Integrated Geophysical Approach for the Detection and Assessment of Ground Ice at Parsons Lake, Northwest Territories

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ABSTRACT

The mapping of ground ice distribution is fundamentally important for oil and gas development in the Arctic because the melting of ice within permafrost destabilizes the ground, which could lead to damage to infrastructure. Although borehole drilling provides accurate subsurface information, the process is expensive, time consuming, and only gives point samples. Alternative geophysical techniques like capacitively-coupled resistivity (CCR) and ground-penetrating radar (GPR), however, are non-destructive, relatively cheap, and surveys can be conducted over a large area. The success of geophysical tools in permafrost environments depends on the variations in physical properties between unfrozen/frozen materials and ice-rich/ice-poor sediments. Although GPR delineates structure and CCR quantifies subsurface electrical properties, the tools have rarely been used together in permafrost areas. In order to test the accuracy of the technology, this study correlates geophysical outputs with ground-truth data at four boreholes from Parsons Lake, a potential hydrocarbon development site in the Mackenzie Delta, NWT. Geophysical research was conducted in July 2009 and March 2010, and the borehole data is from March/April 2004. For three out of four boreholes, gravimetric ice content significantly controls electrical resistivity in winter at site-specific rates with 95% confidence. The R^2 values are 0.46, 0.56, and 0.62. Hence, there are additional environmental factors that need to be considered to improve the regression model, such as salinity, unfrozen water content, and ice structure; we hope to quantify ice structure with GPR in the future. Summer geophysical data, however, correlated poorly with the winter borehole data, partially because of the likely influence of additional unfrozen water content in the shallow subsurface.

RÉSUMÉ

La détection de glace sous-terrain est fondamentalement important pour le développement de pétrole et de gaz dans l'Arctique, parce que la fonte de la glace dans le pergélisol déstabilise la terre, qui pourrait mener à des dommages aux infrastructures. Bien que les trous de forage fournissent des informations précises, le processus coûte cher, prend du temps, et donne seulement des échantillons de points. Les techniques géophysiques alternatives comme la résistivité électrique et le géoradar, cependant, sont non destructives, relativement bon marché, et peuvent être utilisées pour examiner une grande superficie. Le succès des outils géophysiques dans des environnements pergélisolées dépend des variations des propriétés physiques entre les matériaux dégelés/congelés et les sédiments riches en glace/pauvre en glace. Bien que le géoradar délimite la structure et que la résistivité mesure les propriétés électriques, ces outils ont rarement été utilisés ensemble dans des régions pergélisolées. Afin d'examiner l'exactitude de la technologie, cette étude corrèle les résultats géophysiques avec des données obtenues de quatre forages à Parsons Lake, un site potentiel de développement d'hydrocarbure dans le delta du Mackenzie, NWT. La recherche géophysique a s'est déroulé en juillet 2009 et mars 2010, et les données des forages ont été recueuillies en mars et avril 2004. Pour trois des quatre trous, le contenu gravimétrique de glace détermine de manière significative la résistivité électrique durant l'hiver avec une confiance de 95%. Les valeurs de R^2 pour les trois trous sont 0.46, de 0.56, et 0.62. Par conséquent, il y a des facteurs environnementaux additionnels qui doivent être considérés pour améliorer le modèle de régression, tel que la salinité, l'eau dégelée, et la structure de glace; nous espérons mesurer ce dernier avec le géoradar à l'avenir. Les données géophysiques d'été, cependant, ne sont pas bien corrélées avec les données des forages en hiver, en raison probablement de l'influence de l'eau dégelée additionnelle dans la sous-surface peu profonde.

1 INTRODUCTION

The nature and distribution of massive ground ice is one of the most unpredictable and problematic geological variables in near-surface deposits characterized by continuous permafrost. Permafrost underlies 24% of the northern hemisphere with approximately 50% of Canada being affected (Zhang et al., 2000). The amount of ground ice in permafrost varies from nearly 0% by volume in dry permafrost to nearly 100% in the case of wide ice wedges, ice lenses, and massive ice sheets (Williams and Smith, 1989). Occurrences of massive ground ice are widely reported in the Yukon Coastal Plain and Mackenzie Delta areas of the western Canadian Arctic (Mackay and Dallimore, 1992; Pollard and Dallimore, 1988).

Mapping ground ice distribution is an enormous challenge facing land management and resource development related to oil and gas in the Mackenzie Delta, NWT. The melting of ice within permafrost destabilizes the ground, leading to extensive thaw subsidence called thermokarst, which could result in the destruction of ecosystems and damage to infrastructure. Due to ongoing human activities related to oil and gas exploration, as well as climate change effects associated with rising temperatures, permafrost degradation is expected to increase in the western Canadian Arctic (Maxwell, 1997).

