THAW SETTLEMENT OF DEGRADING PERMAFROST: A GEOHAZARD AFFECTING THE PERFORMANCE OF MAN-MADE INFRASTRUCTURES AT UMIUJAQ IN NUNAVIK (QUÉBEC)

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RÉSUMÉ

La dégradation du pergélisol dans les régions nordiques peut provoquer des risques naturels comme la subsidence au dégel qui affecte la performance des infrastructures civiles. Par exemple, le long d'un segment de 300 m de longueur de la route d'accès à l'aéroport d'Umiujaq au Nunavik (Québec), trois zones de subsidence au dégel ont été étudiées durant l'été 2006; soit 15 ans après la construction de la route. La subsidence atteint par endroit jusqu'à 0,63 m pour un volume total de près de 530 m^3. Des levés de géoradar et un profilage de résistivité électrique ont été réalisés afin de caractériser la stratigraphie du sous-sol et les conditions du pergélisol. Le dégel de sédiments marins gélifs sur une épaisseur d'au moins 4 m sous les zones de subsidence a provoqué un tassement et une diminution de l'indice des vides d'environ 15%. Le tassement au dégel est non seulement provoquée par la tendance au réchauffement climatique récemment observée au Nunavik mais aussi par l'accumulation de la neige le long de la route. Le couvert nival isole ainsi la surface du sol et prévient tout regel du sous-sol en hiver. Alors que la route est toujours carrossable, la seule mitigation économiquement viable au dégel du pergélisol est de laisser libre cours au tassement au dégel et de recharger le remblai lorsque cela est nécessaire jusqu'à sa stabilisation.

ABSTRACT

The degradation of permafrost can induce geohazards such as thaw subsidence affecting the performance of man-made infrastructures. For example, along a 300-meter long segment of the road leading to the airport of Umiujaq in Nunavik (Québec), three zones of thaw subsidence were studied in summer 2006, 15 years after construction in 1991. The subsidence can be as high as 0.63 m for a total volume of subsidence close to 530 m^3. Ground penetrating radar profiles and electrical resistivity tomography were carried out to assess the underlying stratigraphy and permafrost conditions. The marine sediments are thawed over a thickness of at least 4 m under the subsidence zones leading to a void ratio decrease of about 15% following the thaw settlement. The thaw settlement is not only due to the recent climate warming trend observed in Nunavik but also the snow accumulation along the road embankment which insulates the ground surface in winter and prevents further ground freezing. While the road is still suitable for traffic, the only economically viable mitigation of thawing of permafrost is to allow free thaw settlement and reload the road embankment when needed until stabilization is attained.

1. INTRODUCTION

1.1 Cold regions geohazards

Climate warming already occurring at high latitudes is accompanied by geohazards such as thaw subsidence and active-layer detachment failure. Among these geohazards associated with the thawing of permafrost, the vulnerability to subsidence is widespread in the Northern Hemisphere (Nelson *et al*. 2001). The thaw subsidence can have major impacts on performance of man-made infrastructures. For example, buildings, roads and airfields founded on ice-rich permafrost in Northern Canada, Alaska and Siberia are already affected by thaw subsidence increasing their maintenance cost, decreasing their useful life span and jeopardizing the population security (Allard *et al*. 2002, Couture *et al*. 2003, Romanovsky *et al*. 2001). In Nunavik (Québec), this vulnerability to permafrost degradation has raised the concern of governmental agencies looking for the development of mitigation approach and adaptation strategies.

1.2 Marine transgression and permafrost in Nunavik

Following the retreat of the Wisconsin Ice Sheet about 8000 years BP, the sea flooded a large band of coastline in Nunavik (Fig. 1). Glaciomarine sediments were then deposited in deep water in the Tyrrell and D'Iberville Seas. Due to the isostatic rebound, once exposed to the cold atmosphere, the raised marine deposits were then eroded and colonized by vegetation, and permafrost aggraded under the cold climate (Fig. 1). In addition to the glaciomarine deposits covering the bedrock along the coast, till on hilltops above the marine limit forms a thin and discontinuous veneer of boulders, sands and fines. The glaciomarine sediments and fines in the till are frost-susceptible materials. Ice in excess can be found in these frozen Quaternary deposits creating problematic thaw-unstable ground conditions for infrastructures construction.

