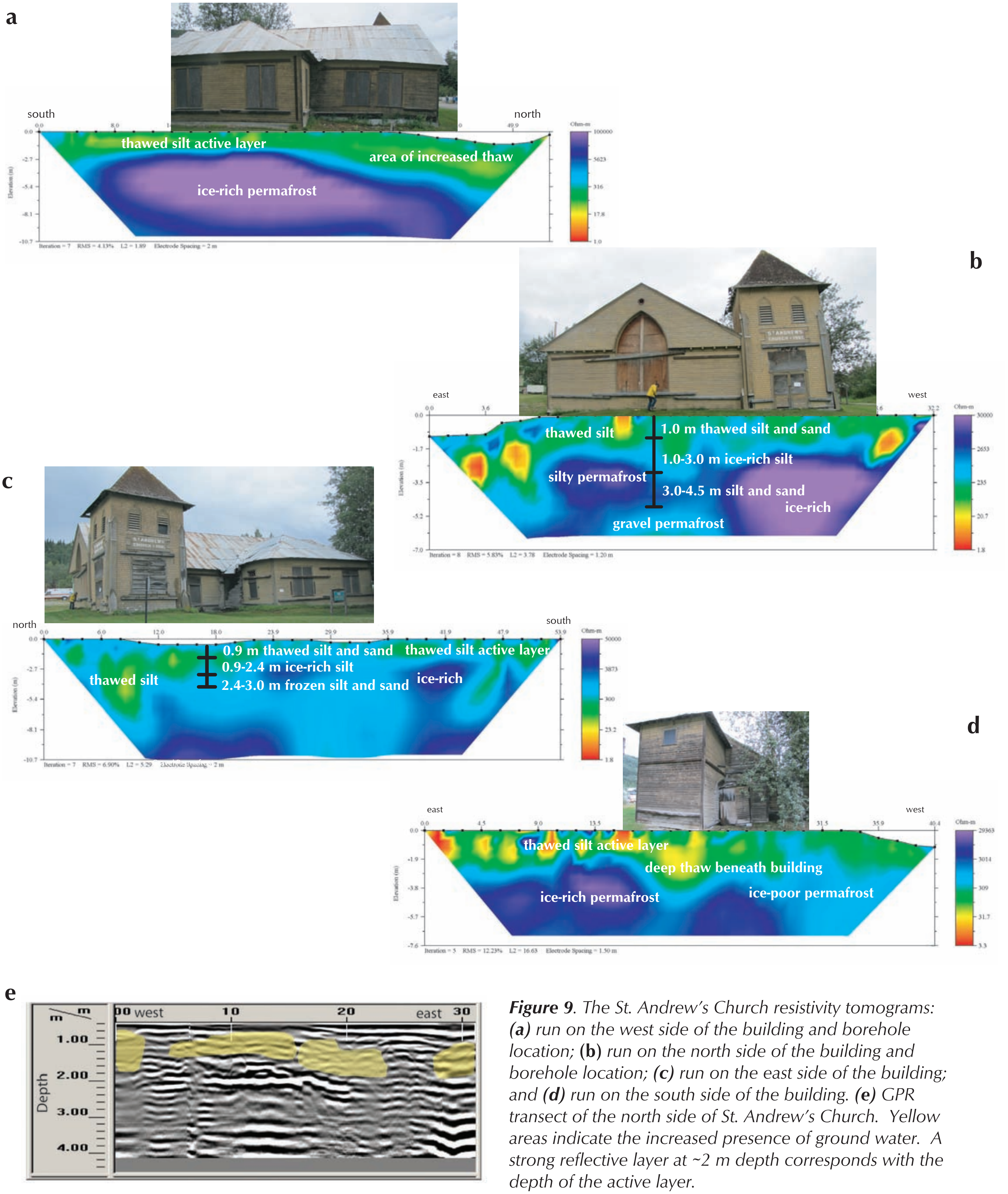

Figure 9. The St. Andrew's Church resistivity tomograms: ***(a)*** run on the west side of the building and borehole location; **(b)** run on the north side of the building and borehole location; ***(c)*** run on the east side of the building; and ***(d)*** run on the south side of the building. ***(e)*** GPR transect of the north side of St. Andrew's Church. Yellow areas indicate the increased presence of ground water. A strong reflective layer at ~2 m depth corresponds with the depth of the active layer.

