Investigations of discontinuous permafrost in coastal Labrador with DC electrical resistivity tomography

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Challenges from North to South
Des défis du Nord au Sud

Robert G. Way & Antoni G. Lewkowicz
Department of Geography – University of Ottawa, Ottawa, Ontario, Canada

ABSTRACT
Investigations of ground conditions within the coastal Labrador communities of Cartwright (54°N) and Nain (57°N) revealed occurrences of discontinuous permafrost. The characteristics of permafrost bodies were examined using a combination of standard field methods and DC electrical resistivity tomography (ERT). In Cartwright, local climate is unfavourable for permafrost with mean annual air temperatures exceeding 0°C in recent years. Consequently, permafrost is thin (<6 m) and restricted to small palsa fields in raised bogs at exposed coastal locations. In the more northerly field area in Nain, permafrost was inferred to be present at numerous sites under both fine and coarse surficial covers. Permafrost up to 18 m thick was inferred in marine deposits at the coast and up to 9 m at a forested site. Despite challenges, a combination of standard field based methods and ERT can discriminate between frozen and unfrozen ground at these sites.

RÉSUMÉ
Une étude sur les conditions du sol dans les communautés de Cartwright (54°N) et Nain (57°N) sur la côte du Labrador a révélé la présence de pergélisol discontinu. Les caractéristiques de ces zones de pergélisol ont été analysées suite à la réalisation de travaux de terrain standard et à l'acquisition de relevés de résistivité électrique et tomographique DC (ERT). Avec des températures moyennes annuelles de l'air dépassant 0°C au cours des dernières années, le climat local de Cartwright est défavorable au maintien du pergélisol. Par conséquent, le pergélisol y est mince (<6 m) et limité aux petites palses dans les tourbières situées dans des zones côtières exposées. Dans la communauté de Nain, le pergélisol est possiblement présent à plusieurs endroits sur les sites plus au nord, à la fois sous les dépôts fins et les dépôts grossiers. Dans les dépôts marins, l'épaisseur du pergélisol a été déduite à près de 18 mètres, comparativement à 9 mètres d'épaisseur dans les secteurs boisés. Malgré les défis rencontrés, les travaux de terrain standard combinés à l'acquisition de relevés ERT ont permis aux sites d'études de discriminer un sol gelé d'un sol non gelé.

1 INTRODUCTION

Projected warming of northern Canada over the next century is expected to cause the thaw of permafrost along the southern boundary of the discontinuous zone (Woo et al. 1992; Zhang et al. 2008). As a result, careful planning and adaptation measures will be required to avoid future structural damage to infrastructure in these regions (e.g. Nelson et al. 2001; Smith and Riseborough 2010; Ford et al. 2014). In the Labrador region of northeastern Canada, there is limited information on the current distribution and physical characteristics of permafrost owing to a paucity of field studies in the past few decades. However, a century-long regional warming trend (Brown et al. 2012; Way and Viau, 2014) has likely impacted local permafrost characteristics, and satellite records show that ground surface temperatures have warmed over the past decade (Hachem et al. 2009; Comiso and Hall 2014).

Comprehensive field studies in the 1970s along the northwestern Labrador/Québec border detailed the distribution of permafrost in the vicinity of Schefferville (e.g. Nicholson 1978), but there is much less information available on permafrost in the coastal regions along the Labrador Sea. Existing maps depict coastal Labrador as spanning from the no permafrost zone in the south at 51°N to continuous permafrost at 58°N (Heginbottom et al. 1995). Permafrost degradation in this region is expected to have a medium overall impact, based on projections of a moderate thermal response and a low physical response, but considerable uncertainty remains at finer spatial scales (Smith and Burgess 2004). A key part of the Labrador Permafrost Project is to fill this knowledge gap by establishing permafrost monitoring sites to evaluate the baseline conditions of discontinuous permafrost in coastal Labrador (Way and Lewkowicz 2014).

Here we report on local permafrost investigations conducted in 2014 in areas around the communities of Cartwright, NL and Nain, NL, located respectively near the southern and northern ends of the discontinuous zone, to test the applicability of DC electrical resistivity surveys (ERT) and standard field methods used in the southern Yukon (Lewkowicz et al. 2011) for permafrost detection in coastal Labrador. A particular focus was placed on detecting permafrost bodies within the community of Nain where degrading discontinuous permafrost has caused building subsidence (Lewkowicz and Way 2014).