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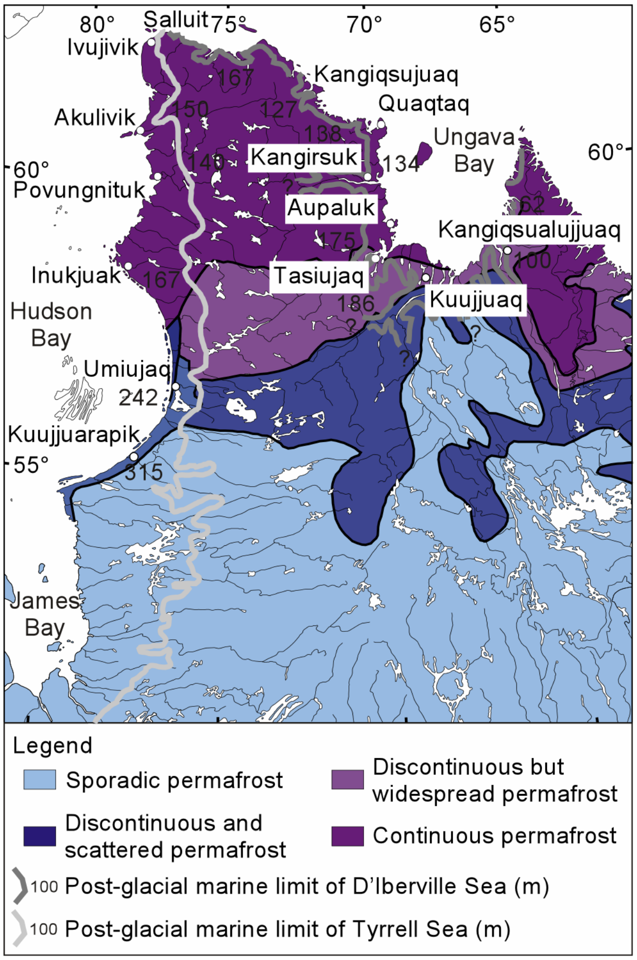

Figure 1: Marine transgression and permafrost distribution in Nunavik (after Allard and Seguin 1987).

1.3 Inuit communities in Nunavik

Under the James Bay and Northern Quebec Agreement signed in 1975, fourteen Inuit communities were created in Nunavik (Fig. 1). That was a milestone for economic and social modernization in Nunavik because the Government of Québec committed to provide the same services to these remote communities as the ones in the south. Major facilities such as roads, airfields, seaports, schools, dispensaries and houses were then renovated and built.

Since the Inuit sustain in major part on sea food, the Inuit communities are located along the coast of Nunavik for easy access to the sea. The man-made infrastructures can be then potentially founded on ice-rich frozen ground and affected by any permafrost instability. Special considerations shall be given for the design of infrastructures. For example, in Nunavik, the houses are supported by screw jacks lying on timber sills and thick gravel pad to avoid any heat exchange between the building and the ground. The roads and airfields are thick embankments to keep the freeze-thaw cycles in the embankment and stabilize the underlying frozen ground.

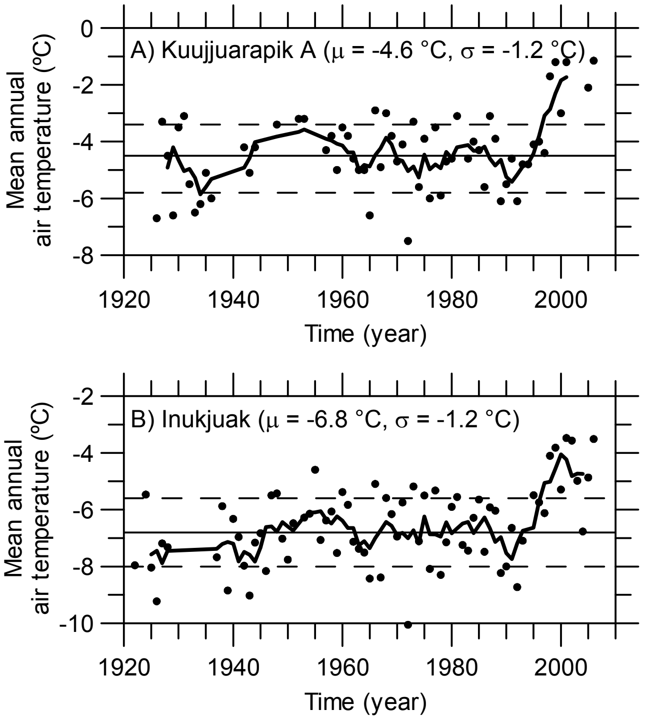

Figure 2: Mean annual air temperature at Kuujjuarapik (B) and Inukjuak (C). Meterological data from Environment Canada. The broken lines correspond to a 5-year running average. Full and dotted horizontal lines are respectively the average and ±standard deviation (values in parentheses) over the reference period 1961-1990.

