

Geophysical imaging of permafrost conditions along the northern Yukon Alaska Highway

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Challenges from North to South
Des défis du Nord au Sud

ABSTRACT

Three sections of the northern Yukon Alaska Highway have been identified for testing the usefulness of geophysical surveys for understanding permafrost degradation and assisting with highway management. Results from capacitive resistivity and ground-penetrating radar surveys are analysed and interpreted along with surficial maps, geotechnical borehole records, and surface observations of highway roughness and distress. Observed damage appears to be associated with a variety of ground ice conditions. The geophysical results help elucidate the terrain conditions and support the conclusion that multiple subsurface processes contribute to highway degradation. Several geophysical signatures are interpreted as indicative of terrain conditions involving ice-rich ground, frozen ground, thaw-susceptible sediments and shallow groundwater.

RÉSUMÉ

Trois sections de la route de l'Alaska - Yukon ont été identifiées pour tester l'utilité de levés géophysiques afin de comprendre la dégradation du pergélisol et aider à la gestion des routes. Les résultats de la résistivité électrique (système couplécapacitivement) et du géoradar sont analysés et interprétés en se basant sur les cartes des dépôts de surface, les forages géotechniques et les observations sur la rugosité de surface et la dégradation de la route. Les dommages observés semblent être associés à une variété de conditions de glace dans le sol. Les résultats géophysiques aident à élucider les conditions de terrain et appuient la conclusion que des processus multiples sous la surface du terrain contribuent à la dégradation de la route. Plusieurs signatures géophysiques sont interprétées comme une indication de conditions de terrain impliquant un sol riche en glace, un sol gelé, des sédiments sensibles au dégel et des eaux souterraines peu profondes.

1 INTRODUCTION

The Yukon Alaska Highway is a vital transportation route for both commercial, tourist and community traffic. On a regional scale, the Yukon Alaska Highway passes through zones of warm discontinuous permafrost with variable ice content (Heginbottom, 1995; Smith and Ednie, 2013). The highway is currently experiencing differential settlement caused by the degradation of permafrost, resulting in a ten-fold increase in maintenance costs for permafrost sections of highway (Murchison, 2012). Research test sections have been established along the Yukon Alaska Highway to investigate local permafrost conditions (Lewkowicz et al., 2011; James et al., 2013) and to examine effects of engineering mitigation techniques (de Grandpré et al., 2012; Stephani et al., 2014). Although understanding of permafrost degradation is increasing, knowledge gaps remain with respect to permafrost distribution and characteristics over affected sections of the highway.

Recently, Yukon Highways and Public Works (YHPW) embarked on a project to assess the utility of geophysical surveys for supporting management of a 190 km stretch of the northern Yukon Alaska Highway from Burwash

Landing to the Yukon/Alaska border (Hammond, 2013; Stevens, 2014). Geophysical data can provide spatially extensive and multidimensional information on permafrost conditions and can therefore be valuable in the planning and maintenance of land-based infrastructure (e.g., Brown et al., 1985). YHPW is interested in using the geophysical survey results to provide nearly-continuous information on permafrost conditions and ground ice occurrence along the highway corridor in order to better understand road distress.

Three sections of the northern Yukon Alaska Highway along the geophysical study corridor were identified by YHPW as priority problem areas exhibiting significant road surface damage and requiring medium to high intensity restoration. For these sections, we analyse and interpret geophysical survey results (provided by YHPW) with an aim to understand permafrost conditions and processes contributing to road distress, and to evaluate the utility of the geophysical surveys. Our interpretation is performed in conjunction with surficial geology, vehicle-level observations of road surface damage, road surface roughness measurements, and observations of ground ice and sediment texture from existing geotechnical boreholes.

2 YUKON ALASKA HIGHWAY

The three separate study sections of the Yukon Alaska Highway are illustrated in Figure 1: km 1811.1–1814.0 near Koidern River, km 1837.5–1842.0 near Dry Creek, and km 1882.6–1898.1 north of Beaver Creek. For each of these sections, we first assess the permafrost conditions and then characterize infrastructure damage using vehicle-level photography and road surface roughness. Finally, we interpret the geophysical survey results in the context of both the permafrost conditions and the damage assessment.

