Capacitive electrical resistivity: an alternative non-invasive method for permafrost monitoring

S. Bazin[1], S.G. Syed[2], G.L. Gilbert[3], B. Etzelmüller[2]

[1] Institut Universitaire Européen De La Mer; [2] Oslo University; [3] Norwegian Geotechnical Institute

Summary

Currently, permafrost is degraded due to global warming and subsurface geophysics can contribute to characterize this degradation. Electrical resistivity tomography (ERT) is very effective in mapping frozen soils due to the strong resistivity contrast between ice and water. We present an example of 2D and 3D resistivity imaging using a capacitive coupling resistivity (CCR) survey method in Svalbard permafrost. Although little work has been published on the mapping of the active layer of permafrost (i.e. the ground layer which thaws annually) with the CCR method, this case study shows its advantage as non-invasive compared to all other investigating methods.

Introduction

Permafrost is made up of ground materials that stay below 0 °C for at least two consecutive years (French, 2018). The Svalbard archipelago is located in the high arctic about half way between Norway and the North Pole. 60% of its land is covered with glaciers or snow while the remaining land is underlain by continuous permafrost. Permafrost can be very heterogeneous in its spatial distribution, due to variations in topography or snow and vegetation cover. The active layer is its near-surface layer subject to summer thaw. The mean annual air temperature in Svalbard has increased between 3 °C and 5 °C during the last 40 to 50 years. Understanding how permafrost may be affected by this warming trend has become a research priority. This relies on long-term monitoring of its active layer.

Thermal monitoring can allow the characterization of permafrost: thermistor strings are placed at several depths in a borehole (for example Fig. 3B). This instrumentation enables long-term monitoring of the ground thermal regime but is expensive and only allows point measurements. Various subsurface geophysical investigation tools have been tested to map the presence of permafrost and to evaluate its active layer thickness (Hauck, 2013). Electrical Resistivity Tomography (ERT) is ideal for permafrost studies, because the presence of ice results in a significant change in resistivity. Ground resistivity increases exponentially during freezing because the content of unfrozen water in the substrate decreases. ERT can therefore provide indirect information on the active layer structure (Bazin et al., 2019). The traditional ERT method, however, suffers practical limitations as the signal strength is limited by electrode grounding complications in resistive ground and cold temperature. This paper investigates how future resistivity monitoring could be improved in the field.

The Adventdalen is a major valley in central Svalbard made of flat terrace-like loess deposit. The study is located (78°13'N, 25 15°28'E, 10 m above sea level) near the city of Longyearbyen (Fig. 1). The site had been chosen by the University of Svalbard (UNIS) to monitor the long-term effect of climate change on permafrost and is referred as the UNISCALM site (Circumpolar Active Layer Monitoring). It belongs to the Global Terrestrial Network for Permafrost (GTN-P) program which aims at providing consistent, representative and high quality standardized long-term data series of selected permafrost parameters at key sites. The site has also been chosen by the Norwegian Geotest Site (NGTS) as a research site to characterize Norwegian saline permafrost. NGTS drilling and coring (Gilbert et al. 2019) have revealed the soil stratigraphy (Fig. 1C): the loess cover is 3 m thick and is underlain by marine and glacial deposits. Ice-rich permafrost is restricted to the upper few meters of the soil stratigraphy. Permafrost between 4 m and 60 m depth is primarily ice poor and is referred as cryopeg.