2 STUDY AREA

The communities of Cartwright and Nain are located on the Labrador Sea coastline within the coastal barrens ecoregion which forms part of the Taiga Shield ecozone. Vegetation cover within this ecoregion is sparse near the coast with the forest composition primarily of Black

Spruce, Tamarack and White Spruce stands which are limited to lower elevations farther inland. Due to its southerly and less exposed position relative to the ocean, the forest cover in Cartwright is much denser and more widespread than in the regions around Nain.

According to Environment Canada climate normals (1981-2010), mean annual air temperatures in Cartwright and Nain are 0.0°C and -2.5°C, respectively, with the warmest mean monthly air temperatures in August (+12.7°C and +11.0°C) and minimum monthly air temperatures in January (-14.3°C and -17.6°C) (Environment Canada, 2015). The presence of seasonal sea ice cover along the Labrador coast in the winter affects the communities by producing more continental conditions than their coastal locations would suggest. However, coastal proximity produces cool conditions in the sea ice-free summers. Large amounts of snowfall occur in both communities with mean cold-season snow depth on the ground averaging ~115 cm at Cartwright and ~68 cm at Nain. Nevertheless, Nain typically has more days with snow on the ground because of earlier snow-on dates and later snow-off dates (Environment Canada, 2015).

The Permafrost Map of Canada (Heginbottom et al. 1995) shows Cartwright within the isolated patches permafrost zone while Nain is located near the northern boundary of the sporadic discontinuous permafrost zone (Figure 1). Past studies of permafrost in and around the two communities have been quite limited. Exceptions include Hustich (1939) and Brown (1979) who noted the presence of palsa fields in the vicinity of Cartwright. Permafrost has not been previously discussed in published reports for Nain although archeological investigations did reveal permafrost on nearby barrier islands (Woollett 2010; Butler 2011).

Unlike the interior of Labrador, where the surficial cover is either till or lacustrine deposits, the communities of Cartwright and Nain are largely below the Holocene marine limit (Occhietti et al. 2011) leading to the deposition of marine sediments that were subsequently overlain by glacial tills. Medium-to-fine-grained marine sediments found in these locations are frost-susceptible and are likely to contain excess ice, making their presence detrimental for infrastructure within the communities (Fortier et al., 2011). In Nain, for example, near-surface layers of fine-grained marine sediments have been implicated as a contributor to housing damage associated with settling and ground movement (Bell et al., 2011). The overlying till cover exacerbates housing issues by allowing a deep seasonal frost penetration and deep active layers where permafrost is present.

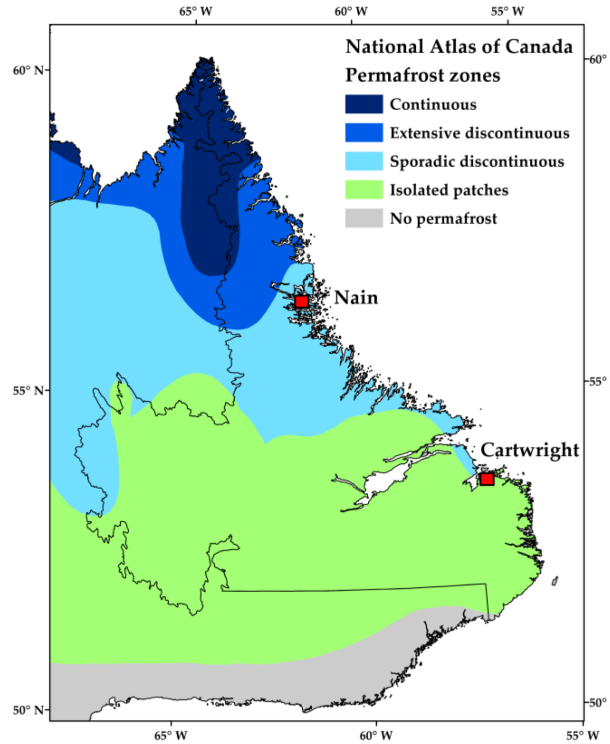

Figure 1. Location of the communities of Cartwright and Nain, Newfoundland and Labrador superimposed on permafrost limits according to the National Atlas of Canada (Heginbottom et al. 1995).

3 METHODS

Investigation of local permafrost conditions in the communities of Cartwright and Nain used ERT profiling and standard frost probing along selected profiles (Lewkowicz et al. 2011).