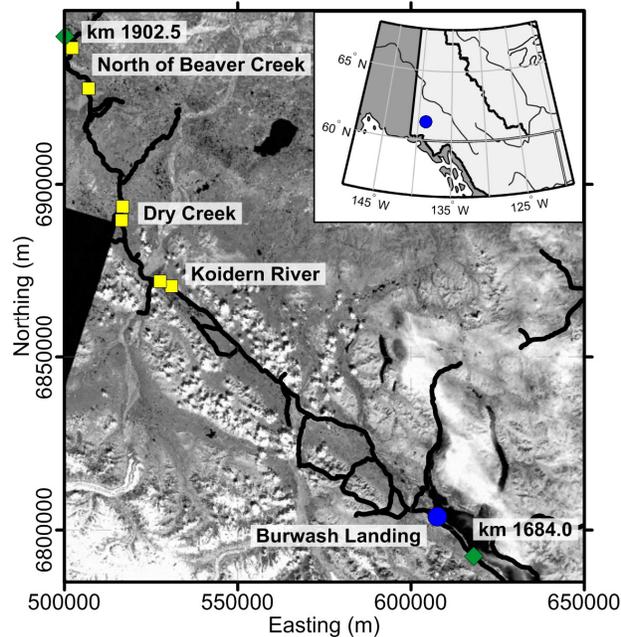


Figure 1. Northern Yukon Alaska Highway showing the three study sections.

2.1 Permafrost Conditions

We assessed permafrost conditions from Kluane Lake to the Canada-US border (km 1684.0–1902.5) using a multi-scale approach to establish terrain type and site specific permafrost and ground ice information. Ground ice conditions were analysed in the context of the surficial geology of Rampton (1979a,b,c,d) using the historical Alaska Highway borehole database (Lipovsky, 2009) and additional geotechnical boreholes drilled in December 2011 (Lister, 2012) and December 2013 (Stevens, 2014).

Observations of visible ice greater than 25 mm thick ("ICE") are generally above 4–6 m depth and occur for most of the surficial geology units excluding colluvial, pre-McConnell glaciofluvial, and modern fluvial deposits (Oldenborger et al., 2015).

2.2 Damage Assessment

We visually assessed road surface damage along the three high-priority damage sections using vehicle-level photographs (provided by YHPW). All of the observed

damage was related to thaw settlement which was classified as 1) local settlement occurring over a small area, 2) linear settlement occurring as elongate damage in any direction, and 3) general settlement occurring over large areas and affecting significant portions of the road surface and/or embankment. Local settlement includes damage such as sinking guardrails, isolated sinkholes and small depressions (Figure 2a). Linear settlement includes damage such as elongated depressions, cracking of the road surface or embankment and culvert failure (Figure 2b). General settlement includes large sections of differential settlement over the road and/or embankment (Figure 2c). In addition, the severity of the observed damage was classified in a purely relative sense as light, medium or severe.

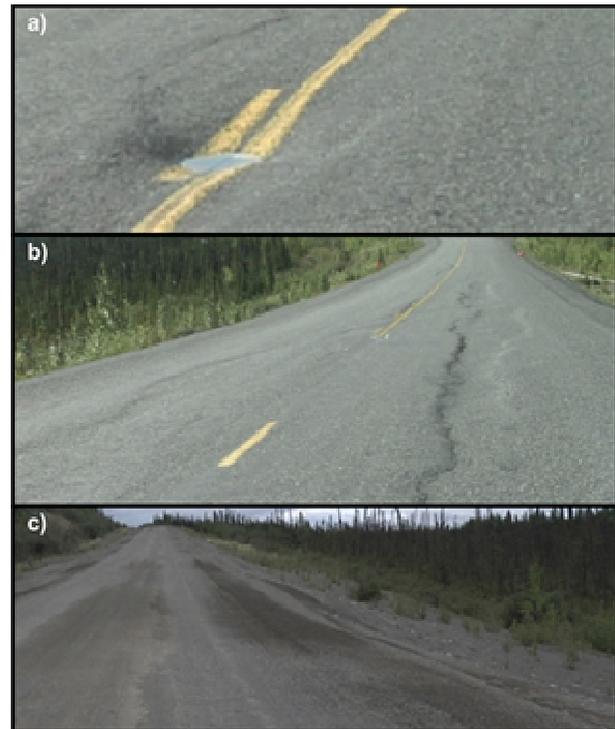


Figure 2. a) Localized damage: punctual thaw settlement, km 1896.2, 2011. b) Linear damage: longitudinal settlement, km 1896.4–1896.2, 2011. c) General damage: differential settlement, km 1894.4–1894.3, 2012.