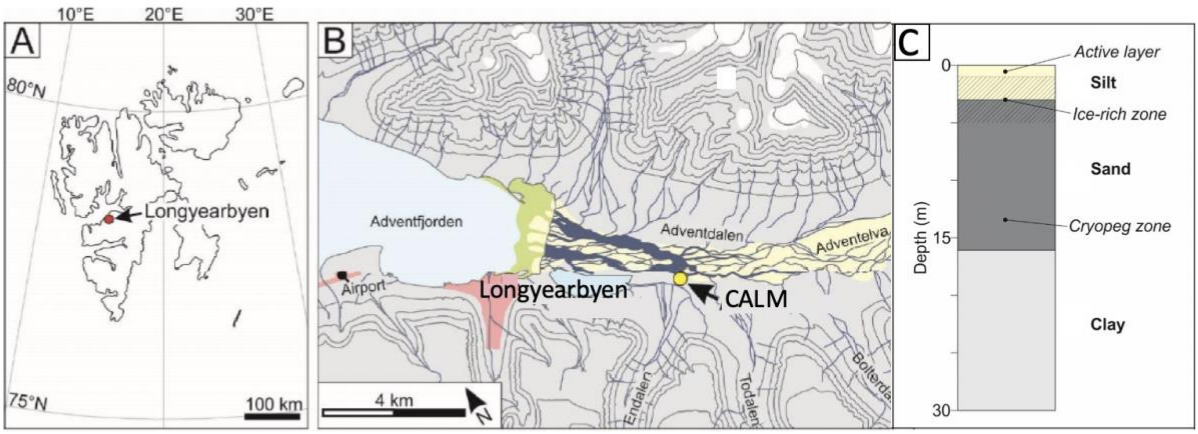

Figure 1 *A) Town of Longyearbyen, Svalbard. B) CALM and NGTS site in the Adventdalen located 5 km inland from Longyearbyen. C) Soil stratigraphy of the study site from Gilbert et al., 2019.*

Method

The concept of capacitive coupling resistivity (CCR) is that AC current can pass through a capacitor. In a CCR streamer, a cable acts as one half of the capacitor, while the earth functions as the other half.

The AC current generated by the transmitter antenna passes from the cable into the ground. The generated ground current produces an AC voltage that can be measured by the receiver antenna. An electrical resistivity survey was acquired in July 2019 with the CCR method, using an OhmMapper instrument from GEOMETRICS (Fig. 2A) with 2 receiver antennas. The CALM site is ideal for towing a CCR streamer as the vegetation is relatively sparse, the ground is flat and the field is free from anthropologic noise (Fig. 2D). Two types of acquisition were tested: a 2D section (shown as the blue line in Fig. 2C) and a 3D map survey (shown as the red box in Fig. 2C). The 2D section was carried out by 10 passes along the same profile and increasing the distance between the dipoles after each pass. A map survey was also carried out by walking with the OhmMapper streamer along 21 parallel lines separated by 5 m within the UNISCALM box (Fig. 2B). Two 3D grids were actually acquired: one with a short dipole configuration (2.5 m rope) following E-W lines, and one with a wider dipole (5 m rope) following N-S lines. Each of these three surveys was completed in less than 2 hours in the field.

