Small-loop surface NMR and high resolution ERT soil evolution monitoring at the Midtre Lovénbreen glacial forefield in Ny-Ålesund, Svalbard

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SUMMARY

Widespread glacier retreat in the Arctic due to climate change is resulting in rapid ecosystem changes which are not fully understood. Geophysical methods can complement biological and chemical measurements to better understand soil evolution in glacier forefields following glacier retreat. In this study preliminary data from a long-term electrical resistivity tomography installation near Ny-Ålesund, Svalbard are presented with accompanying small loop surface NMR data. The NMR data provides valuable information on liquid-phase water and calibration for the ERT data. Our study provides the first [shallow-depth (<2m) surface NMR] data for a remote Arctic forefield, shedding light on the non-saturated state of the subsurface media.

Key words: vadose zone, soil moisture, small-loop NMR, ERT

INTRODUCTION

Ice retreat in the Arctic exposes vast barren expanses of pioneer soils. Over timescales of decades to thousands of years, these desolate and seemingly lifeless areas transform into arctic tundra—supporting a diverse ecological community. Important biological and geomorphological questions about this transition remain unanswered. These include the net carbon balance, the rate of physical, biological and chemical change, and the processes affecting these developments. Much of the initial soil development is thought to be driven by (micro-)biological processes (Botnen et al., 2020). Biological and ecological modelling can shed light on soil development processes and make predictions (Bradley et al., 2015). Data are critical to these ecological models, including: microbiological data, soil moisture (including aggregate state, i.e. frozen vs. liquid phase), seasonal variability, and soil temperature profiles. Both heterogeneity and temporality of these parameters also play a role in microbiological processes.

Geophysical methods can provide insight into soil property parameters in the High Arctic. Two established methods that are particularly applicable include electrical resistivity tomography (ERT) and surface NMR. Challenges in this setting include the remoteness of the study area, as well as the shallow depth of primary interest (0-2 m).

ERT measures electrical resistivity which is related to soil moisture and organic content of the media. ERT tomography is well-suited for shallow investigations pertinent to the application. Recent advances in semi-permanent installations of time-lapse ERT instrumentation enable processes to be monitored on daily, seasonal, and multi-year timescales. While ERT methods provide a powerful means by which to monitor subsurface processes, the link between soil moisture and electrical conductivity is empirical and requires calibration.

Surface NMR (sNMR) is a unique geophysical method that relies on the inherent nuclear magnetisation of liquid-phase water in the subsurface. As a result sNMR measurements can provide a direct measure of water content which can be used to calibrate an ERT installation. Surface NMR has been used successfully in the Arctic previously where the remoteness and high magnetic field intensity contribute to generally favourable conditions (Keating et al., 2018). The shallow depth of investigation of sNMR for soil evolution monitoring in this application is challenging as most instruments are designed around deeper targets. As such, an open research question was how successful small loop NMR would be in the Arctic.

This abstract presents preliminary findings of a long term ERT installation and shallow small loop sNMR soundings in the forefield of the Midtre Lovénbreen glacier near Ny-Ålesund, Svalbard. The data were collected as part of SUN-SPEARS, an interdisciplinary and international project integrating geophysical and microbiological data in order to better understand soil development following glacial retreat. The sites represent a chronosequence with longer-exposed sediments present further from the actively retreating snout of the glacier. The data were collected in July 2021 and findings will be incorporated in biological modelling (e.g. Bradley et al., 2017) in later stages of the project.

METHODS

Two ERT systems (BGS-designed, known as PRIME) were installed in the forefield of the Midtre Lovénbreen glacier. Site 1 was near the snout of the glacier (as of July 2021) and Site 2 was found approximately 800 m from the snout (Fig. 1). Surface NMR data were collected at Sites 1 and 2 as well as in between at Site 1.5. The sNMR data were collected over the ERT arrays (Fig. 2) although the volume of investigation varies between the two methods.