We analysed the International Roughness Index (IRI) measurements (provided by YHPW) from Kluane Lake to the Canada-US border for the year 2010 (Figure 3). IRI represents cumulative vertical displacement of a sprung mass relative to a vehicle axle over a 100 m distance. Very poor highway conditions most frequently occur within Till and Organic surficial units for which ICE is encountered at a range of depths; poor IRI regions are also encountered for units with no observed ICE, although other types of ground ice may be present (Oldenborger et al., 2015). Surficial geology units with better IRI distributions are glaciofluvial, fluvial, colluvial and eolian. Causes of surface roughness may reside below the depth

of the mapped surficial geology. Furthermore, repair history, which is unaccounted for in this analysis, may bias the observed distribution of IRI values in that sporadic and targeted repairs are not evenly distributed among the mapped units.

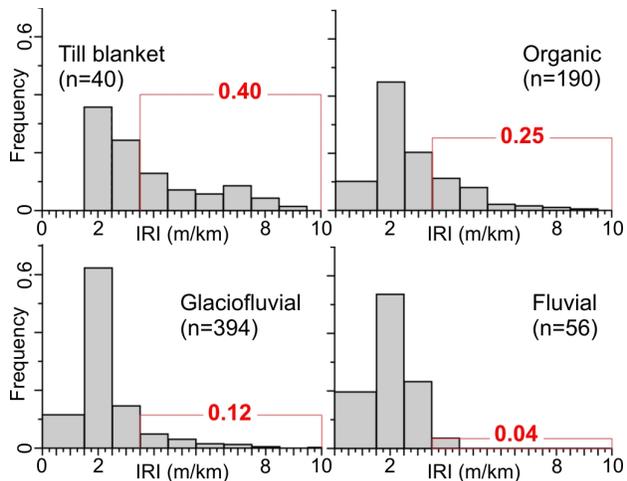


Figure 3. IRI measurements for km 1684.0–1902.5 classified as good: 0.0–1.5 m/km, ok: 1.5–2.5 m/km, poor: 2.5–3.5 m/km and very poor: 3.5–10 m/km. The portion of very poor conditions is indicated in red.

2.3 Geophysical Surveys

In planning the geophysical surveys for the Yukon Alaska Highway, the ability to execute long linear surveys from the highway surface was considered paramount. As such, YHPW contracted capacitive resistivity (CR) and ground-penetrating radar (GPR) surveys that could be deployed from a moving vehicular platform with automated (GPS) positioning. CR and GPR surveys were conducted simultaneously from km 1709.5–1902.5 in October 2012 by Golder Associates Ltd. (Hammond, 2013).

In permafrost terrain, measurements of CR can generally be used to infer some combination of the pore-fluid conductivity and the moisture content, or similarly, the material type and the amount of frozen/unfrozen water. As such, CR can be applied in an attempt to map material type and to characterize the occurrence of ice-bearing permafrost, thaw zones and thermophysical transitions.

Similarly, GPR reflections can generally be used to infer structural, textural, or moisture related changes of the subsurface materials. Active layer characteristics and location of taliks or massive ground ice are traditional GPR targets in permafrost.

3 RESULTS

CR survey results were delivered to YHPW as electrical resistivity sections in 3 km increments, interpolated to a uniform grid for display using a linear color scale (Hammond, 2013). Results were provided with identification of high and low resistivity zones, with some interpretation examples and observations from the 2011

geotechnical boreholes (Lister, 2011). Neither the raw data, nor the un-interpolated models recovered via inversion, nor the inversion parameters and convergence behaviour are available for analysis.

GPR survey results were delivered as interpreted significant coherent reflections (250 and 100 MHz, shielded) in 3 km increments with some interpretation examples (Hammond, 2013). For the sections considered here, there are few interpreted coherent reflections below the reflection identified as the base of road fill. As such, only the base of road fill reflection is considered. Neither the raw data, nor the GPR reflection amplitudes are available for analysis of features such as radar facies, reflection character, ringing or noise.

Geophysical survey results are reproduced here for selected 3 km increments of the identified priority damage sections. We combine the electrical resistivity sections and GPR reflections with observations from the 2011 geotechnical boreholes (Lister, 2011), surficial geology according to the Yukon terrain classification system (Lipovsky and Bond, 2014) and WorldView-2 satellite images from 27 August 2010 (copyright DigitalGlobe Inc., all rights reserved). We analyze each increment in conjunction with IRI measurements and vehicle-level damage observations from 2010. We use geotechnical information from the Alaska Highway borehole database (Lipovsky, 2009) to construct logs of primary sediment texture and ground ice information to assist in interpretation of the geophysical results.