1.4 Climate variability in Nunavik

Meterological data are available for the Inuit communities of Kuujjuarapik and Inukjuak (Figs. 1 and 2). A marked trend to climate warming of at least 3 °C is observed since 1992. The mean annual air temperature is well above the average air temperature found for the reference period 1961-1990 plus one standard deviation since 1998 except for 2004.

1.5 Impacts of the recent trend to climate warming in Nunavik

According to Fortier and Aubé-Maurice (2008), widespread and fast permafrost degradation is currently occurring in the discontinuous permafrost zone (Fig. 1). The thawing of ice-rich permafrost leaves thermokarst ponds modifying the landscape and affecting the hydrology. Climate warming during the 20th century (Fig. 2) is the main driver of the permafrost degradation.

The permafrost degradation affects also the performance of man-made infrastructures. An active-layer detachment failure in September 1998, at the end of one of the warmest summer on meteorological records, forced the moving of 20 homes at Salluit (Allard *et al*. 2002). Many man-made infrastructures such as buildings, roads and airfields at Kuujjuaq, Tasiujaq, Kangirsuk, Salluit, Inukjuak and Umiujaq (Fig. 1) show mechanical distresses due to the thaw subsidence. Because some infrastructures such as the airfields are critical to maintain year round access to the Inuit communities, the permafrost instability affecting their performance and increasing their maintenance cost raises safety concern. Thorough studies of the origin and causes of these geohazards specific to cold regions are needed to develop mitigation approach and adaptation strategies.

A case study is presented herein on recent thaw subsidence observed along the access road to the airport of Umiujaq in Nunavik (Québec). In addition to the measurement of the thaw subsidence, a geophysical investigation including ground penetrating radar surveys and electrical resistivity tomography was carried out to assess the underlying stratigraphy and permafrost conditions, and identify the origin of this geohazard.

2. THAW SUBSIDENCE OF DEGRADING PERMAFROST AT UMIUJAQ

2.1 Location of study site

Situated on the east coast of the Hudson Bay, Umiujaq is a small Inuit community of about 300 people (Figs. 1 and 3). It is located in the discontinuous permafrost zone (Fig. 1). While most village infrastructures are built on raised sandy beaches, a thaw stable material, other major infrastructures such as roads and the airfield lie in part on frozen ice-rich marine sediments, a thaw instable material, outcropping or buried underneath a sand veneer. The road leading to the airport built in 1991 is a good example of an infrastructure affected by permafrost degradation mainly under the form of localized zones of thaw subsidence (Fig. 4). A 300-meter long road segment lying on a sand cover in a depression between two rock outcrops was studied in 2006 (Fig. 3). At the distance 2+430 m, two culverts one over the other across the road embankment concentrate the runoff water flowing to the west along the gentle slope of the seaward-dipping bedrock.

2.2 Measurement of thaw subsidence

The elevation of the road surface was measured in July 12th 2006 using an electronic level (Fig. 5A). The elevation measurement can be compared to the drawings as built of the airfield and access road of Umiujaq (Ministère des Transports du Québec 1991). The thaw subsidence, the difference in elevation between 2006 and 1991, can be as high as -0.63 m (Fig. 5B). The total volume of subsidence is close to 530 m^3 for a road embankment 7.4 m wide. The embankment thickness is in excess of 5.6 m at 2+420 m for an average value of 3.6 m along the studied road segment.

Figure 3: Inuit community of Umiujaq. The ends of the 300-meter long road segment affected by thaw subsidence are identified according to the location system of the Ministère des Transports du Québec (1991).

Figure 4: South view of the localized zones of thaw subsidence along the access road to the airport of Umiujaq. The all-terrain vehicle is located in one zone of thaw subsidence. Note the snow accumulation on each side of the road embankment. The photograph was taken in April 30th 2007. The snow cover was already degrading following the spring warming.