Traditional methods for identifying ground ice involve the drilling of holes to directly measure ice content (Moorman et al., 2003). This technique, however, is expensive, destructive, and only provides point samples. Furthermore, lateral interpolation between holes is unreliable in areas of high variability. A non-destructive geophysical technique like capacitively-coupled resistivity (CCR) is effective for quantifying the electrical properties of near-surface materials in permafrost environments (Kneisel et al., 2008). The success of geophysical tools in permafrost environments depends on the variations in physical properties between unfrozen/frozen materials and ice-rich sediments/ice-poor sediments (Kneisel et al., 2008). Ground-penetrating radar (GPR) is effective for imaging the near-surface structure and stratigraphy of permafrost (Moorman et al., 2003), so it is a useful complement to electrical methods. Each of these geophysical tools has been used successfully to map various aspects of permafrost, but only a few studies have incorporated two or more systems in a complementary fashion (De Pascale et al., 2008).

The primary objective of this paper is to evaluate if CCR and GPR can measure ice contents at Parsons Lake, a potential hydrocarbon development site in the Mackenzie Delta. Furthermore, we wish to understand how different environmental and surficial geological conditions affect geophysical outputs, and hence, our conclusions about ground ice distribution. Using geophysical tools to detect permafrost properties should enable land use planners to estimate the thermokarst risk of an area using a faster and cheaper approach.

2 BACKGROUND

2.1 Permafrost and Ground Ice

Permafrost is defined as the thermal state of ground where temperatures remain at or below 0°C for two years or more (*Permafrost Subcommittee*, 1988). Its formation, persistence, and disappearance are dependent on climate. Furthermore, its temperature, distribution, and thickness respond to natural environmental changes and anthropogenic disturbances like natural gas exploration that disrupt the thermal regime of the ground.

In both buried and intrasedimental forms, massive ground ice is defined as having a gravimetric ice content exceeding 250% (*Permafrost Subcommittee*, 1988). The gravimetric moisture content is a ratio equal to the mass of water divided by the mass of bulk material. For ice structures, it can be greater than 100%, because the ice content in the host sediments can exceed the maximum amount of water the material is capable of holding under unfrozen conditions. The volume of ice exceeding the saturation moisture content is called excess ice. When permafrost containing excess ice thaws, the ground surface subsides in proportion to the volume of excess ice (Williams and Smith, 1989). As a consequence, understanding the ice content and distribution of ground ice is important for engineering plans related to natural gas development in the Mackenzie Delta.

2.2 Study Area

Fieldwork activities were conducted at Parsons Lake, NWT (68°59' N, 133°33' W), the site of a natural gas field located approximately 75 kilometres northeast of Inuvik (Figure 1). To help in calibrating the geophysical surveys with a known ground ice body, data was also collected at a pingo near Swimming Point in March 2009, which is approximately 40 kilometres NW of Parsons Lake. In order to correlate geophysical data with borehole data, GPR and CCR surveys were conducted along two transects at Parsons Lake, and each transect intersected two boreholes (Figure 2). The research team conducted fieldwork at Parsons Lake in July 2009 and March 2010.

Figure 1. The location of Parsons Lake, NWT, shown in Google Earth

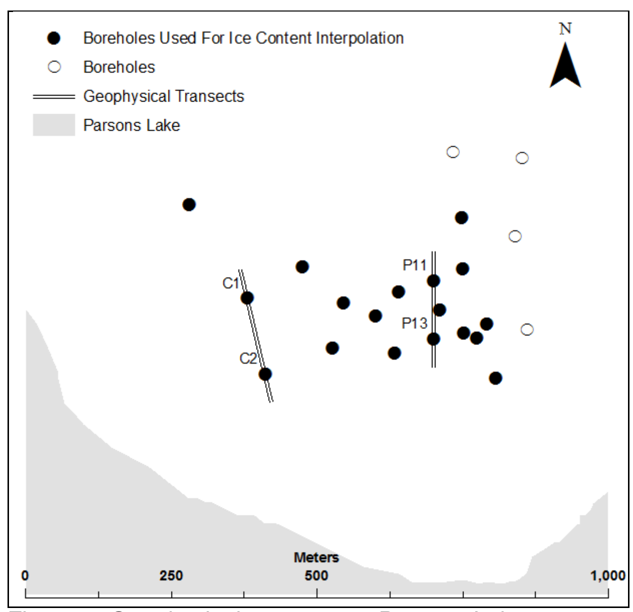

Figure 2. Geophysical transects at Parsons Lake

3 METHODS

3.1 Ground-Penetrating Radar

GPR is a non-destructive geophysical technique that involves the transmission of electromagnetic waves (10 – 1000 MHz) into the ground. Low frequency antennas are characterized by high depth penetration and low resolution, whereas high frequency antennas are characterized by low depth penetration and high resolution (Annan, 2004). This study employed a 50 MHz unshielded antenna.