3.1 Koidern River

The Koidern River highway section extends from km 1811.1–1814.0 (Figure 1) and crosses a fluvial plain consisting of silt with organic surface cover (Figure 4). Geotechnical boreholes indicate that the sediment texture transitions from mostly silt with sand to sand and gravel across nearby fluvial terraces. The highway section extends across thermokarst terrain which closely follows the limit of the silt-rich fluvial plain. Boreholes confirm that ground ice is a major component of the cryostratigraphy (boreholes 261-254 to 254-237).

Highway damage along the Koidern River section was identified in 2010 mostly as light-to-severe linear settlement coincident with poor to very poor IRI measurements. Conversely, poor and very poor IRI measurements are not necessarily accompanied by observable surface damage as classified here using vehicle-level photographs. Observable damage appears to be confined to the thermokarst terrain and related to observations of ground ice, whereas poor to very poor IRI measurements extend across thermokarst terrain into morainal tills with no observed ground ice (boreholes 271-514 to 271-516).

Despite the multiple borehole observations of ground ice, recovered electrical resistivity is generally low along the Koidern River section. The transition from the more resistive morainal tills (300–800 Ω m) to silt-rich ground (<400 Ω m) is apparent near 1809.9 km. From there, a conductive anomaly extends below the interpreted depth of road fill from 1810–1812 km which corresponds to the extent of the thermokarst terrain and may result from

appreciable unfrozen water in the silty sediments. Observed damage does not seem to be related to the conductive anomaly over its entire length. In fact, the observed damage and the historical ground ice observations occur within a region of increased resistivity (1811.1–1811.6 km). This zone of increased resistivity is interpreted to represent ice-rich frozen ground that is undergoing degradation in the midst of relatively unfrozen and wet, but more stable ground. After repairs in 2010,

the IRI measurements over the interpreted frozen ground continued to increase whereas the remaining IRI values, although poor, remained the same (Oldenborger et al., 2015).

The frozen sediment in the 2011 borehole BH11-29 may be manifest as the increase in resistivity at approximately 8 m depth. However, resolution loss at depth and model smoothness make identification of a transition at this depth difficult, and the conductive