The SUN-SPEARS project will also collect subsurface temperature data from buried sensors recorded on a Campbell Scientific data logger and tower installation. These data will also be used to calibrate the ERT data at later stages in the project. The installation of temperature sensors included the augering of test holes at Sites 1 and 2. Site 1 was dominated by fine glacial sediment, but also included some large cobbles and boulders; the water table was at approximately 75 cm. Site 2 contained more cobbles and boulders than Site 1, especially below ~0.7 m. Augering did not encounter the water table at Site 2.

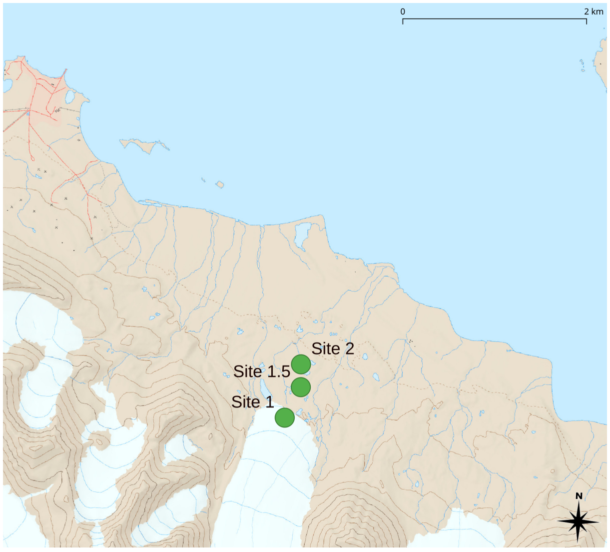

Figure 1. Location of field sites in front of the Midtre Lovénbreen glacier. Sites 1 and 2 include a full PRIME installation, sNMR data were also acquired in between Sites 1 and 2, at Site 1.5. The town of Ny-Ålesund is in the NW corner of the map.

Electrical Resistivity Tomography. Two semi-permanent ERT installations were installed at Sites 1 and 2 in this study. The PRIME system was developed by the British Geological Survey (Holmes et al., 2020) and included solar panels and wind turbines to provide power through the Arctic winter. Each PRIME installation includes 222 electrodes at 30 cm line and electrode separation. A rectangular configuration was adopted with 6 elongated electrode lines of 37 electrodes each. Each PRIME grid therefore covers a 1.5 x 10.8 m rectangular area. The PRIME installations are semi-autonomous and collect a suite of data regularly. Different electrode survey configurations are collected including dipole-dipole and multiple-gradient. The data in this manuscript were processed using Res3DInvX64 (https://aarhusgeosoftware.dk/res3dinv).

Surface NMR. The MRS-MIDI II surface NMR instrument manufactured by Radic Research was used in this study. It is a relatively low power instrument transmitting approximately 30 A peak current at the maximum pulse moment. The MIDI II is relatively lightweight and fits into a backpack for transport to and from the fieldsite. The MIDI II was connected to a lightweight 24 V Li-ION power supply. The transmitter (single turn) and receiver (12 turn) wires were both 40 m long. A combination of coincident single turn 6.4 m circular and 10 m square loops were used. Single pulse FID datasets were collected with 24 evenly spaced pulse moments. In most cases 64 stacks were acquired.

The inducing field was estimated from the International Geomagnetic Reference Field (IGRF) model (accessed through http://noaa.gov). For the survey dates the inclination and declination of B_0 was approximately 82° and 7.6°, respectively. The IGRF field intensity was estimated to be 55 062 nT, corresponding to a Lamor frequency of 2 344 Hz. In the field Larmor frequencies from 2 336–2 342 Hz were observed. The sNMR data were processed and inverted using the Akvo sNMR workbench (akvo.lemmasoftware.org).