***Table 1.** Summary of borehole results, July 2010.*

Borehole	Active layer depth (m)	Ice-rich silt thickness (m)	Depth to gravel (m)
St. Andrew's east side	0.9	0.9-3.6	3.6
St. Andrew's north side	1.0	1.0-3.0	4.5
St. Andrew's inside	0.56	1.4-3.0	3.8
Palace Grand east side	1.4	1.4-?	N/A
Palace Grand north side	1.4	1.4-3.4	3.4

ROSS RIVER

Ross River School

Building history

The Ross River School has experienced damage relating to foundation settlement for over 10 years (Fig. 2b). An insulated crawlspace and thermosiphons are being used to prevent thaw of the underlying ice-rich permafrost; however, continued thaw and settlement is occurring (Fig. 10a).

Surficial geology, ice content

A borehole drilled adjacent to the building in 2007 by EBA Engineering, and observed by J. Coates, revealed that deep active layers (up to 4.5 m in depth) occur in the area, which is underlain by up to 20 m of ice-rich silt below 4-5.0 m of silty gravel.

Ground temperature

Ground temperatures at the Ross River School are warm. At depths of 4.5 m, adjacent to the school, the active layer fluctuated between -0.3 and 2°C. This is near the base of the active layer, and agrees well with the resistivity. At depths of 13 m, temperature varied between -0.2 and -0.5°C. This is very vulnerable permafrost that is often within 0.1°C of thawing.

Geophysics

The two high-resistance regions labeled as ice-rich (500-1000 Ωm) are separated by a lower resistance region (200-300 Ωm) that is likely the same temperature as the surrounding permafrost, but may have much higher unfrozen water content (Fig. 10a). In this case, future thaw and subsidence may take place in this region, which lies beneath an area of already deep thaw. A region of very low resistivity (40-100 Ωm) near the centre of the image may indicate the presence of a large buried metal object or an area of groundwater infiltration. Groundwater infiltration is the more likely explanation, as a drain pipe from the roof eaves trough disgorges in this area. GPR was used along the same transect and revealed an area of increased signal attenuation over the resistivity anomaly, an indication of groundwater presence (Fig. 10b).

Interpretations of the geophysical data indicate that water drainage from the roof may be a contributing factor for the deep thaw in the very warm permafrost adjacent to the west side of the school.

DISCUSSION

DAWSON

Geothermal Modeling

Permafrost conditions in Dawson City were modeled as part of a YG Transportation Engineering Study (Coates, 2009) using the MUT 1D, a finite element analysis geothermal modeling program designed by the Alaska Department of Transportation. Results from Coates (2009) indicate that active layer depths are expected to increase by up to 1 m, from 2.6 to 3.6 m, by 2020 in ice-rich permafrost in the Dawson town site due to anticipated climatic warming rates of 0.1˚C per year (Fig. 11).

Projected impacts on infrastructure

Palace Grand Theatre

The permafrost beneath the Palace Grand Theatre is extremely ice-rich and warm with an approximate temperature above -1.0˚C, making it very prone to thaw. Active layer depth increases in this area will lead to subsidence of the surface and to the reduction of bearing capacity of the soils. A region of nearly pure buried ice has been identified immediately adjacent to the north side of the Palace Grand Theatre. This poses a significant structural risk to the foundations of the building. Should the massive ice body located behind the Palace Grand Theatre thaw, a surface subsidence of up to 0.75 m can be expected. This would have serious consequences for the integrity of the structure. With projected active layer depth increases due to climatic warming, some thaw of ground ice may be anticipated (Coates, 2009). Surface subsidence and structural damage would likely follow.