ERT is a geophysical technique which measures variation in the electrical resistivity of the subsurface by sending electrical current through the ground between sets of contact points (electrodes). ERT profiles show differences in the moisture and thermal characteristics of the subsurface because the ground's resistance to electrical current is strongly impacted by these variables (Hauck 2013). Although ERT has been most commonly used in the mineral exploration industry, its application to permafrost investigations has become more common, particularly in mountainous and discontinuous environments (e.g. Hauck et al. 2003; Lewkowicz et al. 2011; Hauck 2013; You et al. 2013). Frozen ground is generally more resistive to electrical current than unfrozen ground. This contrast is particularly evident where permafrost is surrounded by unfrozen ground because the unfrozen moisture content of the ground is much lower in the permafrost body than in the surrounding sediments (Hauck 2013).

The ERT equipment used was an ABEM Terrameter LS profiling system with a Wenner electrode array configuration. The terrameter's internal battery was used to send electricity to sets of electrodes which consisted of 30 cm steel nails that were inserted ~20 cm into the ground. Resistivity data were processed using the RES2DINV software (Loke and Barker 1996; Loke et al. 2003) with the robust inversion method used in an iterative manner until the modelled pseudosection's root mean square error did not appreciably decline (<1%) from the prior iteration (typically 5% error and five iterations). Resistivity profiles were then topographically corrected using slope measurements taken along the ERT profiles using a Brunton compass in conjunction with multiple elevation values from a digital hand-held GPS collected at profile endpoints (e.g. Lewkowicz et al. 2011). The depth of penetration of the ERT profile depends on the spread of the electrode array with penetration of approximately 6 m for a 40 m survey, 12 m for an 80 m survey and 25 m for a 160 m survey (excluding roll-along surveys).

Although ERT is a useful technique for permafrost investigations, it requires other data in order to validate the results as there is no universally applicable resistivity boundary for discriminating between unfrozen and frozen ground (Hauck 2013). For example, in the glaciomarine sediments on the eastern Hudson's Bay coastline, Fortier et al (2008) used 1000 Ω m to delineate between unfrozen and frozen ground whereas in the organic soils of the southern Yukon, Lewkowicz et al. (2011) used values as low as 300 Ω m. Additional problems for the interpretation of ERT profiles include the potential presence of coarse sediments, which may have similar resistivities to those of fine-grained warm permafrost (e.g. Hilbich et al. 2009), and bedrock at depth which typically has high resistivities, similar to those of cold permafrost (Lewkowicz et al. 2011).

A 120 cm long titanium frost probe was used to detect the presence (and depth) of a frost table wherever possible along each of the ERT profiles. At selected sites, where the frost table was not encountered or where probing results were uncertain, instantaneous ground temperature profiles (e.g. James et al. 2013) were recorded continuously by an Onset Hobo Pro v2 logger for 15 minutes using four thermistors attached to a wooden dowel at 20 cm increments. These were used to predict or measure if frozen ground was present at the probing site. Reconnaissance level surveying was also done at each site to detect periglacial landforms and to record the vegetation characteristics and surficial cover. Continuous temperature records for one year obtained using Onset Hobo Pro v2 loggers are available for the air, ground surface, and 50 cm soil depth for one Cartwright permafrost site. At four additional sites, mean annual ground temperatures were calculated from 4-hour interval measurements s at depths ranging from 50 to 120 cm using Thermochron iButton loggers placed inside CPVC tubes which were inserted into the ground.

4 RESULTS

A total of 16 ERT surveys with lengths of 40 to 240 m were undertaken, seven in Cartwright and nine in Nain. Bodies of frozen ground were detected in parts of 14 surveys with permafrost conditions inferred for at least 12 of these. Here we present results from a selection of the surveys in order to illustrate the range of observations.

4.1 Survey results in Cartwright

ERT and field surveys in Cartwright targeted previously identified palsa fields in three elevated peat bogs adjacent to the community. Frozen ground, interpreted as permafrost, was detectable via probing in mid-summer on individual palsas and in some peat covered areas around the features. ERT surveys suggested that permafrost was unlikely to be present unless detectable in the near-surface. Typical frost table depths, where detectable in late-July, ranged from 35 to 65 cm with a few instances where they were nearly 100 cm. Along the longest ERT profile (Figure 2a), a frost table was encountered on individual palsas and often in the peat surrounding them, with full (120+ cm) penetration occurring at a distance of several metres from individual palsas.