With GPR, pulses propagate through the ground, and reflections occur from subsurface objects, structures, and other materials where there are changes in electrical properties. The type of material, density, temperature, and moisture content determine the dielectric constant (k). If there is sufficient contrast between dielectric constants at a boundary between materials, reflections of the transmitted pulse are generated. Since reflections are strong between unfrozen/frozen material, as well as ice-poor/ice-rich sediments (Kneisel et al., 2008), GPR works well in permafrost environments. As shown in Figure 3, GPR is effective at mapping the upper and lower contacts of massive ground ice bodies within a pingo close to Parsons Lake.

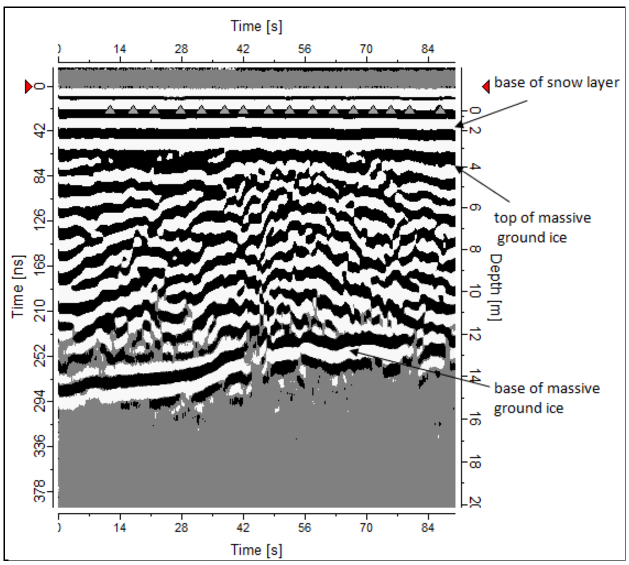

Figure 3. 50 MHz GPR survey across a pingo 40 km NW of Parsons Lake in March 2009

Figure 3 suggests that the thickness of the massive ice structure is approximately 9 metres, but since GPR depends on user-defined velocities to convert radar pulse travel times to depth measurements, the results could be inaccurate.

The correct propagation velocity of a radar pulse is controlled by (k), which is primarily affected by water content in the soil matrix. The relationship between (k) and electromagnetic velocity through a particular material under conditions of low conductivity (< 10 mS/m) is shown in Eq. (1) from Annan (2004). Typical velocity values for common geological materials of interest are 33 m/µs (fresh water), 74-150 m/µs (clay), 100-150 m/us (permafrost), and 150-173 m/µs (ice).

$$v_{material} = \frac{v_{air}}{\sqrt{k}} \quad [1]$$

GPR systems assume a flat topography for radar pulse trajectories. The system records the correct two-way travel time (t) and multiplies the latter by the user defined velocity (v) to obtain the distance travelled by the radar pulse. Hence, the depth to a reflector is calculated by Eq. (2). Topographic changes can be corrected by taking GPS points or surveying with an engineer's level over the profiles.

$$z = \frac{\sqrt{(vt)^2 - s^2}}{2} \quad [2]$$

z = depth to reflector
v = user defined velocity
t = two-way travel time measured by GPR
s = transmitter-receiver separation

The attenuation rate of a radar pulse is controlled by spreading, scattering, and absorption by conductive materials (Annan, 2004). Since GPR is a point source of electromagnetic radiation, the strength of a radar signal decreases by a factor or $1/r^2$ with depth. Scattering and/or reflection is a function of the radar target's geometry and electrical properties.

Absorption by conductive materials, however, is the predominant factor controlling signal attenuation. The work performed by the electric field to accelerate free ions causes the transmitted pulse to lose energy (Annan, 2004). Since higher conductivity materials are associated with higher concentrations of free ions, they effectively attenuate radar signals. Hence, signal penetration is limited in permafrost environments characterized by salty ground ice bodies or clay-rich materials.

3.2 Capacitively-Coupled Resistivity

The goal of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the surface. Underground resistivity is determined by porosity, fluid saturation, geochemical characteristics, temperature, phase composition of interstitial water, as well as the amount and composition of clay in soil (Loke, 2001; McNeill, 1980). By injecting a current into the ground and measuring the resulting potential difference between two points, the observed resistivity for a particular depth can be determined by Eq. (3).

$$\rho = kV/I \quad [3]$$

ρ = observed resistivity
V = voltage
I = current
k = geometric factor

When the current is transmitted into the ground, it propagates in all directions except above the surface due to the extremely resistive properties of air (Burger et al., 2006). As shown in Figure 4, the current follows many different paths from the transmitter to the receiver for one transmitter-receiver spacing.