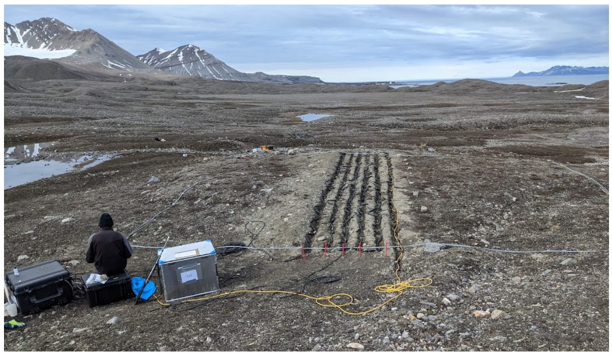

Figure 2. Example of survey configuration at Site 2. The sNMR loop (grey wire) encompassed a larger area than the ERT array (trenches).

RESULTS

Preliminary results from Sites 1 and 2 are discussed below. In both cases the ERT results are based on the inversion of a single dataset (not time lapsed). The NMR inversions are based on a QT-style inversion with a depth of investigation (DOI) derived from a point-spread function. No DOI analysis was performed on the ERT inversions at this stage in the project.

Site 1. The PRIME inversion at Site 1 indicates a more conductive top 0.5 m of soil on the side of the ERT array nearest the glacier (Fig. 3). A sNMR loop was set up on the edge of the array biased towards the conductive edge of the ERT inversion (running from approximately 8 m to 18 m using the same grid). The sNMR data was good quality with a noise floor estimate of 2.7 nV (Fig. 4). The signal was not particularly high, but apparent T_2^* decays were in the range of 200 ms. Inversion of the sNMR data was consistent with increased water content at approximately 0.6 m depth. The water content pinches out near 2 m, but increases again at a depth of about 5 m (Fig. 5).

The combination of relatively long decays with low water content may appear paradoxical at first consideration. However, this is consistent with liquid phase water in permafrost. Permafrost often contains substantial quantities of liquid phase water. Most conceptualizations of permafrost are consistent with ice found around the edges of pores with a nucleus of liquid phase water. Since ice has a low surface relaxivity, long NMR decays are often observed in these settings (Kass et al., 2017). The deeper water (6-7 m) could also be another layer of fine sediments below cobbles, similar to Site 2.

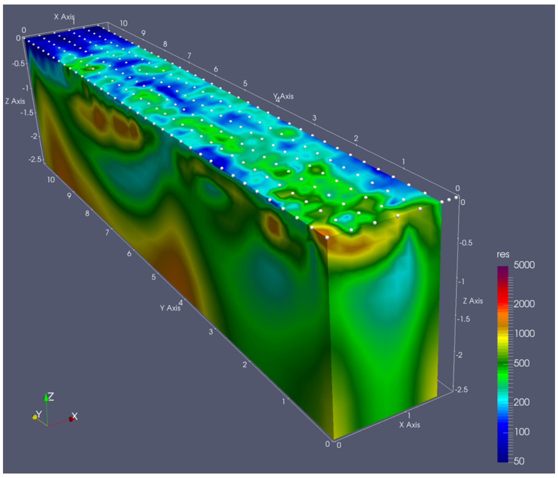

Figure 3. An inversion of PRIME data collected at Site 1. The 'y'-axis runs in the same direction as the glacier and most of the contrast is expected along this line. The area nearest the glacier has higher conductivity in the shallow subsurface.

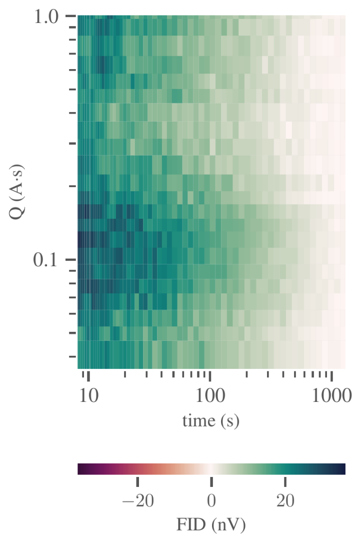

Figure 4. Surface NMR data collected at Site 1. The noise level appeared uniform and was estimated at 2.7 nV.