Comparison between the ERT surveys and the frost probing results puts the modelled resistivity boundary between frozen and unfrozen ground at between 300 Ω m and 400 Ω m, values similar to those for organic materials in the southern Yukon (Lewkowicz et al. 2011). Consequently, these threshold values were adopted for delineating between frozen/unfrozen ground in all the Cartwright ERT profiles. However, some resistivity values exceeding 300-400 Ω m were not interpreted as permafrost but as seasonally frozen ground. In addition, the slightly higher resistivity values immediately beneath some of the larger palsas (Figures 2a and 2b) are believed to be artefacts of the inversion process, and the high resistivity values at depths greater than 10 m (Figure 2a) are interpreted as bedrock.

The thickest body of permafrost encountered in Cartwright was about 6 m thick and was located along the longest profile (Figure 2a) 54 m from the survey start. At the northernmost Cartwright site (Figure 2b), a 5.7 m borehole was water-jet drilled and instrumented with Onset Hobo loggers to record bi-hourly variations in ground temperatures at six depths (0.5 m, 1.0 m, 2.0 m, 3.0 m, 4.25 m, 5.7 m). Resistance to the advance of the pipe stem during water-jet drilling was noted until 3.5 m which is comparable to the ERT-derived maximum permafrost thickness of 4 m at this site.

The monitoring station located in the largest Cartwright palsa field recorded a mean annual air temperature (Aug. 2, 2013 to Aug. 1, 2014) of -0.5°C and a mean ground surface temperature of 0.8°C, corresponding to a surface offset of only 1.3°C (Smith and Riseborough 2002). Annual ground temperatures measured at depths of 25 cm and 49 cm (base of active layer) were -0.3°C and -1.7°C, respectively. Using the freezing degree days in the air and at the ground surface, this site's n-factor is calculated to be 0.62 which can be used to estimate the average winter snow depth when including the mean annual air temperature (see Smith and Riseborough 2002). According to this approach the average winter snow depth at this site is less than 20 cm, which concurs with comments by community members that described a very thin snow cover (*Gary Bird, personal communication, August 2014*).

4.2 Survey results in Nain

ERT and field surveys in Nain targeted areas identified by Nunatsiavut Government personnel as being sites of future infrastructure development. Additional surveys were also conducted at sites that were interpreted as being most likely to have permafrost on the basis of surface features and local geomorphology. Permafrost was inferred to occur in patches within seven of the nine surveys undertaken. However, confirmation of the presence of a frost table via probing could only be done along four transects due to overlying community infrastructure (buildings and roads) and coarse near-surface surficial cover consisting of gravels and sands which are impossible to penetrate with a frost probe.

The modelled resistivity boundary between unfrozen/frozen ground in the vicinity of Nain was inferred to occur between 800Ω m and 1000 Ω m based on the results from the ERT surveys and probing, but the presence of surficial deposits with high modelled resistivities (coarse gravels and sands) made delineation challenging. Bedrock, which is common around Nain was also an issue, but was generally distinguishable by resistivity values exceeding 10,000 Ω m. The thickest permafrost was inferred to occur beneath the construction site of the Torngâsok Cultural Centre in Nain with a maximum thickness of ~18 m based on two ERT profiles (Figure 3a; second profile not shown). Permafrost, inferred to be about 7 m thick, was also present beneath a grassed area to the southwest of the gravel pad where well-defined frost tables were less than 120 cm deep. Moderate ground subsidence appears to have occurred directly upslope of this site at a decommissioned fire station while severe ground subsidence has occurred at the nearby Puffin Snacks convenience store.

A 160 m long ERT survey was conducted in a forested zone adjacent to the local primary school ~120 m upslope of the Cultural Centre surveys. Frost probing and instantaneous ground temperature measurements detected frozen ground along sections of this transect and ERT results indicated permafrost virtually continuously along the profile. The maximum thickness of permafrost along this survey line was inferred to be ~9 m (Figure 3b). In the remaining surveys, permafrost was inferred to occur in small patches along two transects while a third gave uncertain results. Frozen ground was detectable using both ERT and probing along several profiles but its shallow depth and the mid-July survey dates suggest that some of this may have been seasonally frozen ground rather than permafrost (results not shown). Near-surface bedrock also affected the interpretation of a survey in a forested zone which transitioned upslope into tundra where the resistivity values were particularly high (Figure 4a). The presence of a frost table was inferred along portions of this section but could not be confirmed by the ERT results because of the impact of the bedrock. The existence of permafrost at this site is considered to be undetermined but possible given the survey results.