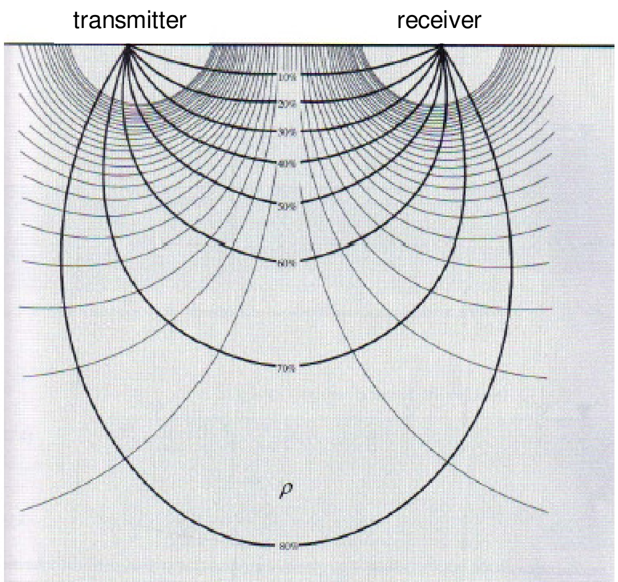

Figure 4. Current flow trajectories in a homogeneous subsurface (Burger et al., 2006)

Hence, the resistivity observed in the field is a value characteristic of a homogeneous subsurface. Essentially, the resistivity value computed by the instrument is an average of all the resistivity values calculated for each path from the transmitter to the receiver. Since Figure 4 assumes uniform resistivity with depth and lateral extent, the average resistivity is accurate throughout the entire hemisphere. In a heterogeneous subsurface, the current paths shorten when they encounter a less resistive layer and lengthen when they encounter a more resistive layer. Hence, the penetration depth of a given transmitter-receiver spacing is enhanced in resistive environments.

If one were to double the transmitter-receiver separation from that shown in Figure 4, the outer hemispherical shell would propagate further into the subsurface and cover a wider area. As a result, the observed resistivity would be averaged over a greater depth and lateral extent, which implies that the setup in Figure 4 is more reliable if one were interested in the shallow subsurface. In order to determine the true resistivity for multiple layers, an inversion using post-processing software (i.e. RES2DINV) must be applied. Since the positions of layer boundaries depend on the transmitter-receiver separation, the boundaries do not necessarily reflect accurate stratigraphic contacts between two materials of differing electrical properties. If, however, resistivity is used in conjunction with GPR, a representation of electrical properties within stratigraphic contacts can be shown. Furthermore, internal ice structure, which is detectable with GPR, can potentially be used as an index to quantify the connectivity of unfrozen water films, which affects electrical resistivity values.

For many permafrost materials, resistivity increases exponentially as unfrozen water content decreases (Pearson et al., 1983). The amount of unfrozen water is a function of soil texture, temperature, overburden pressure, and geochemical factors like salinity (Williams and Smith, 1989). As overburden pressure and salinity increase, the freezing point decreases. Furthermore, the amount of water that can exist in liquid form for a given freezing temperature increases as particle size becomes smaller (Williams and Smith, 1989). The presence of unfrozen water decreases resistivity, because it provides a conduit for current flow (Fortier et al., 1994). As water freezes in the soil, the ice content increases and as a consequence, the electrical resistivity also increases. Hence, electrical methods are effective at not only identifying frozen ground, but being able to delineate relative magnitudes of ice content within a ground ice structure. The absolute ice content is much more difficult to quantify, because the magnitudes of electrical resistivity values also depend on geochemistry and ice structure. In marine sediments, the resistivity of permafrost can be exceptionally low due to the higher conductivity of saline pore water (Kneisel et al., 2008). Furthermore, ice structure can significantly impact resistivity results. In interstitial ice, the unfrozen water films are continuous in pores and interconnected passages, and as a consequence, the structure of the ice allows the unfrozen water content to reduce electrical resistivity values (Fortier et al., 1994). In stratified cryostructure, however, the unfrozen water films are discontinuous, and as a consequence, the current flow through ice is impeded, which increases resistivity values. The effects of ice structure are linked to the spacing between ice lenses, the thickness of the ice lenses, and the dependence of electrical resistivity of ice on temperature.

In a geophysical logging study by Fortier et al. (1994), unfrozen water and ice contents were directly measured in the field using adiabatic calorimetry to define the relationship between the physical properties of frozen ground and electrical resistivity values at four shallow borehole sites in Umiujaq, Quebec, Canada. Linear regression models revealed poor R^2 values between physical properties (ice content, unfrozen water content) and electrical resistivity. Non-linear regressions, however, generated R^2 values ranging from 0.71 to 0.82 for unfrozen water content and values between 0.58 and 0.72 for ice content estimates (variations in R^2 depended on instrument setup design). The results suggest that the mass proportion of unfrozen water content in a sample decreases exponentially with increasing resistivity and the mass proportion of ice in a sample increases logarithmically with increasing resistivity.