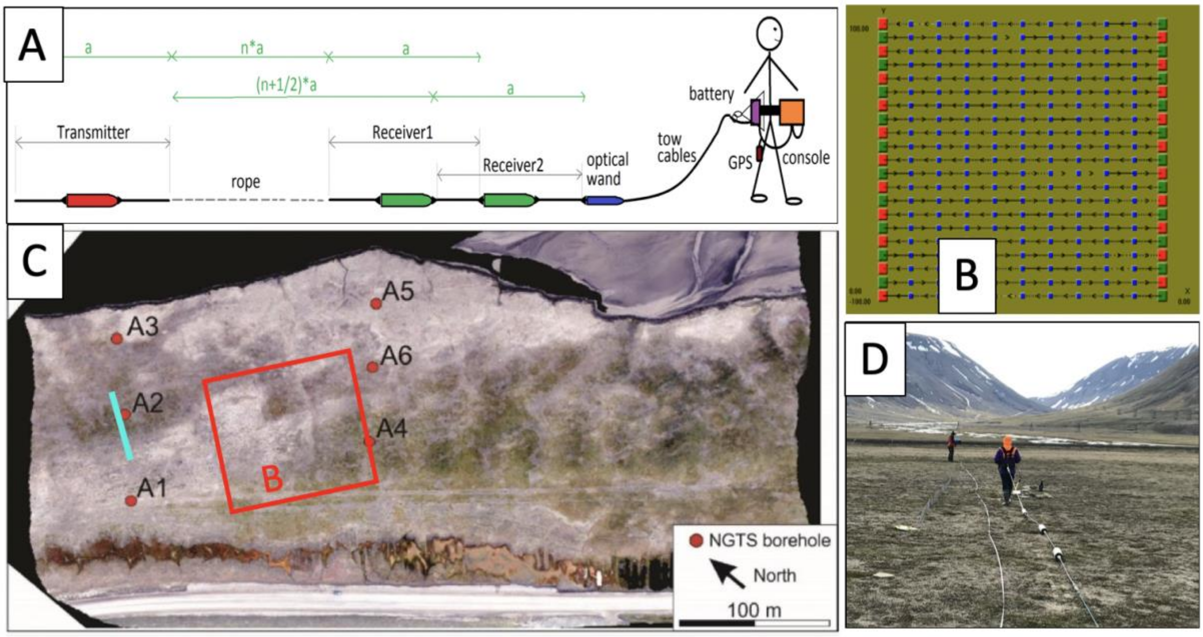

***Figure 2** A) CCR acquisition with a streamer: different dipole sizes can be chosen by changing the rope length between the transmitter antenna and the two receivers. B) A map mode consists of towing the streamer along parallel lines. The survey consists of 21 lines separated by 5 m. C) Aerial image of the study site with the two types of aquisition: a 50 m long profile marked in blue and a 100 X 100 m box marked in red. A6 is a ground temperature monitoring borehole (Fig. 3B). D) Photo of the field survey.*

The data acquired during the 10 passes along the 2D profile is concatenated to produce a vertical section. The 2D dataset is processed with Res2Dinv and the two 3D datasets are processed separately with Res3Dinv software. Due to the flatness of the site area, no topographic correction is implemented. The depth of investigation is 10 m along the 2D section (Fig. 3A). The depth of investigation is 2.1 m in the shallow 3D grid (with the short rope, Fig. 4), and 2.8 m in the deeper 3D grid (Fig. 5). The raw data of the 2D profile is quite noisy, which is probably caused by lateral shifts in the streamer during successive passes. As a result, the inverted model has a high root mean square error (RMS = 41%) and does not appear very smooth. The raw data of the 3D grids are less noisy and the inverted models have lower errors (RMS = 16 % for the shallow 3D grid and 8 % for the deeper 3D grid).

The validation of resistivity models with other types of data is essential as resistivity is not only dependent on temperature, but varies with soil type, porosity and water content. For this purpose, the depth of the active layer was measured manually along the 2D profile: a steel rod is pushed into the ground penetrates unfrozen ground soil until it hits the hard frozen layer (Fig. 3C). This tool is the method used to monitor weekly the GTN-P active layer data at the UNISCALM box. The probed thaw depth occurs roughly at the resistivity contours between 76 and 212 Ωm, but its shape is much flatter than the resistivity contours (Fig. 3A).

Results

The 2D model (Fig. 3A) imagines 3 horizontal layers which concur with the soil stratigraphy observed in the NGTS boreholes (Fig. 1C). The conductive layer (ρ < ~200 Ωm) near the surface corresponds to the active layer of permafrost. Its thickness varies between 0 and 2 m along the CCR profile, while manual measurements indicate an average of only 59,2 cm and much less variability. Below, the CCR model images the ice rich zone (ρ up to ~2 kΩm) down to approximately 5 meters depth, then the cryopeg zone (ρ ~ 10Ωm) where freezing is prevented by the salinity of the soil.