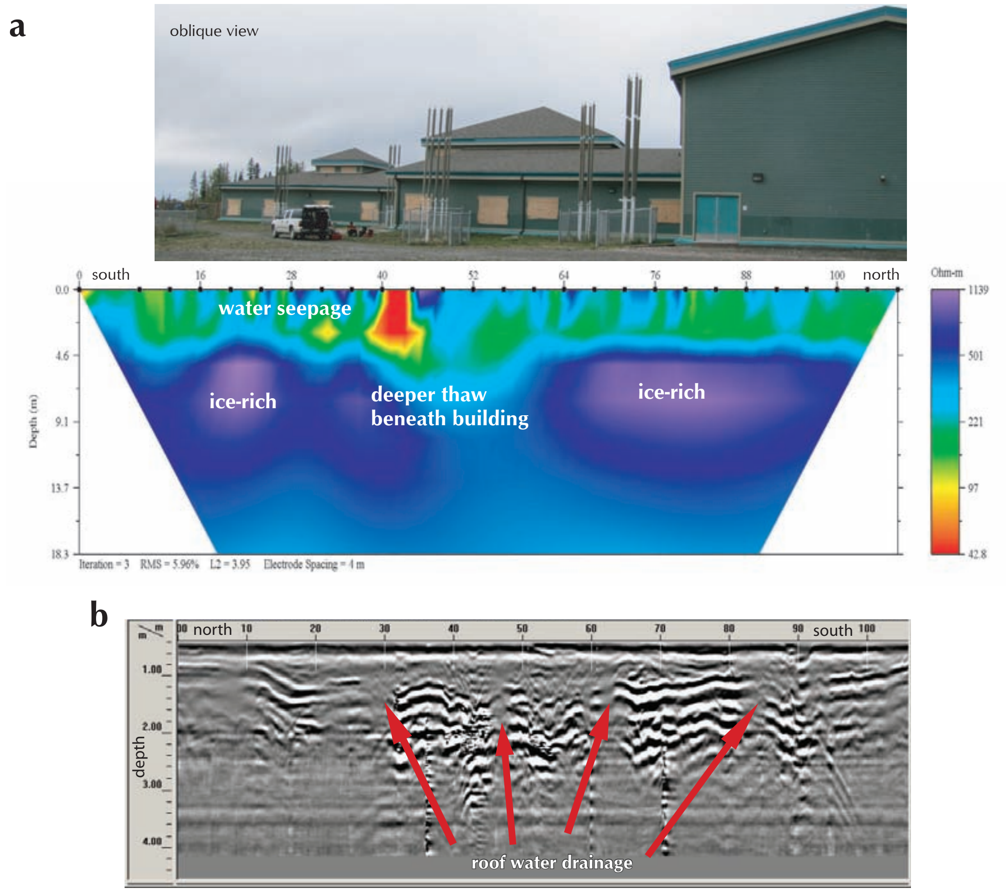

Figure 10. ***(a)*** *Ross River School resistivity profile on the west side of the building;* ***(b)*** *GPR transect following the same path as the resistivity profile. The red arrows indicate regions where water runoff from the roof of the school has infiltrated into the ground.*

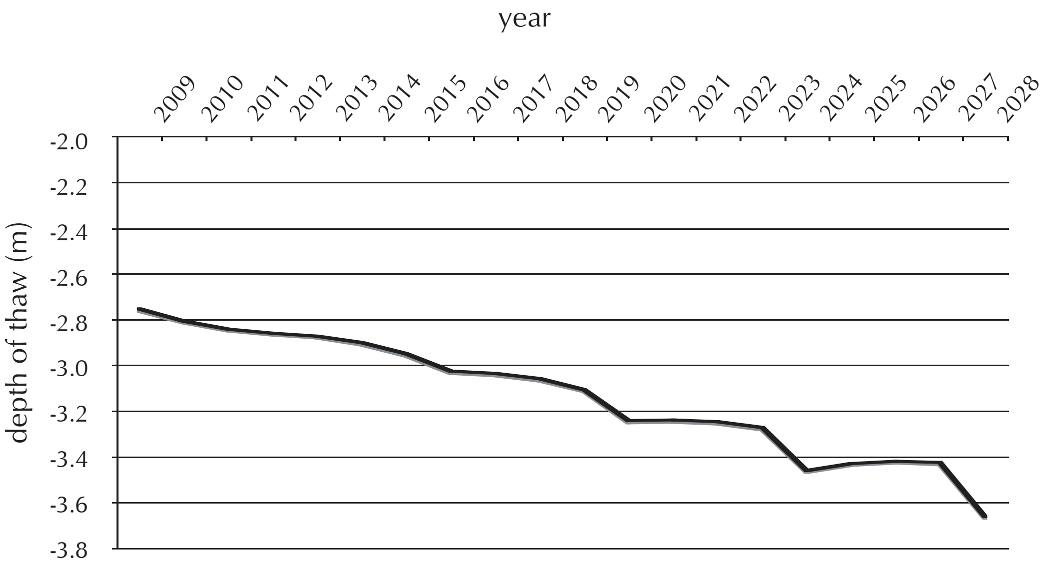

Figure 11. *Projected increase in maximum depth of seasonal permafrost thaw by 2020 for Dawson (Coates, 2009).*

Old Territorial Building

The Old Territorial Administration Building appears to be underlain by mostly unfrozen sediments. Resistivities in these sediments on the north and east sides of the structure are within the range expected for ice-poor silt and gravel. However, the lack of sharp boundaries between higher resistance materials at depth and lower resistance materials at the surface indicate that ice-rich silt are not expected. Therefore, this structure is not expected to experience further permafrost thaw or damage due to settlement.