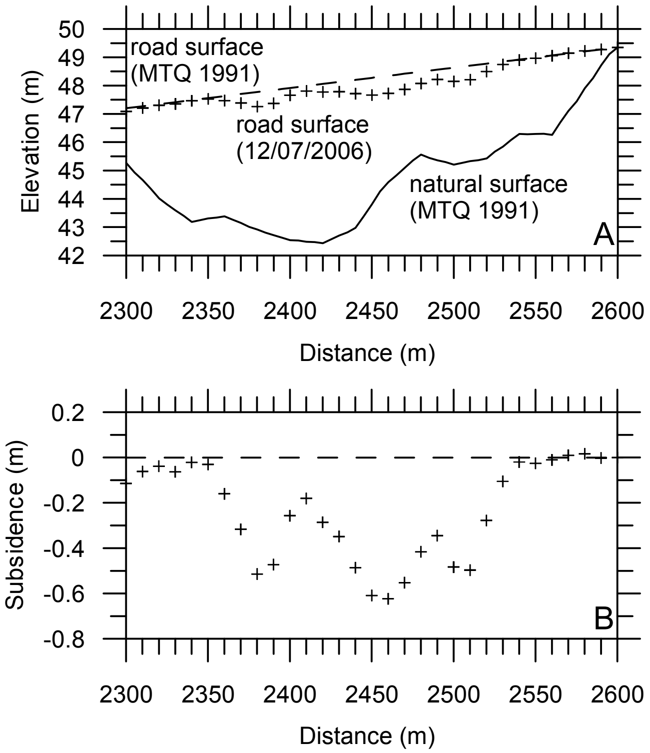

Figure 5: A) Elevation of the road surface and the natural surface in 1991 (dashed and full lines respectively), and the road surface in July 12th 2006 (+ symbols). B) Thaw subsidence of the road surface between 1991 and 2006.

2.3 Geophysical surveys

2.3.1 Ground Penetrating Radar

Ground penetrating radar (GPR) surveys were carried out in July 2006 along two 300-meter long segments over the road and in the field 10 m away from the west shoulder of the road embankment (Fig. 3) to assess the ground stratigraphy underneath the road embankment and in the field. The GPR used was a pulseEKKO 100 from Sensors & Software inc. with antennas of 50 and 100 MHz for the road and field investigation respectively. The lowest frequency was used for a deep penetration across the thick embankment and in the underlying ground. Two types of GPR survey were employed: 1) fixed-offset reflection profile and 2) common mid-point sounding (CMP sounding).

By moving at regular interval along a survey line the antennas at a fixed offset, a high-resolution stratigraphic profile can be produced. Reflectors as a function of the position along the survey and the travel time can be then identified on the travel time profile. They are associated to the reflection of the radar signal back to the surface on ground interfaces characterized by a contrast of dielectric permittivity. The GPR reflection profiles over the road and in the field are given in figures 6 and 7 respectively. Major reflectors in the ground are identified in figures 6B and 7B.

To transform the travel time profile in a depth profile for assessing the depth of the reflectors, the velocity of the radar signal into the ground is needed. It can be estimated from a CMP sounding by varying the antenna spacing but keeping fixed the common mid point between the antennas. According to the CMP soundings carried out in the present study (results not shown), the radar signal velocity is about 0.12 m/ns; characteristic value for a moist sand. This value can be then used to produce depth profiles (Figs. 6 and 7).

2.3.2 Electrical resistivity tomography

Among the available near-surface geophysical methods, electrical resistivity tomography (ERT) is a powerful tool for permafrost investigation because the electrical resistivity of a medium is highly sensitive to the transition from unfrozen to frozen state. An ERT was carried out along the same 300-meter long GPR reflection profile in the field 10 m away from the west shoulder of the road embankment (Figs. 3 and 8) to assess the permafrost conditions. Values of apparent electrical resistivity were measured using a 4-electrodes resistivity system Terrameter SAS300 from ABEM and a Wenner array made of four stainless steel electrodes. The four electrodes were aligned along the survey line. The direct injection of electrical current between the two outer electrodes induced electrical potential measured between the two inner electrodes. The array with a 2-meter spacing between the electrodes was first moved at 2-meter interval along the survey line. The spacing was then increased to 4 m and the array was moved again at the same interval along the survey line. The same procedure was applied for spacings from 6 to 20 m. A 2-dimensional data set of apparent electrical resistivity was thus obtained through the variations in depth of investigation according to the increase in array length and moving centre points along the survey line. The results from the ERT carried out in the field are shown in figure 8A in the form of a pseudo-section of apparent electrical resistivity which gives a distorted picture of the subsurface geology. Because the road embankment was too stiff, it was not feasible to drive the electrodes into the gravel pad and carry out an ERT for the investigation of the embankment and underlying ground.

The data set of apparent electrical resistivity was then inverted using the software packages RES2DINV (Loke 1996) to produce a model of electrical resistivity (Fig. 8C). This inversion algorithm based on the smoothness-constrained least-squares method taking into account the topography along the survey line minimized the difference between the predicted and measured values of apparent electrical resistivity by adjusting the electrical resistivity of each block making of the model. The error between the predicted and measured values of apparent electrical resistivity is shown in figure 8B. After 5 iterations, the root-mean-square error (RMS error) was 13.3%.