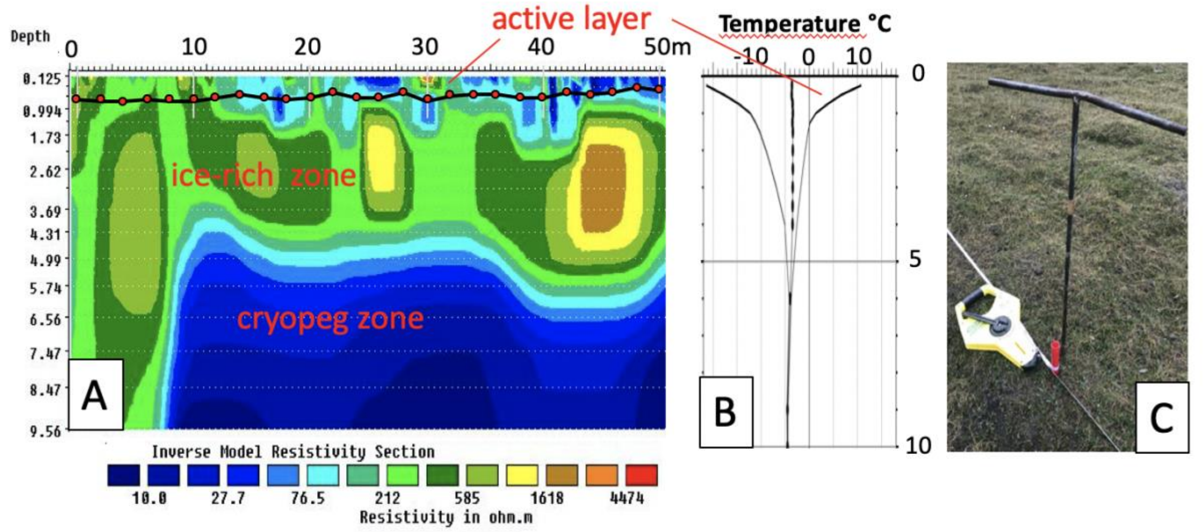

Figure 3 *A) Vertical resistivity model with proposed soil interpretation in red. The depth of the frozen layer measured manually is marked as red symbols. B) Minimum and maximum ground temperature measured in A6 monitoring borehole: the ground temperature at 10 m depth is -5 °C. The symbols mark the annual average. C) Mechanic probe used to measure the depth of the thaw layer.*

The advantage of the CCR method is revealed for acquisitions in map mode. This is because the operator does not need to change the spacing between the dipoles during acquisition, and he can quickly carry out a 3D survey by walking along parallel profiles. In addition, the measurements do not suffer from the noise induced by successive misaligned passes. Fig. 4 shows the 100 m X 100 m resistivity model acquired at the CALM box. It images the conductive active layer and some elongated resistive ridges that correspond to ice wedges. These features are typical of the Adventdalen valley (Christiansen, 2005). They were not visible during field work but can be seen on aerial photos (Fig. 2C) and are clearly revealed on the shaded DEM imagery (Syed, 2021). These ice wedges are ice-filled cracks that are caused by volumetric expansion of water during freezing. They are often arranged in polygons.

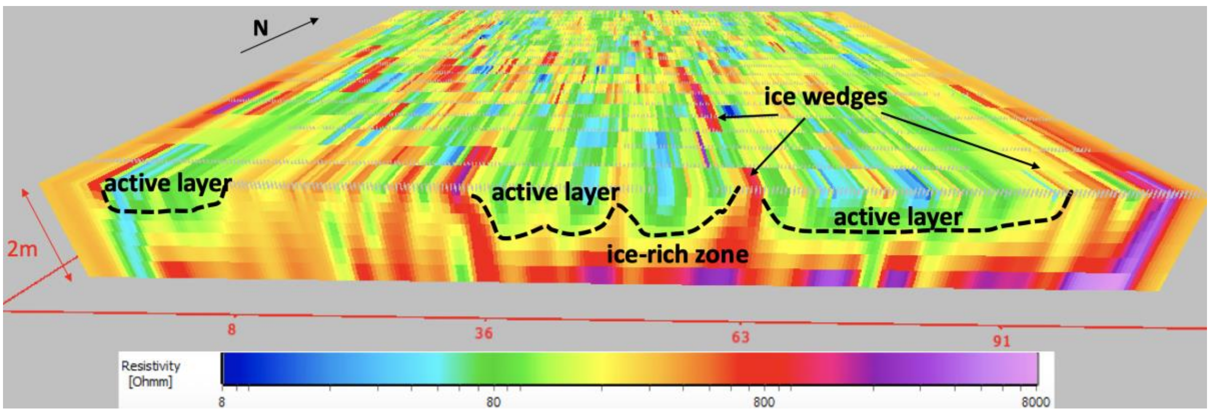

Figure 4 *The shallow 3D resistivity grid (100 m X 100 m X 2 m) seen from the top: it images the active (conductive) layer and ice wedges (long resistive ridges) characteristic of Adventdalen permafrost.*

The deeper grid (Fig. 5), acquired in the N-S direction, reaches the top of the cryopeg brine and images a conductive patch confirming that the ice-rich zone is not uniform as seen in the 2D profile (Fig. 3A).