Site 2. The ERT inversion at Site 2 (Fig. 6) indicates a more homogenous setting along the survey direction (less lateral trend than at Site 1). The ERT data indicate resistive sediments below approximately 70 cm. The augering of temperature sensor boreholes is consistent with a zone of large cobbles at this depth. The sNMR data collected at Site 2 had a similar noise floor to Site 1 (2.87 nT) but a lower level of NMR signal and shorter decays (Fig. 7). As a result, the S:N at site 2 was lower than Site 1. Less variation in water content with pulse moment was shown in the sNMR data at Site 2 compared to Site 1. Inversion of this dataset yielded a fairly uniform water content model between 0.01 and 0.03 m^3/m^3 with faster T_2^* decay rates than Site 1 (Fig. 8).

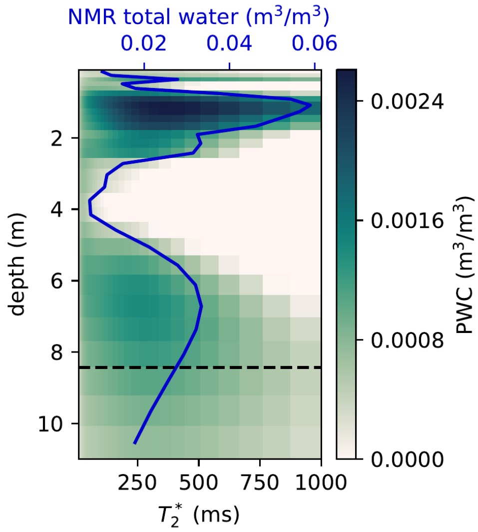

Figure 5. Inversion of sNMR data at Site 1, the black dashed line represents a DOI based on point spread analysis. Total water content is shown in blue.

Interpretation of the geophysical data at Site 2 is consistent with less overall water availability. The large cobbles at Site 2 will have less pore space than the finer sediments at Site 1 and more significantly will contain less small pores with the capillary pressure needed to retain water in the presence of drainage forces. For these reasons, it is postulated that the water availability for microorganisms at Site 2 is seasonally dependent on the availability of snowmelt.

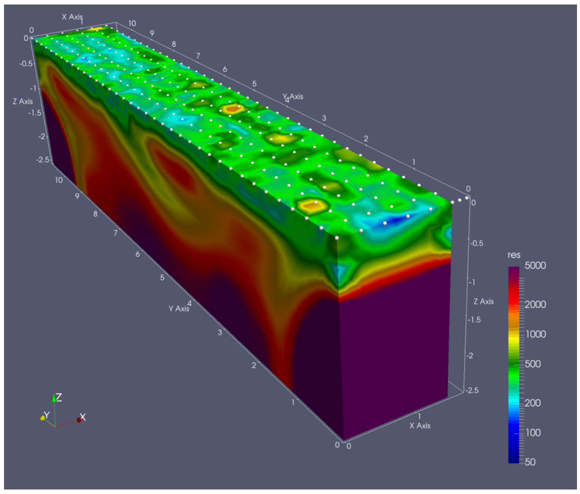

Figure 6. The PRIME inversion at Site 2 indicates more electrically conductive materials down to about 0.5 m at which point a more resistive medium is encountered.

Contrasting Site 1 and Site 2 suggests that water availability for microorganisms is spatially and temporally variable. Sites near the snout of the glacier have an abundant source of water during melt season. Locations even a short distance away from the toe may be significantly drier during summer months.