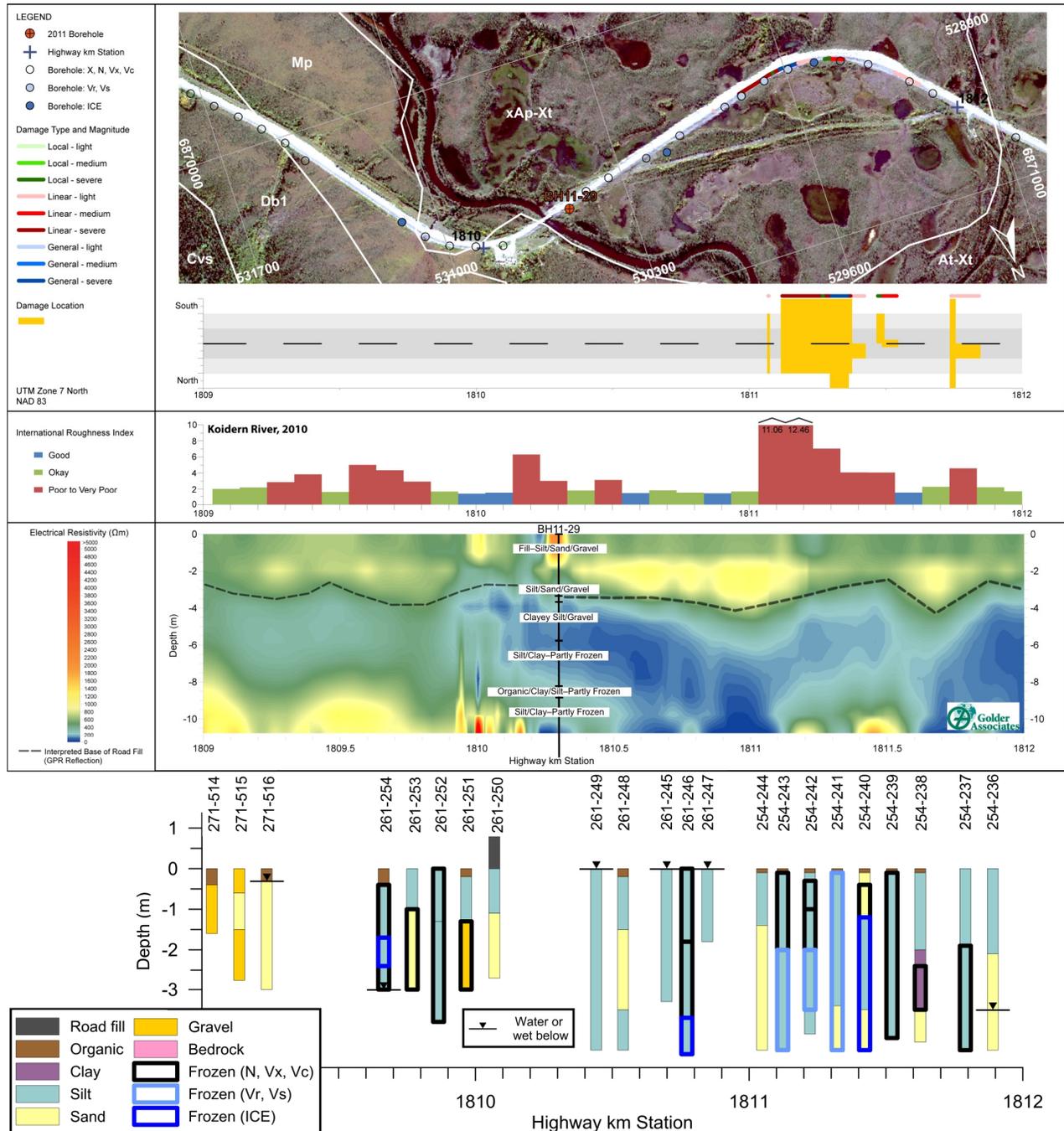


Figure 4. Koidern River section: surficial geology (Lipovsky and Bond, 2014), damage observations, IRI measurements, geophysical survey results (Hammond, 2013), geotechnical borehole record (Lister, 2011) and sediment texture and ground ice data from 1993 (Lipovsky, 2009).

anomaly at the bottom of BH11-29 is very likely an artefact. The increase in resistivity at approximately 7 m depth at the eastern end of the section is interpreted as a weak bedrock signature. Also due to resolution loss, the magnitude of the recovered resistivity is not likely representative of the true resistivity, but a bedrock interpretation is consistent with surficial mapping of

weathered bedrock (Db1) along the section.

3.2 Dry Creek

The Dry Creek section extends from km 1837.5–1842.0 (Figure 1) and crosses glaciofluvial and organic terrain underlain by glaciofluvial sediments of McConnell age