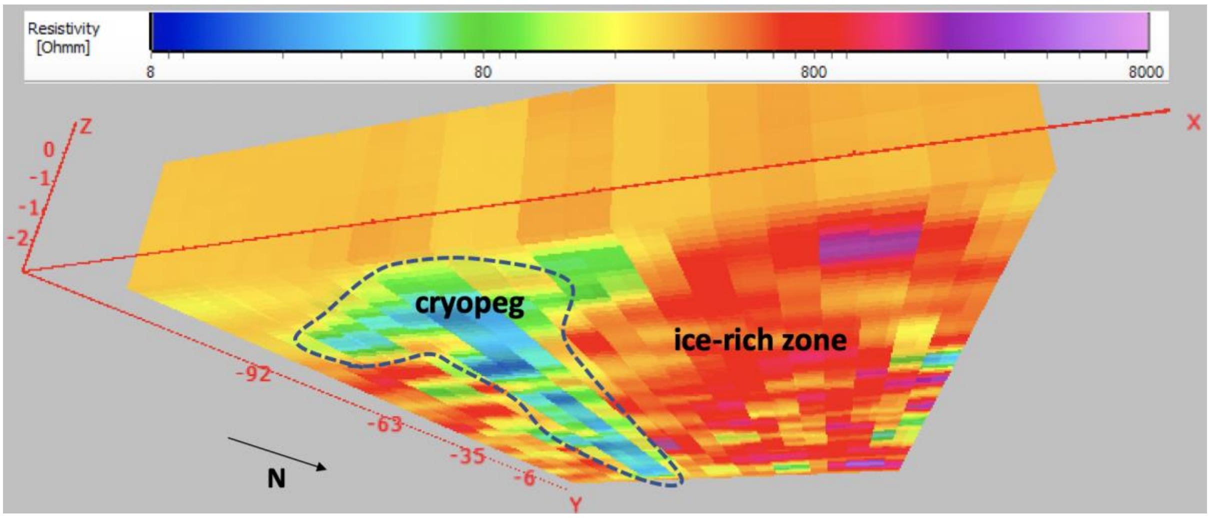

Figure 5 *The deeper 3D resistivity grid (100 m X 100 m X 2.8 m) seen from below: it images the bottom of the ice-rich soil (in red) and reveals a conductive patch (in blue) which belongs to the cryopeg.*

Conclusions

This case-study shows that even if the UNISCALM site has a uniform stratigraphy, its thermal structure is far from 1D. Subsequently, point-measurements of ground temperature and/or thaw depth may not be representative of the entire site. Instead, CCR surveying is a suitable tool for mapping the active layer strucuture. The CCR method is flexible (2D and/or 3D acquisition modes) and relatively easy to deploy. In addition, it overcomes the problem of electrical coupling between the ground and the electrodes, which is a challenge for the traditional galvanic method in cold and resistive environments. The CCR technique is also non-destructive unlike the traditional ERT method that uses stakes as electrodes, and unlike the GTN-P monitoring method that drives a mechanical probe into the ground. In addition, there is much inaccuracy associated with the method of the mechanical probe as the reached depth varies with the applied force and is therefore operator-dependant.

Acknowledgments

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References

Bazin, S., Lysdahl, A., Olaus Harstad, A., and Frauenfelder, R. [2019] Resistivity and Induced Polarization (ERT/IP) survey for bedrock mapping in permafrst, Svalbard. *25th European Meeting of Environmental and Engineering Geophysics*, doi: 10.3997/2214-4609.2019023622019.

Christiansen, H.H. [2005] Thermal regime of ice-wedge cracking in Adventdalen, Svalbard. *Permafrost and Periglacial Processes*, **18**, 687-98.

French, H.M. [2018] The Periglacial Environment, John Wiley and Sons, Ltd., 515 pages.

Gilbert, G., Instanes, A., Sinitsyn, A.O., and Aalberg, A. [2019] Characterization of two sites for geotechnical testing in permafrost: Longyearbyen, Svalbard. *Geosciences*, **5**, 868-885.

Hauck, C., [2013] New concepts in geophysical surveying and data interpretation for permafrost terrain. *Permafrost and Periglacial Processes*, doi:10.1002/ppp.1774.

Syed, S.G., [2021] Testing of different resistivity investigation methods for mapping permafrost. Master Thesis, Universitet i Oslo.