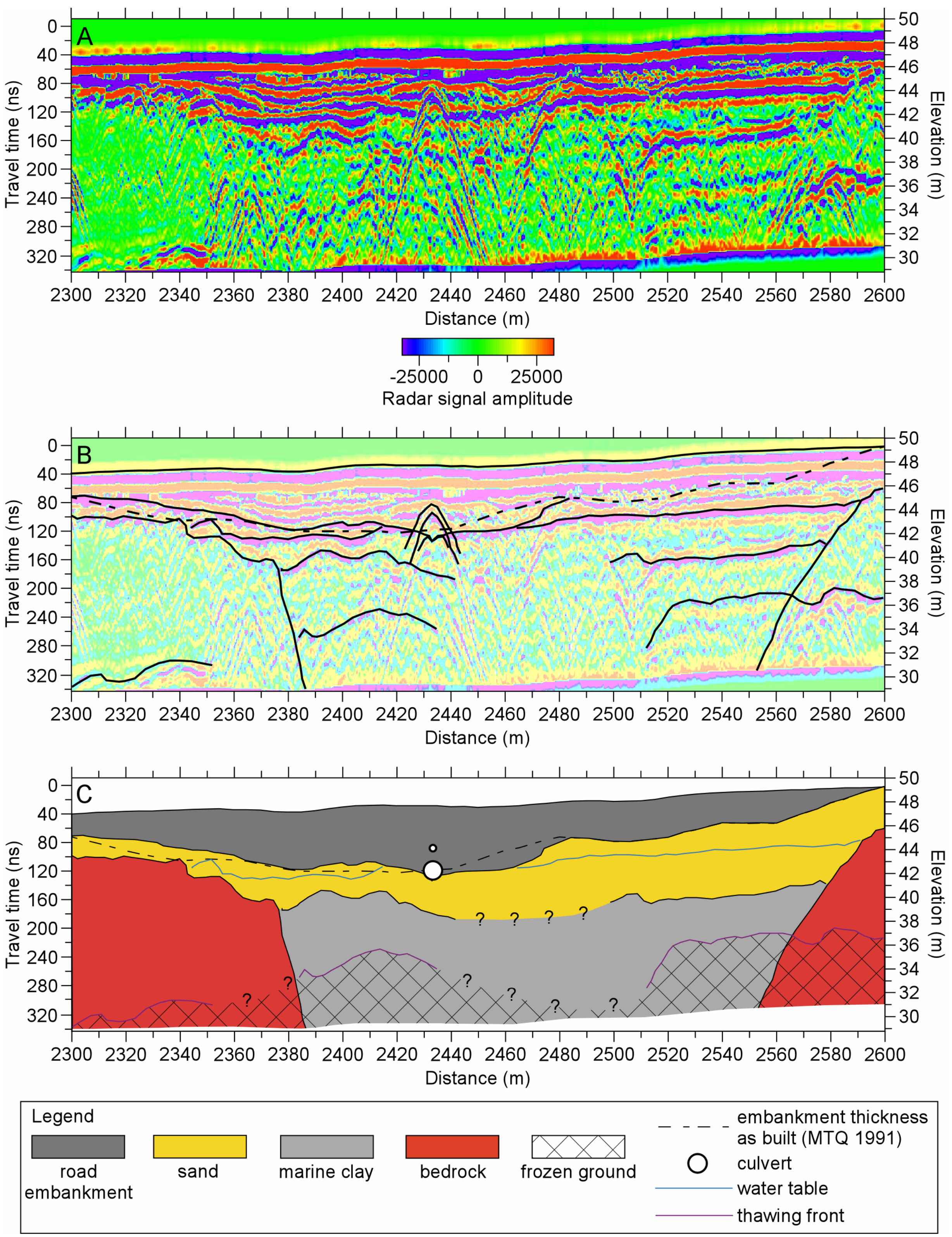

Figure 6: A) GPR reflection profile carried out over the road embankment with antennas of 50 MHz at a fixed offset of 2 m. B) Major reflectors identified on the GPR reflection profile. C) Cross-section of the road embankment and underlying ground interpreted from the GPR reflection profile. Note the vertical exaggeration (1:4.4).