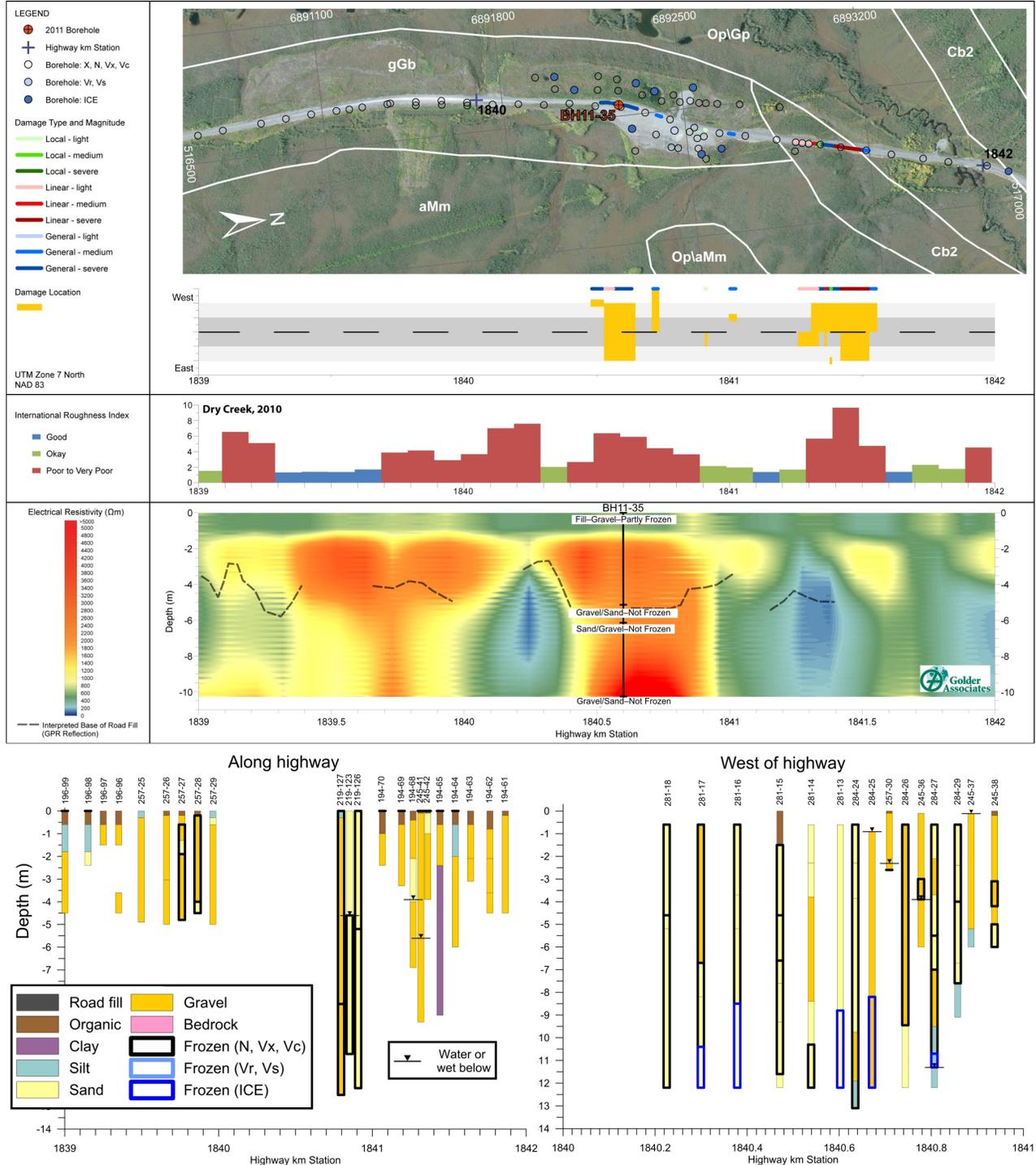


Figure 5. Dry Creek section: surficial geology (Lipovsky and Bond, 2014), damage observations, IRI measurements, geophysical survey results (Hammond, 2013), geotechnical borehole record (Lister, 2011) and sediment texture and ground ice data from 1992–1994 (Lipovsky, 2009).

(Figure 5). The general cryostratigraphy for the glaciofluvial deposit is characterized by relatively ice-poor sands and gravels underlain by deep-seated ground ice below about 6–7 m (boreholes 281-17 to 284-25). Given the low potential for ice segregation in sand and gravel, it is postulated that the ground ice described in the geotechnical boreholes for the Dry Creek section represents relic massive ice buried under glaciofluvial deposits.

Observed highway damage includes all forms of settlement characterized mostly as moderate to severe. Local and linear settlements predominately occur west of the highway, extending from the embankment to the adjacent highway lanes. Again, observed damage coincides with poor and very poor IRI measurements, but there are many poor IRI measurements that have no apparent associated damage.

Observed road damage near 1840.6 and 1841.4 km is associated largely with unfrozen sand and gravel (glaciofluvial) with limited potential for segregation ice. However, there is a distinct cluster of ICE and other ground-ice observations located near the road. There is apparent correspondence between ice occurrence, observed damage and poor IRI measurements near 1840.6 km. Degradation of deep ice may explain the observed highway damage and the absence of thermokarst directly adjacent to the road.

Borehole observations of ICE are perhaps deeper than the reliable depth of investigation of the CR survey. However, there is a clear resistive anomaly ($>4000 \Omega\text{m}$) at 1840.5 km starting around 8 m depth underneath the already resistive sands and gravels ($2000\text{--}4000 \Omega\text{m}$). This is likely the signature of massive ice, but it does not appear to be encountered by BH11-35.