For surface methods, Calvert (2002) showed that CCR was able to delineate relative changes in ice content for a 7.4 km transect at Lousy Point in the Mackenzie Delta. Highly resistive areas correlated well with the presence of ground ice. More specifically, resistivity exceeded 12,000 ohm-m for areas characterized by ground ice greater than 10 metres thick or exceeding 30% volumetrically. Unlike Calvert (2002), this paper is a statistical study that correlates ice content with results from surface resistivity methods.

4 RESULTS AND DISCUSSION

4.1 Delineating Relative Changes in Ice Content

Figure 5 is a 350 m by 220 m 3D interpolation of ground ice conditions for a portion of Parsons Lake. It was generated in MATLAB using the gravimetric ice contents at different depths taken from the boreholes shown in Figure 2. The two vertical slices represent the approximate locations of geophysical transects (CCR and GPR) surveyed in July 2009 and March 2010. Each transect intersects two boreholes, as indicated by C1, C2, P11, and P13. For visual clarity, all gravimetric ice contents exceeding 250% (threshold for massive ground ice) are illustrated in red. By examining Figure 5 and comparing it to Figures 6 and 7, it is clear that CCR is able to delineate relative changes in ice content at Parsons Lake. For example, by analysing the shallowest z-slice (2-metre depth) in Figure 5, it is apparent that site C is much more ice-rich near the surface than site P.

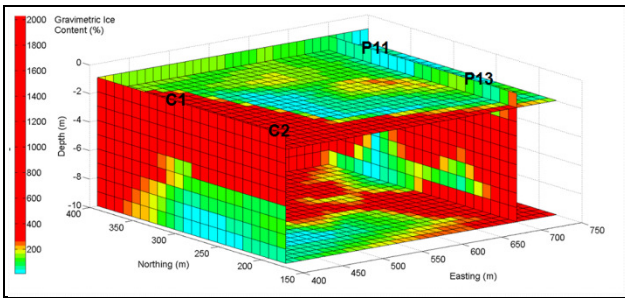

Figure 5. MATLAB generated 3D interpolation of gravimetric ice content from multiple boreholes at Parsons Lake. The vertical slices represent the locations of CCR/GPR surveys conducted in July 2009 and March 2010. The coordinates are relative to the bottom left corner of Figure 2.

Furthermore, site C is much more resistive near the surface than site P as shown in Figures 6 and 7. More specifically, site C, which is characterized by massive ground ice at 2 metres depth, is associated with resistivity values exceeding 12,000 ohm-m. Conversely, site P, which is characterized by ground ice contents less than 250% at 2 metres, shows resistivity values ranging between 1500-7000 ohm-m. In addition, high resistivity values near the surface can be explained by lower ground temperatures. At lower depths (6-10 m) where gravimetric ice contents fall below 250% for site C, electrical resistivity values decrease to values ranging from 0-7000 ohm-m. For site P, however, the situation is more complicated. Although Figure 7 shows that electrical resistivity decreases from the surface to a depth of 5 m and increases from 5-8 m, Figure 5 does not reveal the same pattern with gravimetric ice content for possibly two reasons. Firstly, all ice contents greater than 250% are coded with the same colour, so ice content trends between roughly 3-6 m depths cannot be seen. Secondly, CCR resolution may not have been sufficient to generate resistivity values that correlate with the peaks and troughs of ice content versus depth. For example, resistivity values for the shortest transmitter-receiver spacing applied (5 m) could be an average of low ice contents between 0-2 m depths and higher ice contents immediately below 2 m. As a consequence, CCR profiles show relatively higher resistivity values near the surface and lower values towards a depth of 5 m.

4.2 Correlating Geophysical Results with Ice Content From Borehole Data

Since the goal of the project is see how well geophysical tools measure absolute ice contents, vertical slices of electrical resistivity profiles from winter 2010 were correlated with gravimetric ice contents for all four borehole locations (Figure 8). At boreholes C1 and C2, electrical resistivity increases logarithmically with ice content. At borehole P11, however, electrical resistivity increases linearly with gravimetric ice content, but there may not be enough data points to produce a logarithmic curve. For sites C1, C2, and P11, it is clear that gravimetric ice content controls electrical resistivity at site-specific rates. The R^2 values range from 0.46, 0.56, and 0.62 for C2, C1, and P11 respectively. All correlations are significant at the 95% confidence level, and the p-values for C1 and C2 were computed after linearizing the functions in Figure 8 by plotting electrical resistivity versus the natural logarithm of gravimetric ice content. The p-values for C2, C1, and P11 are 0.004, 0.009, and 0.003 respectively. Nevertheless, there are still additional environmental factors that need to be considered to improve the regression model, such as unfrozen water content, ice structure, and geochemical variables like salinity. The reason P13 yields no relationship between electrical resistivity and gravimetric ice content could be because we did not have sufficient CCR resolution (transmitter-receiver separations) to generate enough resistivity values to correlate with the ice content versus depth for this borehole.