Two profiles undertaken at the site of a future multiplex development indicated that permafrost was absent across the lot but present downslope in undisturbed forest (Figure 4b). Along this transect, frozen ground was detected by both frost probing and instantaneous ground temperature measurements with ERT surveying showing a maximum permafrost thickness of about 7.5 m. The profile at this site was challenging to interpret due to the presence of very high modelled resistivities at depth and conspicuous subsurface contrasts inferred to be due to bedrock (Figure 4b).

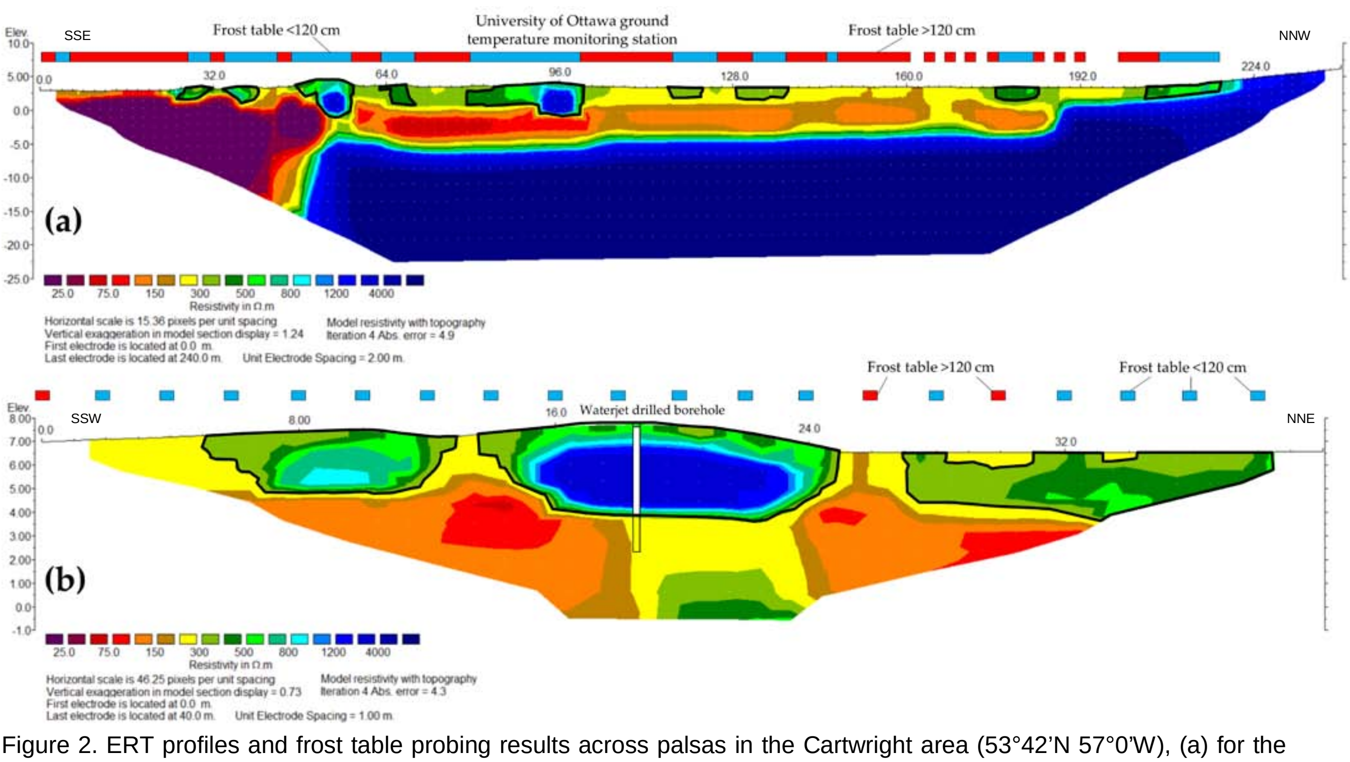

Figure 2. ERT profiles and frost table probing results across palsas in the Cartwright area (53°42'N 57°0'W), (a) for the longest ERT survey line and (b) across a water-jet drilled borehole. Ground interpreted as either seasonally or perennially frozen is outlined in black.