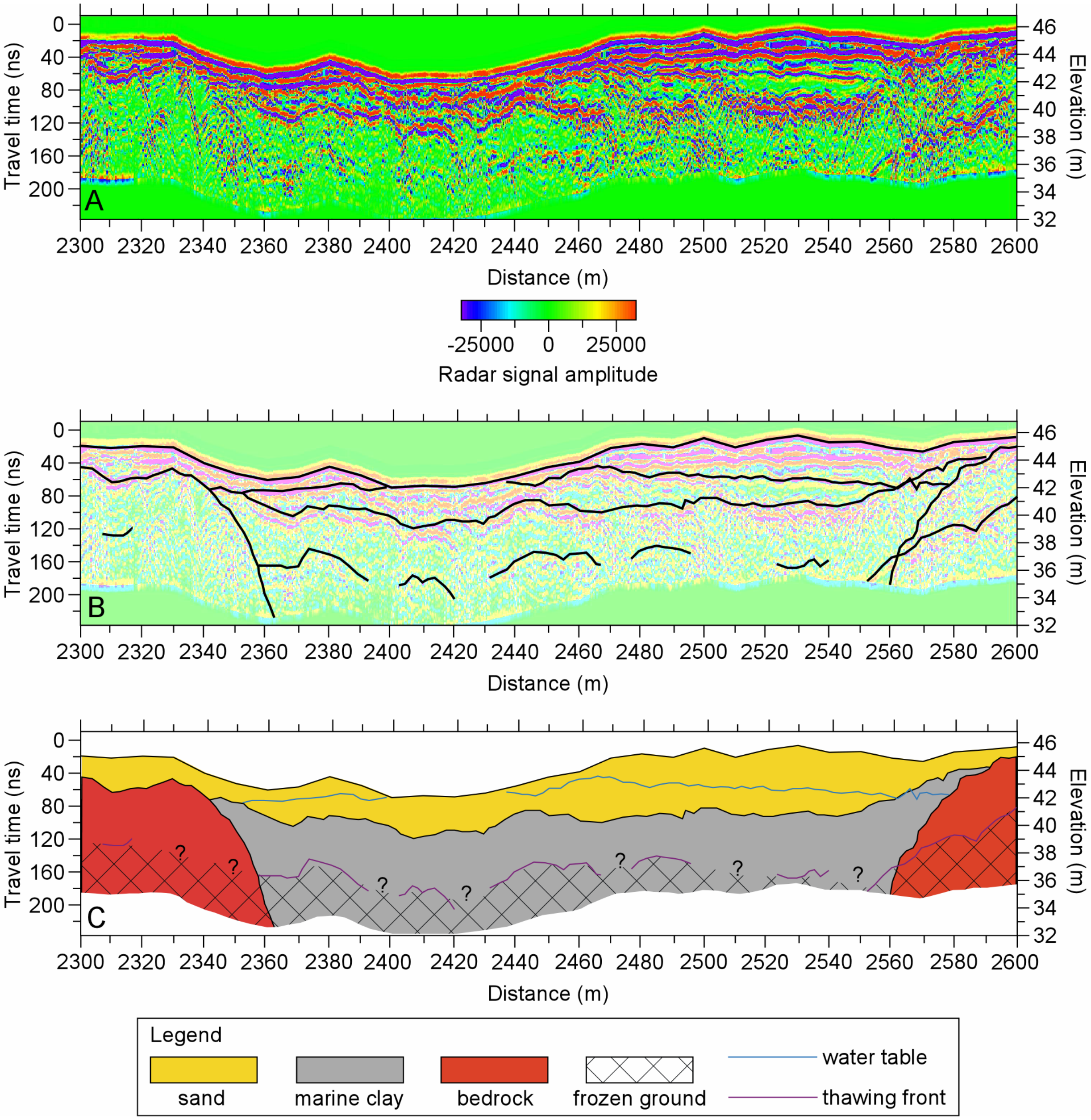

Figure 7: A) GPR reflection profile carried out in the field with antennas of 100 MHz at a fixed offset of 1 m. B) Major reflectors identified on the GPR reflection profile. C) Cross-section of the ground interpreted from the GPR reflection profile and model of electrical resistivity (Fig. 8C). Note the vertical exaggeration (1:4.4).

2.4 Sampling

In August 1990 before the road construction, two split spoon samplings TF41 and TF42 were carried out along the road line at 2+416 and 2+491 m respectively (Ministère des Transports du Québec 1991). These samplings reached a depth of 0.8 and 1.7 m in sand respectively. The water table and the thawing front were 0.4 and 0.6 m respectively in TF41 and 1.4 and 1.6 m deep respectively in TF42. A borehole was also drilled with a diamond core barrel directly in a rock outcrop along the road line at 2+600 m (Ministère des Transports du Québec 1991). In July 18th 2007, 17 years later, a flow-through sampling with a Pionjar hammer was carried out 5 m away from the west shoulder of the road embankment at 2+505 m. A 4.2 m thick sand layer was first sampled. The water table was met at a depth of 2.4 m in this layer. At depths larger than 4.2 m, a clay unit was sampled. The borehole was stopped at 6.4 m in this unit without reaching the thawing front.