St. Andrew's Church

St Andrew's Church is underlain by degraded ice-rich permafrost which has caused significant damage to the structure in the past. However, the permafrost table has recovered within the unheated and unoccupied structure to within 50 cm of the surface. An increase in active layer depths due to climatic warming may cause increased subsidence of certain parts of the structure where ground and surface water collection occurs.

Ross River School

The Ross River School has a very deep active layer. The depth of the active layer adjacent to the school ranges from 4.5 to 8.0 m. Future permafrost thaw will likely occur due to warm water drainage from the roof. The heat transfer from this water through the granular materials beneath the school is a very effective method of permafrost thaw. Increases in thaw depth and subsidence may be expected until water is rerouted away from the building.

CONCLUSIONS

Resistivity and GPR were successfully used to identify regions of permafrost beneath structures located in the extensive discontinuous zone of central Yukon. Regions of high resistivity were interpreted as ice-rich permafrost. Regions of low resistivity within permafrost regions were interpreted as high unfrozen water content within permafrost. Interpretations of the geophysical investigations were confirmed by boreholes drilled along the geophysical transects. GPR was successful in delineating the permafrost table and identifying areas of groundwater within the active layer. The Palace Grand Theatre and Ross River School are identified as regions where projected climatic warming may lead to permafrost thaw and structural damage.

The impacts of climatic warming are likely to be more pronounced in urban areas than forested terrain as there is no insulating organic mat to shield permafrost from temperature increases. Comprehensive monitoring of permafrost conditions within townsites will be required in order to mitigate damage to buildings and other infrastructure.

Baseline conditions have now been established using two-dimensional DC electrical resistivity. Future measurements at the sites may provide insight into changing active layer depths, regions of increased thaw, groundwater movement and areas where increased unfrozen water content signals imminent thaw of ice-rich permafrost. The installation of four PVC pipe casings in the ice-rich materials will allow for future thermal measurements of the permafrost temperature and monitoring of thaw.

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REFERENCES

ACIA, 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press.

Canadian Standards Association, 2010. Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation. PLUS 4011-10, 112 p.

Coates, J., 2009. Dawson City Front Street Thaw Depth Model. Report delivered to Yukon Highways and Public Works Transportation Engineering. Prepared by Kryotek Arctic Innovation.

Commonwealth Historic Resource Management Limited. 1984. St. Andrew's Presbyterian Church, Dawson: A Structural and Land Use Study. Parks Canada, MRS # 171, 206 p.

Coutts, R., 1984. The Palace Grand Theatre, Dawson City, YT: An Interpretive History. Parks Canada, MRS # 428, 121 p.

Duk-Rodkin, A.,1996. Surficial Geology, Dawson, Yukon Territory. Geological Survey of Canada, Open File 3288, scale 1:250 000.

Duk-Rodkin, A., Barendregt, R.W., White, J.M. and Singhroy, V.H., 2000. Geologic evolution of the Yukon River: implications for placer gold. Quaternary International, vol. 82, p. 5-31.

Environment Canada, 2010. National Climate Data and Information Archive. http://www.climate.weatheroffice.gc.ca/Welcome_e.html [accessed Dec. 8, 2010].

Fortier, R., LeBlanc, A., Allard M., Buteau S. and Calmels, F., 2008. Internal structure and conditions of permafrost mounds at Umiujaq in Nunavik, Canada, inferred from field investigation and electrical resistivity tomography. Canadian Journal of Earth Sciences, vol. 45, p. 367–387.

Froese, D.G., Barendregt, R.W., Enkin, R.J. and Baker, J., 2000. Paleomagnetic evidence for Multiple late Pliocene – early Pleistocene glaciations in the Klondike area, Yukon Territory. Canadian Journal of Earth Sciences, vol. 37, p. 863-877.

Froese, D.G., Duk-Rodkin, A., Bond, J.D. (eds.), 2001. Field guide to the Quaternary Research in the central and western Yukon Territory, CANQUA 2001. Occasional Papers in Earth Sciences, vol. 2, Heritage Branch, Government of Yukon.