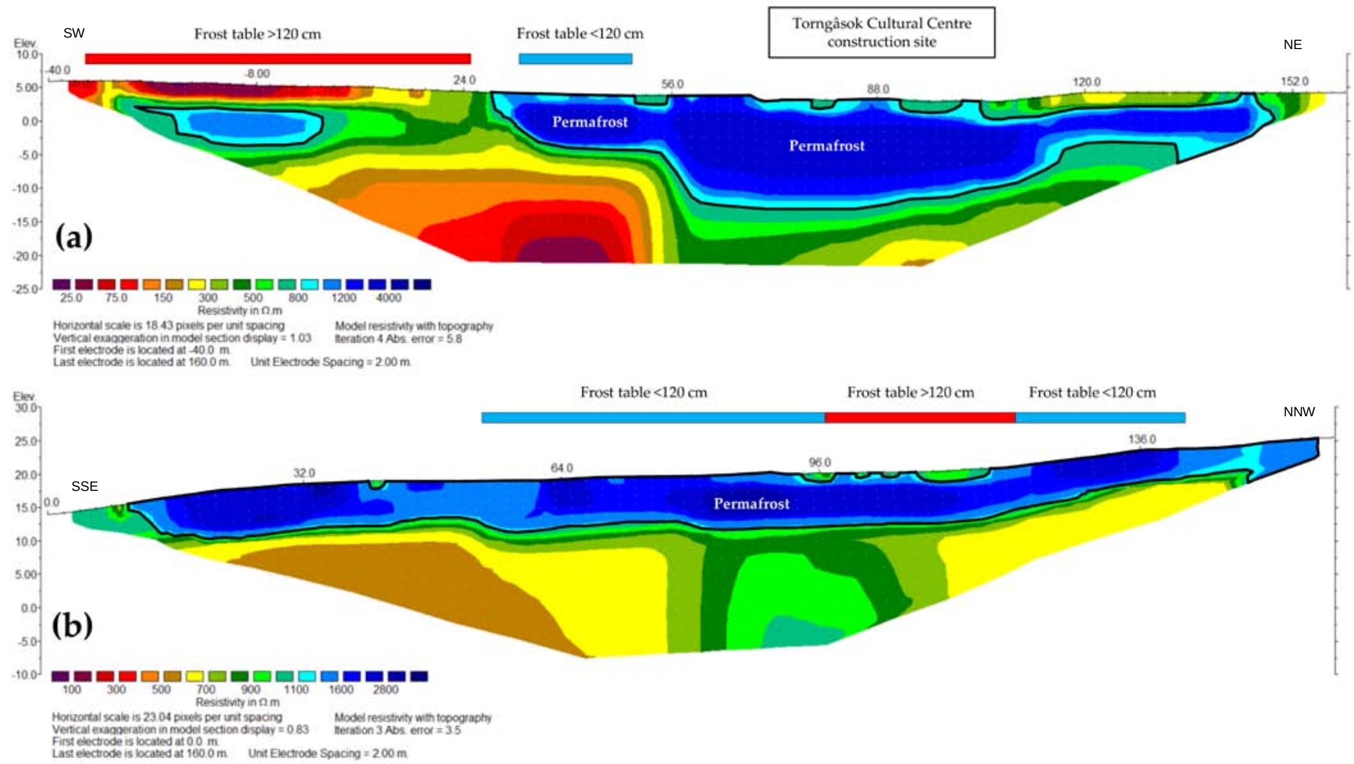

Figure 3. ERT profiles and corresponding frost table measurements (a) across the construction site of the Torngâsok Cultural Centre and (b) along a forested site upslope of (a) near the elementary school, within the community boundary of Nain, Labrador (56°33'N, 61°41'W). Ground interpreted as either seasonally or perennially frozen are outlined in black. Note: the resistivity scales differ for the two profiles.