In contrast, there are no observations of ICE along the road near the damage location of 1841.4 km. This zone is associated with a conductive anomaly ($<400 \Omega\text{m}$) that occurs near borehole observations of unfrozen clay. The anomaly appears to continue into the highway embankment. Such an observation would be consistent with increased moisture content or active groundwater within the embankment and natural ground. Heat advection, thaw settlement of any partially frozen clay, mechanical erosion and seasonal freeze/thaw would all contribute to damage of the highway surface for this zone.

3.3 North of Beaver Creek

The Beaver Creek section extends from km 1882.6–1898.1 (Figure 1). From km 1883–1886, organic surficial material overlies fluvial sediments and thermokarst features appear across portions of the organic units (Figure 6). Sediment texture is variable; observations of ground ice are prevalent and confined largely to silt. There are some observations of thick frozen organic material that will be highly susceptible to thaw settlement. This section of highway is oriented perpendicular to the direction of surface hydrological flow. Poorly-drained terrain surrounds the highway from 1884–1886 km and surface hydrology or shallow groundwater may play an important role in highway performance.

This part of the Beaver Creek section appears to have a strong relationship between observed damage, poor IRI measurements, and the occurrence of ground ice (boreholes 110-172 to 110-178). However, there is no obvious consistent electrical resistivity anomaly that coincides with the zones of damage. Both sections of elevated IRI measurements near BH11-44 and BH11-45 seem to exhibit reduced resistivity of the embankment material, and high attenuation of the GPR signal is observed near BH11-45 (Hammond, 2013) consistent with increased unfrozen water content or shallow groundwater. These conductive embankment sections occur over silt and organics with ground ice as observed in BH11-44 and BH11-45. It is inferred that the combination of a conductive embankment over conductive frozen silts represents a resistivity anomaly indicative of shallow groundwater-related settlement.

In contrast, the highest observed embankment conductivity is from 1884.1–1884.8 km, but is over borehole observations of bedrock and gravel and coincides with stable good IRI measurements. The resistivity signature of bedrock is not readily apparent, but is interpreted as the moderately resistive anomaly ($1200 \Omega\text{m}$) from 1884.7–1885.1 km below 1–2 m depth. The weakly resistive anomaly ($800 \Omega\text{m}$) from 1884.2–1884.6 km below 2 m depth is interpreted as predominantly gravel. Therefore, a conductive embankment signature alone is not necessarily indicative of settlement.

4 DISCUSSION

Geophysical surveys were contracted by YHPW with the objectives of characterizing permafrost conditions and mapping ice-rich ground which would lead to identification of thaw sensitive areas and improved understanding of highway distress. Analysis of the geophysical results in the context of highway roughness and observed damage allows an assessment of the usefulness of the geophysical surveys for highway management. We observe several different subsurface resistivity structures that are interpreted to represent a variety of subsurface conditions that are consistent with damage observations. However, no obvious electrical resistivity anomalies are observed that could be used as unique indicators of potential degradation. Furthermore, the relationship between electrical resistivity and observed damage, or electrical resistivity and IRI measurements is complicated and site-specific.

The task of geophysical interpretation or terrain characterization is further hindered by the non-uniqueness and limited dynamic range of the CR survey results. For this survey, the range of electrical resistivity is considerably less than expected for unfrozen sedimentary material, frozen ground, ice and bedrock (e.g., Scott et al., 1990) and considerably less than that observed in other studies in the region (Lewkowicz et al., 2011). It is expected that results could be improved by correcting the raw CR data for effective dipole length (e.g., Oldenborger and LeBlanc, 2013).

5 CONCLUSIONS

Results from CR and GPR surveys from the northern Yukon Highway are analysed and interpreted along with surficial maps, geotechnical borehole records, and surface observations of highway roughness and distress. Observed damage appears to be associated with a variety of ground ice conditions, hydrology and surficial

geology. Highway damage appears to be associated with poor IRI measurements, but poor IRI measurements are not necessarily accompanied by observed damage.