Note that points plotted in Figure 8 are located at depths ranging between 0-10 metres. Although the geophysical data is from winter, unfrozen water content can still be a factor, especially close to and below the depth of maximum seasonal annual temperature variation. For example, the temperature was approximately -5°C at a depth of 6 metres (depth of maximum seasonal annual temperature variation) for sites C1 and C2 in 2004 (Kiggiak-EBA Consulting, 2005), and unfrozen water content can still be prevalent under the aforementioned environmental conditions (Williams and Smith, 1989).

As noted in the methods section, ice structure can significantly impact resistivity results. By quantifying the potential connectivity for unfrozen water films through GPR profiles, we hope to improve the regression model. If one observes Figure 7 and Figure 9, it is clear that the electrical resistivity values across the shallow subsurface (0-2 m) are more relatively variable in summer compared to winter at site P. In summer, unfrozen water content is more variable at shallow depths, and where there is a noticeable change in CCR values in summer, there is a very noticeable change in ice structure as shown in the GPR image.

Widespread evidence suggests that the origin of massive ground ice in the western Canadian Arctic is intrasedimental (Mackay and Dallimore, 1992). Results from borehole drilling show that materials overlying massive ground ice bodies are fine-grained and conductive to segregation ice, whereas the underlying sediments are coarse-grained and conductive to the lateral and upward flow of groundwater toward aggrading permafrost. These observations argue against these material being marine sediments. Hence, we do not expect salinity, whose influence is usually associated with marine sediments, to be a statistically significant variable capable of explaining differences in electrical resistivity between boreholes.

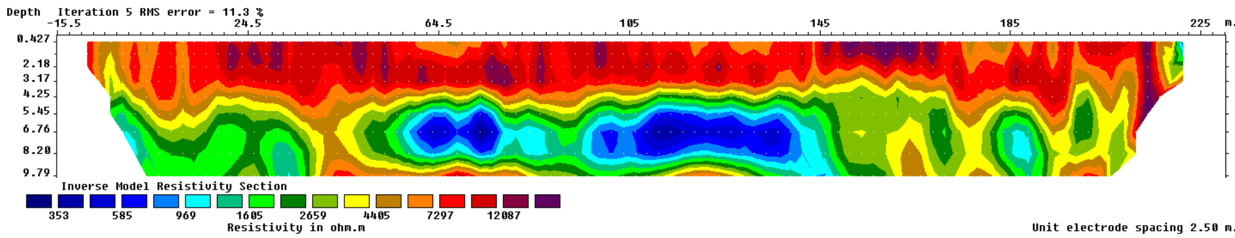

Figure 6. CCR survey conducted at C-site in March 2010 (5,10,15,20,25,30,35, and 40 m transmitter-receiver separations were accomplished)

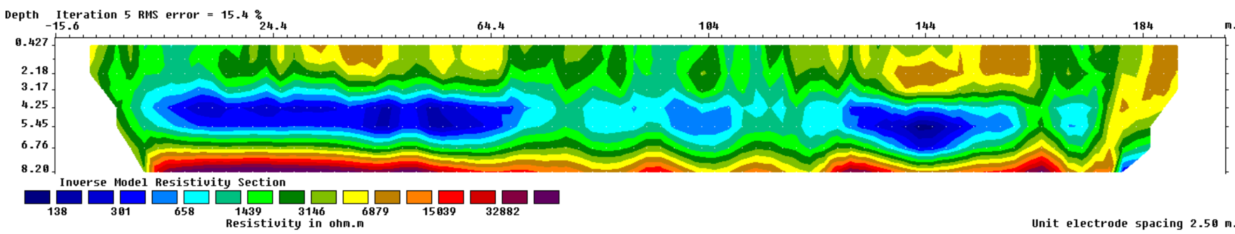

Figure 7. CCR survey conducted at P-site in March 2010 (5,10,15,20,25,30, and 35 m transmitter-receiver separations were accomplished)