5 DISCUSSION

5.1 Permafrost distribution and characteristics

Preliminary investigations of permafrost conditions around Cartwright and Nain revealed the presence of discontinuous permafrost within sections of both communities, in accordance with the Permafrost Map of Canada. In Cartwright, frozen ground was found to be restricted to areas around and beneath palsas on exposed raised bogs where the peat cover is well-drained. ERT was shown to be very useful for permafrost detection in these palsa bogs because of the strong temperature and moisture contrasts between unfrozen and frozen ground. The existence of permafrost at Cartwright where mean annual air temperatures equal or exceed 0°C can be explained by both the large thermal offset (Burn and Smith, 1988) and the small surface offset calculated for these sites. Thick peat overlying the permafrost bodies provides a measured thermal offset of -2.5°C (2013-2014 data). Combining this and the relatively small surface offset (1.3°C) yields a total offset of -1.2°C. This suggests that permafrost preservation could potentially occur at mean annual air temperatures up to +1.2°C, slightly lower than the decadal mean air temperature of +1.4°C (2004-2013). The 2014 mean annual air temperature recorded at Cartwright Airport of -0.4°C and the University of Ottawa monitoring station mean of -0.5°C indicate that 2013-2014 was almost 2°C colder than the prior 10-year period.

These observations suggest that the recent decadal average of air temperatures at Cartwright approximate the limit of viability for palsas in the region. It is also probable that the observed century long warming in air temperatures since the end of the Little Ice Age (e.g. Zhang et al. 2006; Way and Viau 2014) has reduced the areas viable for permafrost to the most exposed sites with the greatest negative total offset. In this context, the large thermal offset may be the cause of permafrost or may be the result of its presence: a relatively large thermal offset can exist at sites in a rapidly transitioning climate due to the lagged response of ground temperatures to regional atmospheric warming. Continued monitoring of these palsas is therefore a priority for evaluating the sensitivity of regional permafrost to rapid warming projected to occur in Labrador in the coming decades (Finnis 2013; Way and Viau 2014).

Permafrost conditions in the areas around Nain are more complex than in the vicinity of Cartwright for a number of reasons. First, permafrost was inferred as being present beneath both mineral and organic soils in both undisturbed and disturbed conditions. Second, permafrost bodies are in varying states of stability with some showing signs of degradation. Third, ERT was able to discriminate between frozen and unfrozen ground along all surveys in Cartwright whereas in Nain sources of external validation were required. The relatively thick permafrost (>15 m) detected beneath the future site of the Torngâsok Cultural Centre contrasts with the absence of permafrost in other sections of the community, implying that local factors have contributed to its site-specific preservation of permafrost. These likely include surficial materials, the history of human settlement and subsurface hydrology. In particular, the presence of fine-grained marine sediments below coarse-grained glacial tills in the lower slopes and valley bottoms in Nain may explain why some permafrost contains excess ice as these fine-grained marine sediments can be particularly frost-susceptible (Fortier et al. 2008). Damage due to heaving and subsidence has been noted for several houses and other buildings in Nain. Some of this may be due to deep winter frost penetration in the coarse near-surface soils but permafrost has potentially been of historical significance. The combined effects of several hundred years of human occupation, widespread surface disturbance and climate warming, may have led to the degradation of permafrost bodies, causing the subsidence of older buildings and leaving only isolated residual patches within the community itself. This inference is supported by the model predictions of Zhang et al. (2006), which show the areas surrounding Nain as experiencing widespread permafrost degradation over the interval between the Little Ice Age and the present-day in response to regional warming.

5.2 Challenges and limitations of detecting permafrost conditions in coastal Labrador

The moderating presence of the cold Labrador Current along coastal Labrador results in cool summers which promote the preservation of seasonally frozen ground well into the summer. Frost probing and instantaneous ground temperature profiles detected frozen ground in both Cartwright and Nain, some of which the ERT profiling suggested was seasonally frozen.

In Cartwright, seasonal frost likely existed between palsas at several locations, distinguished on the ERT profiles by their lack of surface topographic expression, the relatively thin nature of the near-surface higher modelled resistivity layer, and by the layer's lower values compared to those of the adjacent palsas (Figure 2a). Seasonal frost is also interpreted to have been present at several profiles in Nain, but deep frost penetration (>200 cm) along several transects makes it difficult to distinguish it from thin permafrost. The coarse surficial cover around Nain consists primarily of glacial tills which allow deep temperature penetration due to high thermal conductivities. As a result, ERT profiles and field data also indicate the presence of deep active layers (>120 cm) along portions of several surveyed sections (Figure 3a, b). This would pose a problem if frost probing alone were to be used for permafrost detection.