The geophysical results help elucidate the terrain conditions and support the conclusion that multiple subsurface processes contribute to highway degradation. Several geophysical signatures are interpreted as indicative of terrain conditions involving ice-rich ground,

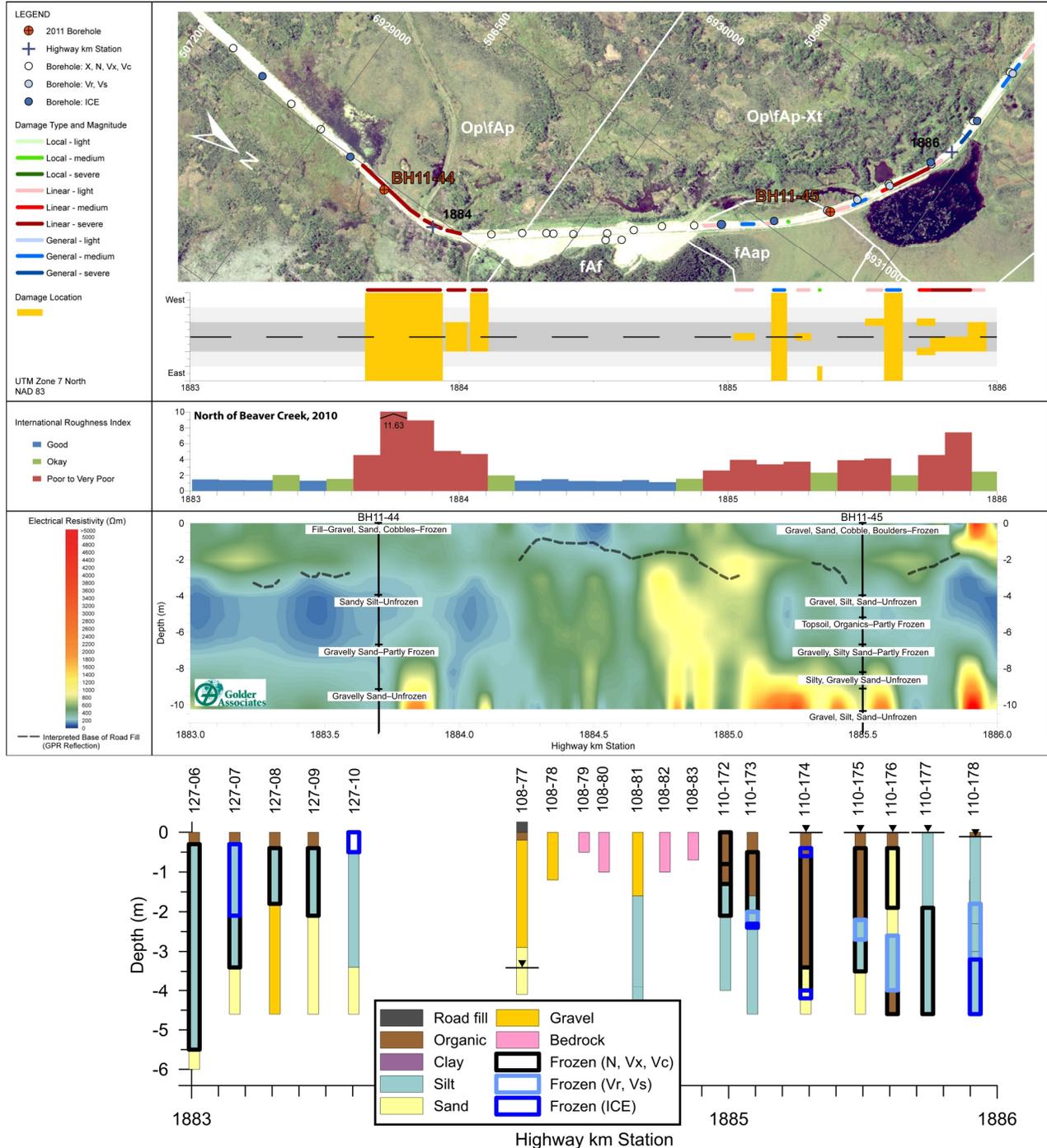


Figure 6. North of Beaver Creek section: surficial geology (Lipovsky and Bond, 2014), damage observations, IRI measurements, geophysical survey results (Hammond, 2013), geotechnical borehole records (Lister, 2011) and sediment texture and ground ice data from 1990–1991 (Lipovsky, 2009).

frozen ground, thaw-susceptible sediments and shallow groundwater. However, consistent identification of material type or ground ice conditions is difficult and no unique resistivity signature is indicative of thaw susceptibility. The geophysical results are most useful when interpreted in the context of local conditions and supporting data.

The level of analysis contained herein is preliminary. Increased understanding would result from additional work on a number of fronts including advanced processing of the CR data, investigation of any statistically significant correlation between observed damage, IRI and geophysical signature, consideration of the temporal context of the borehole data base records and thermal evolution of the ground, or investigation of the data in the context of climatic trends.

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