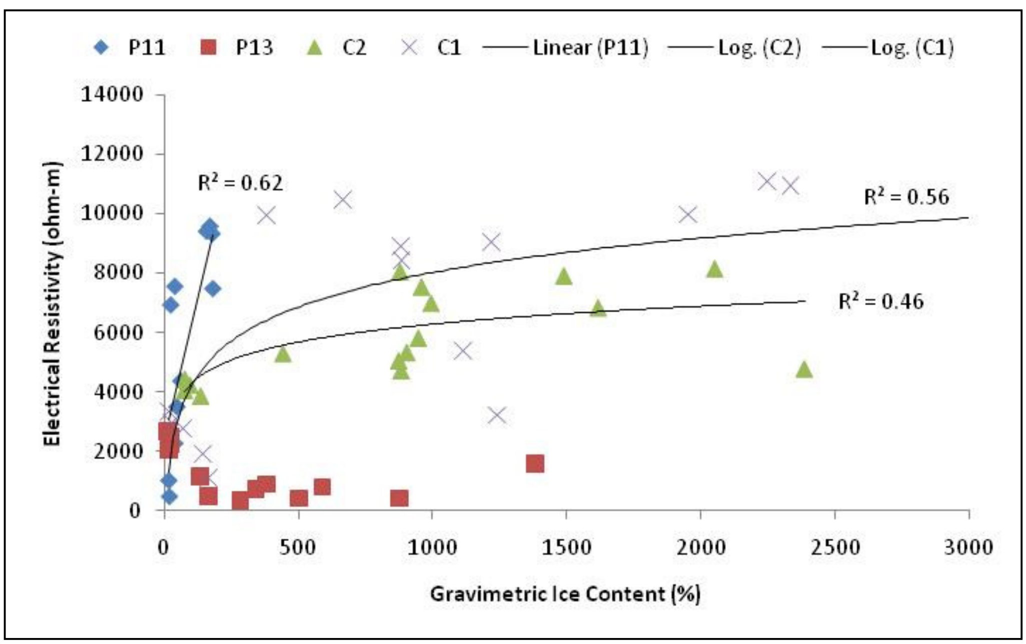

Figure 8. The relationship between electrical resistivity and gravimetric ice content at four borehole locations (note that a point of ice content exceeding 8000% is not shown, but was still included in R^2 calculations)

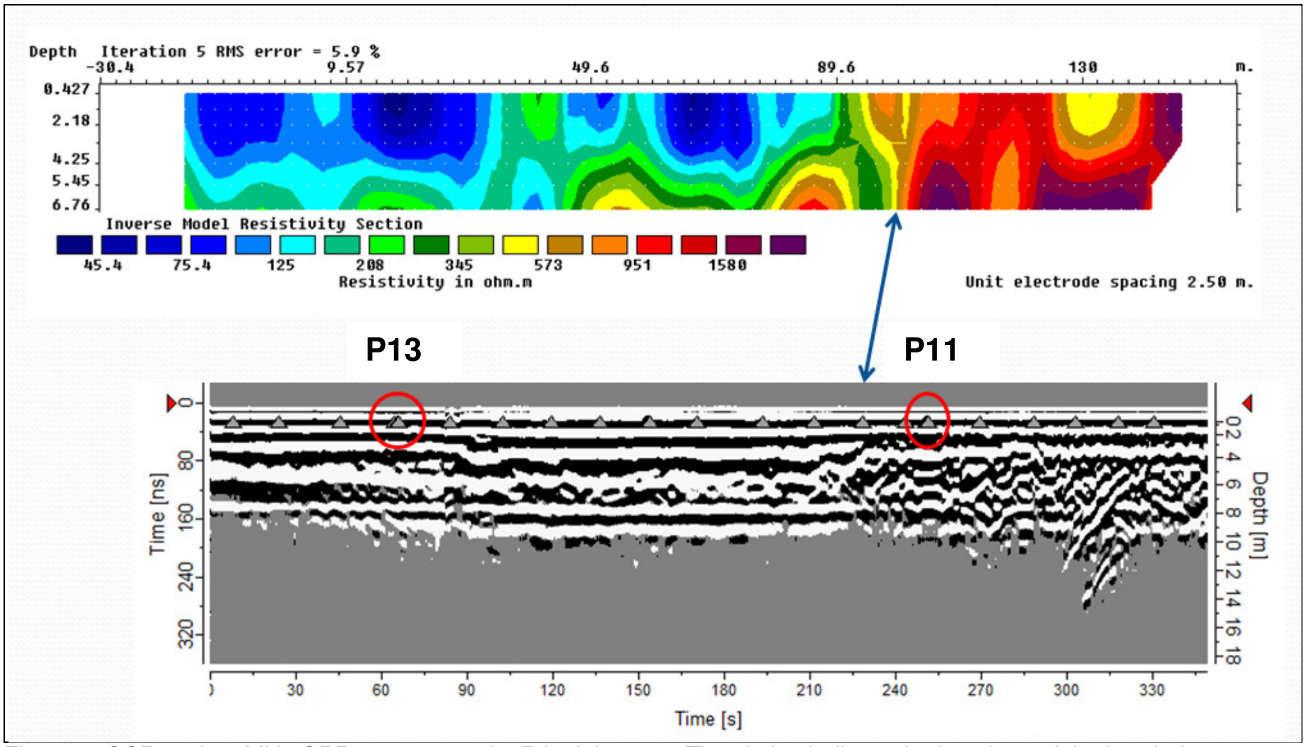

Figure 9. CCR and 50 MHz GPR transect at site P in July 2009. The circles indicate the locations of the boreholes.