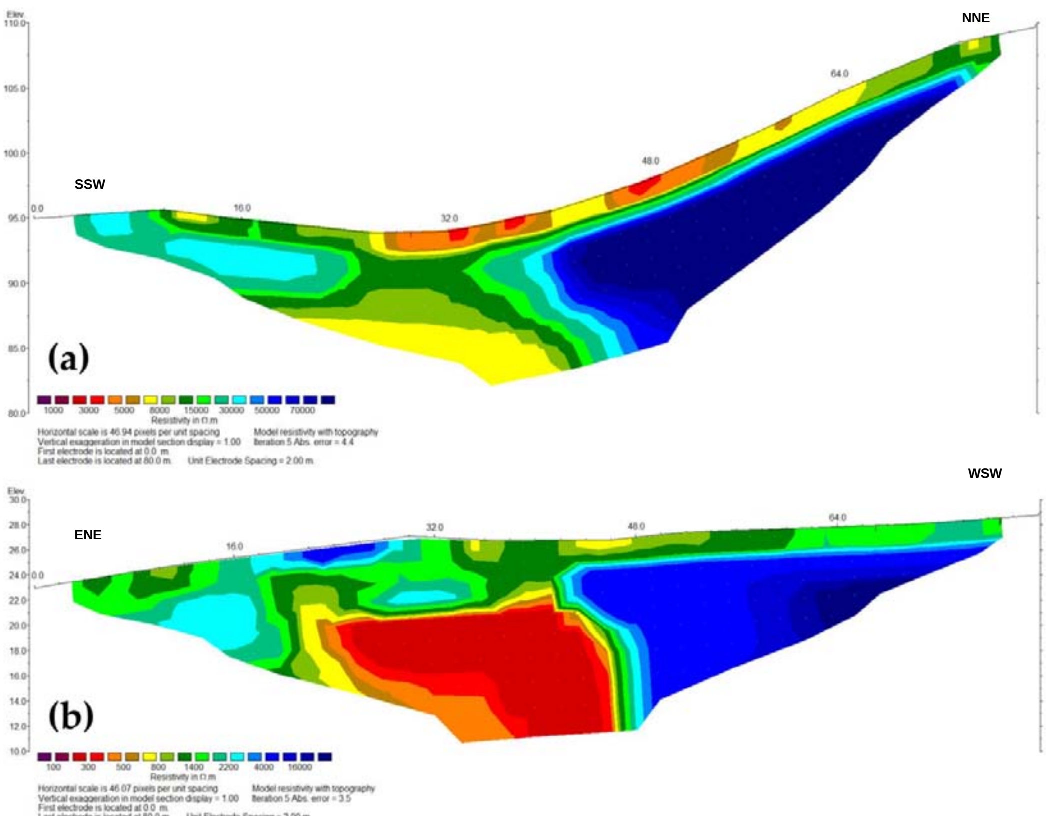

Figure 4: ERT profiles (a) in the forest-tundra transition zone and (b) across the proposed site of a multiplex housing development, within the community of Nain, Labrador. Note: the resistivity scales differ for the two profiles.

Near-surface bedrock present along ERT profiles in both Cartwright and Nain also complicated the interpretation of ERT results. Generally, bedrock could be detected by resistivities which exceeded those normally recognized for the sites as being due to frozen ground (Figure 4a,b). However, bedrock resistivity values were almost indistinguishable from those expected for permafrost along several transects in Nain. Heterogeneous ground and hydrological conditions within the community coupled with a long history of human settlement in Nain further complicated the interpretation of ERT results.

6 CONCLUSION

This study demonstrates the utility of ERT for permafrost investigations in the discontinuous permafrost environments of coastal Labrador. In Cartwright, permafrost was found only in palsas in elevated bogs with a thick peat cover. Permafrost was confirmed by probing, ground temperature monitoring and ERT at these sites. Permafrost conditions were either confirmed or inferred within numerous small patches in the community of Nain in both undisturbed and disturbed environments. The lack of surface features indicative of permafrost and the coarse surficial cover demonstrate both the challenges for interpreting local permafrost conditions and the utility of ERT which can identify permafrost bodies at depth.

The two locations highlight the contrasting permafrost environments present in Labrador where discrimination of permafrost varies from easy (Cartwright) to challenging (Nain). We emphasize the necessity of having external validation of ERT results in the form of either standard field methods or information from nearby boreholes. Without direct confirmation of permafrost presence or absence along a particular ERT transect, permafrost can only be inferred after calibration against sites with known subsurface characteristics. Future work in both communities should help identify the spatial extent of permafrost bodies and the primary drivers of permafrost persistence in these marginal environments.

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