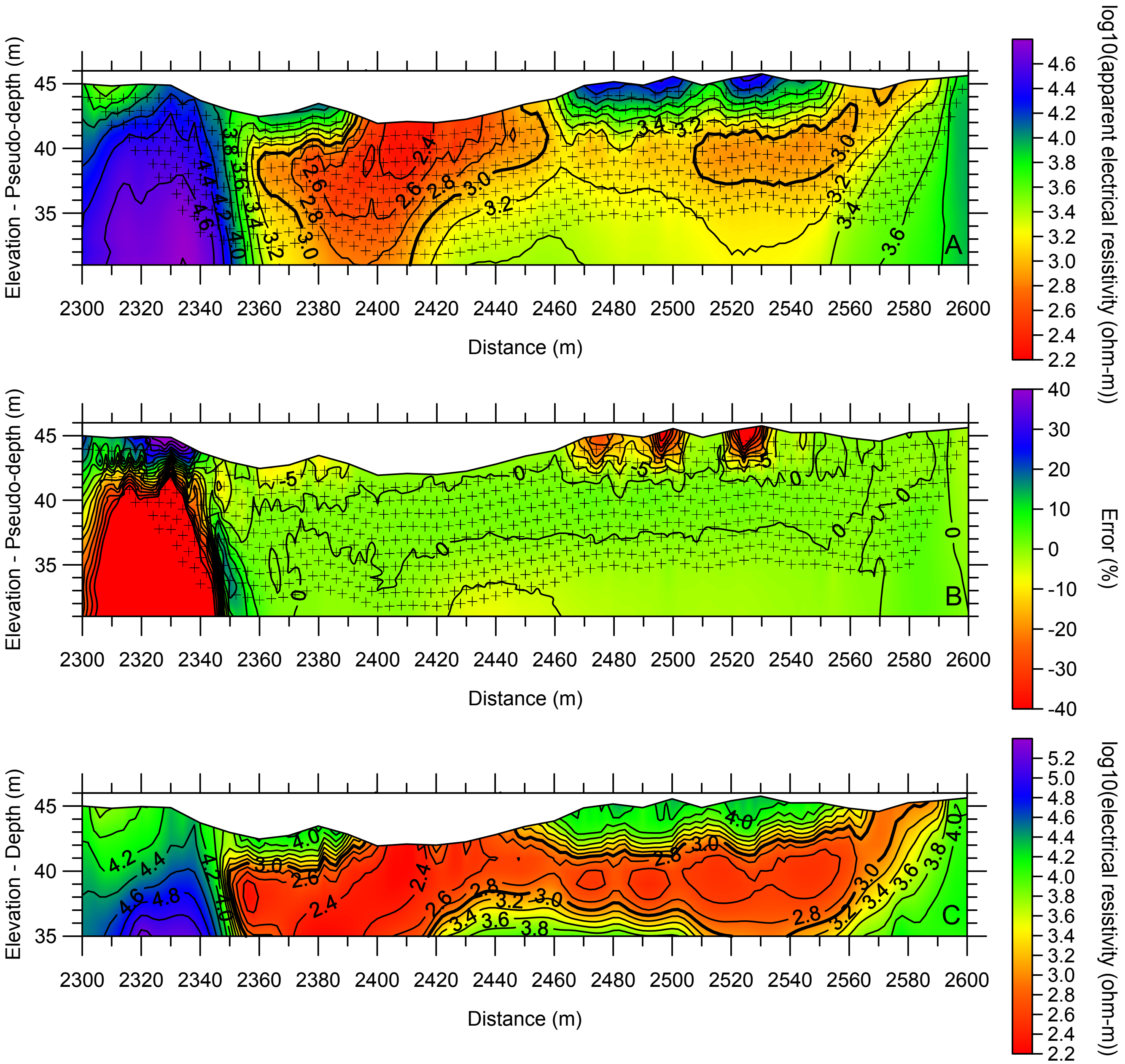

Figure 8: ERT carried out in the field. A) Pseudo-section of measured apparent electrical resistivity. B) Errors between the values of apparent electrical resistivity predicted from the inversion and the measured ones. C) Model of electrical resistivity recovered from the inversion of the pseudo-section. Note the vertical exaggeration (1:4.4).