4.3 Seasonal Effects on Geophysical Results

Although three out of the four boreholes reveal significant correlations between electrical resistivity and gravimetric ice content, the relationships are seasonally dependent. Borehole data collected in the winter of 2004 reveal that the highest ice contents are located between the surface and the depth of maximum seasonal annual temperature (MSAT) variation. As noted previously, ground thermal regime logs reveal that the depth of MSAT was approximately 6 m for both sites in 2004 (annual variations could exist due to snow cover and surface temperature changes). As shown in Figure 10, in winter, the peak of electrical resistivity occurs at roughly the same depth as gravimetric ice content for C1. In summer, however, the peak of electrical resistivity occurs at a lower depth. Hence, additional unfrozen water content in the shallow subsurface in summer could be responsible for the displacement of the resistivity peak. For boreholes C1 (Figure 10) and C2 (Figure 11), it is clear that the magnitudes of the resistivity peaks are lower in summer than in winter, which could be the result of seasonal changes in unfrozen water content, as well as higher ground temperatures. Figure 10, however, shows that summer resistivity values exceed winter resistivity values between 4-8 m depths. This could be the result of 2D subsurface model assumptions in the inversion process granted that there were seasonal changes in current flow distributions. Variations in resistivity perpendicular to the survey line (e.g. changes in ground ice conditions) could have led to distortions in the lower sections of the model obtained.

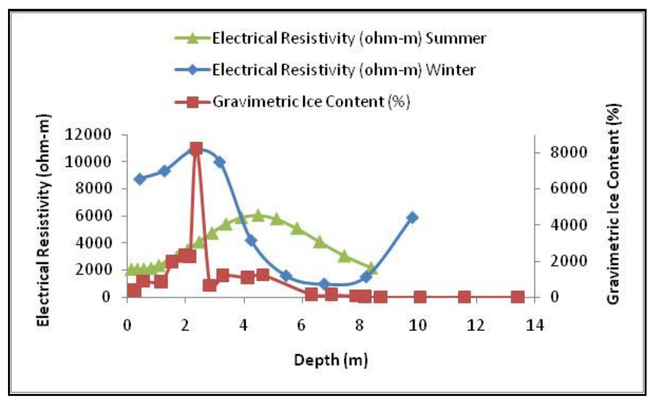

Figure 10. Seasonal changes in CCR results at C1.

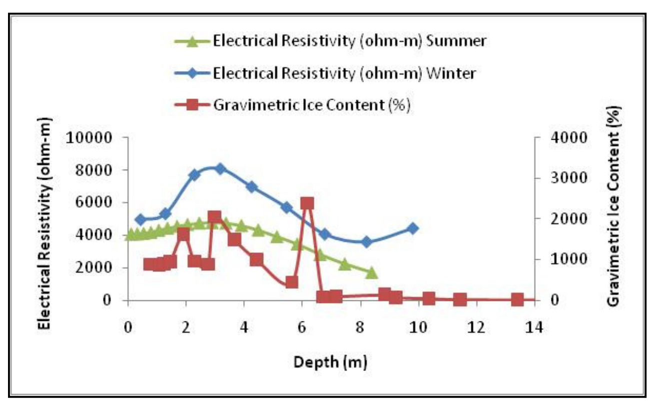

Figure 11. Seasonal changes in CCR results at C2

5 CONCLUSIONS

As water freezes in the soil, the ice content increases and as a result, the electrical resistivity rises. For many permafrost materials, resistivity increases exponentially with decreasing unfrozen water content. As a consequence, electrical methods are effective at not only identifying frozen ground, but being able to delineate relative magnitudes of ice content within a ground ice structure. Results from previous studies suggest that unfrozen water content decreases exponentially with increasing resistivity and ice content increases logarithmically with increasing resistivity. The absolute ice content is much more difficult to quantify, because the magnitude of electrical resistivity values also depends on geochemistry and ice structure.

At boreholes C1 and C2, electrical resistivity increases logarithmically with ice content. At borehole P11, however, electrical resistivity increases linearly with gravimetric ice content. For P11, there may not be enough data points needed to ultimately produce a logarithmic curve. For sites C1, C2, and P11, it is clear that gravimetric ice content controls electrical resistivity at site-specific rates. The R^2 values range from 0.46, 0.56, and 0.62 for C2, C1, and P11 respectively. Hence, there are additional environmental factors that need to be considered to improve the regression model, such as unfrozen water content, ice structure, and salinity. In addition, inaccuracies could have resulted from 2D subsurface model assumptions in the inversion process. In order to account for resistivity variations perpendicular to the survey line, a 3D inversion technique must be used.

Although three out of the four borehole sites reveal encouraging correlations between electrical resistivity and gravimetric ice content, the relationships are seasonally dependent. For C1 and C2, the magnitudes of electrical resistivity peaks are lower in summer than winter. Furthermore, in winter, the peak of electrical resistivity occurs at roughly the same depth as gravimetric ice content for C1. In summer, however, the peak of electrical resistivity occurs at a lower depth. Hence, seasonal changes in geophysical results could be due to seasonal changes in unfrozen water content and current flow distributions.

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