Harris, S.A., French, H.M., Heginbottom, J.A., Johnston, G.H., Ladanyi, B., Sego, D.C. and van Everdingen, R.O. 1988. Glossary of permafrost and related ground ice terms. Permafrost Subcommittee, Associate Committee on Geotechnical Research, National Research Council of Canada, Ottawa.

Hauck, C., Vonder Mühll, D. and Maurer, H., 2003. Using DC resistivity tomography to detect and characterize mountain permafrost. Geophysical Prospecting, vol. 51, p. 273-284.

Heginbottom, J.A., Dubreuil, M.A. and Harker, P.A., 1995. Canada – Permafrost, *In:* National Atlas of Canada, 5th Edition, National Atlas Information Service, Natural Resources Canada, MCR 4177.

Kneisel, C., 2004. New Insights into mountain permafrost occurrence and characteristics in glacier forefields at high altitude through the application of 2D resistivity imaging. Permafrost and Periglacial Processes, vol. 15, p. 221-227.

Leverington, D.W. and Duguay, C.R., 1997. A Neural Network Method to Determine the Presence or Absence of Permafrost near Mayo, Yukon Territory, Canada. Permafrost and Periglacial Processes, vol. 8, p. 205-215.

Lipovsky, P. and Huscroft, C., 2007. A reconnaissance inventory of permafrost-related Landslides in the Pelly River watershed, central Yukon. *In:* Yukon Exploration and Geology 2006, D.S. Emond, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 181-195.

Munroe, J.S., Doolittle, J.A., Kanevskiy, M.Z., Hinkle, K.M., Nelson, F.E., Jones, B.M., Shur, Y. and Kimble, J.M., 2007. Application of Ground-Penetrating Radar Imagery for Three-Dimensional Visualization of Near-Surface Structures in Ice-Rich Permafrost, Barrow, Alaska. Permafrost and Periglacial Processes, vol. 18, p. 309-321.

National Round Table on the Environment and the Economy (NRTEE), 2009. True North: Adapting Infrastructure to Climate Change in Northern Canada. Ottawa, ON.

Plouffe, A. and Jackson, L.E., Jr., 1995. Quaternary stratigraphy and till geochemistry in the Tintina Trench, near Faro and Ross River, Yukon territory. *In:* Drift Exploration In the Canadian Cordillera, P.T. Bobrowsky, S.J. Sibbick, J.M. Newell and P.F. Matysek, (eds.), British Columbia Ministry of Energy, Mines, and Petroleum Resources, Paper 1995-2, p. 53-66.

Ross, N., Harris, C., Christiansen, H. and Brabham, P.J., 2005. Ground penetrating radar Investigations of open system pingos, Adventdalen, Svalbard. Norsk Geografisk Tidsskrift – Norwegian Journal of Geography, vol. 59, p. 129-138.

Wahl, H.E., Fraser, D.B., Harvey, R.C. and Maxwell, J.B., 1987. Climate of the Yukon. Atmospheric Environment Service. Environment Canada, Ottawa, Ontario.

Werner, A.T., Jaswal, H.K. and Murdock, T.Q., 2009. Climate Change in Dawson City, YT: Summary of Past Trends and future Projections, Pacific Climates Consortium, University of Victoria, Victoria, BC, 40 p.

Yukon Bureau of Statistics, 2010. Yukon fact sheet. http://www.eco.gov.yk.ca/stats/yukonfactsheet.html [accessed Nov.21, 2010].

Yukon Ecoregions Working Group, 2004a. Klondike Plateau. *In:* Ecoregions of the Yukon Territory: Biophysical properties of Yukon landscapes. C.A.S. Smith, J.C. Meikle and C.F. Roots (eds.), Agriculture and Agri-Food Canada, PARC Technical Bulletin no. 04-01, Summerland, BC, p. 159-168.

Yukon Ecoregions Working Group, 2004b. Yukon Plateau-North. *In:* Ecoregions of the Yukon Territory: Biophysical properties of Yukon landscapes. C.A.S. Smith, J.C. Meikle and C.F. Roots (eds.), Agriculture and Agri-Food Canada, PARC Technical Bulletin no. 04-01, Summerland, BC, p. 197-206.

Yukon Government, 2009. Yukon Government Climate Change Action Plan, 45 p.