3. DISCUSSION

3.1 Stratigraphy and permafrost conditions

Since the end of construction in 1991 to 2006, the surface subsided as much as 0.63 m along the studied road segment. This subsidence is due to the thaw settlement taking place in the underlying ground following the thawing of permafrost. However, without a good knowledge of the ground stratigraphy, the origin of this subsidence is not exactly known.

The GPR and ERT are complementary geophysical methods for permafrost investigation. While a GPR reflection profile provides stratigraphic information at high resolution without identifying the soil layers (Figs. 6A and 7A), the ground conditions can be assessed from the ERT but the stratigraphic contacts are not accurately located in the model of electrical resistivity (Fig. 8C). The combined interpretation of the GPR reflection profile and ERT carried out in the field results in a cross-section of the ground (Fig. 7C). This cross-section in the field can be then used to help in the interpretation of the GPR reflection profile over the road embankment (Fig. 6A) for the identification of the underlying soil layers and assessment of the permafrost conditions. This interpretation procedure leads to a cross-section of the road embankment and the underlying ground (Fig. 6C).

The studied road segment crosses a small valley delimited by two rock outcrops and partially filled from top to bottom with a veneer of deltaic sand and a deposit of marine clay. The contacts between the bedrock and the Quaternary deposits are subvertical. They appear on both ends of the GPR reflection profiles (Figs. 6A and 7A) as countless hyperbolic reflectors due to the diffraction on the subvertical contrasts of dielectric permittivity. The hyperbolic reflectors at 2+430 m are due to the two culverts in the road embankment (Figs. 6A and 6C). The bedrock resistivity is in excess of 10 000 ohm-m (Fig. 8C). The inversion algorithm was unable to resolve this high resistivity contrast between the bedrock and the Quaternary deposit inducing large errors in apparent electrical resistivity predicted from the inversion (Fig. 8B). The water table, the stratigraphic contacts between the road embankment, the sand layer and the clay unit in depth, and the thawing front are characterized by high contrasts of dielectric permittivity. They can be followed along the GPR reflection profiles (Figs. 6 and 7). There are some discrepancies between the expected contact at the embankment base and the selected reflector (Fig. 6). The water table is near the ground surface between 2+400 and 2+440 m. The reflector associated with the thawing front is not continuous all along the GPR reflection profiles. From 2+350 to 2+390 m and from 2+450 to 2+570 m, both the water table and the stratigraphic contact between the sand layer and silt unit are marked by a sharp decrease in electrical resistivity from 10 000 ohm-m for the moist sand close to the ground surface to below 1000 ohm-m for the unfrozen clay (Fig. 8C). Between 2+420 and 2+520 m, the electrical resistivity increases over 1000 ohm-m in depth because the clay unit is still frozen. Without this increase in electrical resistivity, it would have been impossible to associate the reflector in the GPR reflection profile with the thawing front (Fig. 7). A clay layer of at least 4 m thick is then unfrozen underneath the sand layer. From 2+360 and 2+420 m, the thawing front is deeper than the previous section (Fig. 8C).

3.2 Causes of thaw subsidence

The subsidence observed along the access road to the airport of Umiujaq took place in the clay unit underneath the road embankment and sand layer. The thawing of permafrost between 1991 and 2006 induced a thaw consolidation and a decrease in void ratio of about 15% (subsidence of 0.63 m over a 4-meter thick unfrozen layer). Contrary to the initial design of a thick road embankment, the freeze-thaw cycles reach now the underlying ground. Moreover, the thick road embankment disrupts the gentle topography and acts as a barrier favoring the snow accumulation. The thawing of permafrost is therefore not only due to the recent climate warming trend observed in Nunavik (Fig. 2) but also the snow accumulation along the embankment shoulders which insulates the ground surface in winter and prevents further ground freezing (Fig. 4).

4. CONCLUSIONS

While the road is still suitable for traffic despite the major thaw subsidence, the only economically viable mitigation of thawing of permafrost is to allow free the thaw settlement and reload the road embankment when needed until stabilization is attained. The monitoring of subsidence is recommended to assess the rate of thaw settlement. Other geophysical investigation and deep sampling would provide the clay unit thickness and undisturbed frozen samples to carry out thaw consolidation test. These data could be then integrated in a numerical simulation of the thermal regime and consolidation behavior of permafrost according to different scenarios of climate warming. The assessment of the vulnerability to thawing of permafrost is fundamental to maintain this critical access to Umiujaq.

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