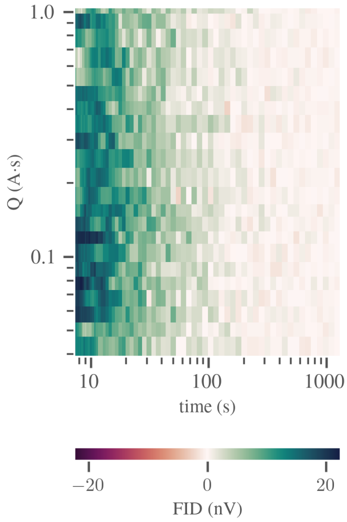

Figure 7. The sNMR data at Site 2 had an estimated noise level of 2.87 nT but lower overall NMR signal amplitude than Site 1.

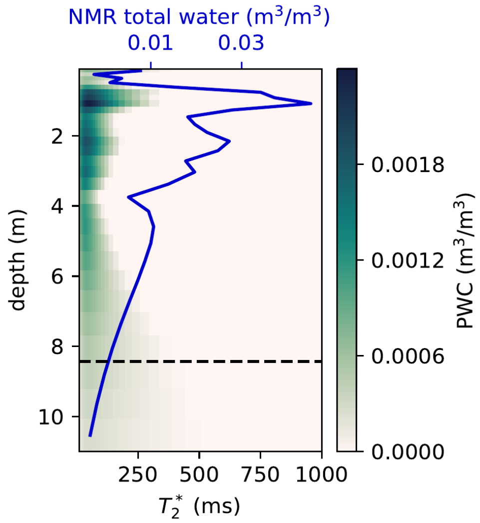

Figure 8. Surface NMR inversion at Site 2. The recovered water content model at Site 2 is much more uniform with depth and has faster decays than Site 1.

CONCLUSIONS

The current rapid retreat of Arctic glaciers is resulting in large swaths of land undergoing transformation from recently-exposed glacial sediments to tundra. Biological activity contributes to soil formation, however the biota requires resources (including water availability) in order to become established in these soils. Geophysical surveys can provide valuable information about material properties and water availability and can therefore increase the understanding of soil evolution in this setting.

Preliminary results from an ERT monitoring array installation confirm that electrical resistivity provides a useful proxy for subsurface properties. Surface NMR provides a powerful tool for calibration and interpretation of ERT data and increases the value of the ERT data. Small loop sNMR can be an effective tool in the Arctic where ambient noise levels are low and the technique is uniquely capable of detecting shallow water content.

The installation of long-term ERT monitoring equipment will be valuable in providing a picture of how conditions change temporally and spatially in this dynamic setting. Continued monitoring at Sites 1 and 2 in the Midre Lovénbreen glacier with intermittent sNMR support data will provide a glimpse at the seasonal processes which contribute to microorganism ecology in this unique environment.

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REFERENCES

Botnen, S. S., S. Mundra, H. Kauserud, and P. B. Eidesen, 2020, Glacier retreat in the High Arctic: opportunity or threat for ectomycorrhizal diversity? FEMS Microbiology Ecology, 96.

Bradley, J. A., A. M. Anesio, and S. Arndt, 2017, Microbial and Biogeochemical Dynamics in Glacier Forefields Are Sensitive to Century-Scale Climate and Anthropogenic Change: Frontiers of Earth Science in China, 5, 26.

Bradley, J. A., A. M. Anesio, J. S. Singarayer, M. R. Heath, and S. Arndt, 2015, SHIMMER (1.0): a novel mathematical model for microbial and biogeochemical dynamics in glacier forefield ecosystems: Geoscientific Model Development, 8, 3441–3470.

Bradley, J. A., S. Arndt, M. Šabacká, L. G. Benning, G. L. Barker, J. J. Blacker, M. L. Yallop, K. E. Wright, C. M. Bellas, J. Telling, M. Tranter, and A. Anesio, ForthcomingMicrobial dynamics in a High-Arctic glacier forefield: a combined field, laboratory, and modelling approach: .

Holmes, J., J. Chambers, P. Meldrum, P. Wilkinson, J. Boyd, P. Williamson, D. Huntley, K. Sattler, D. Elwood, V. Sivakumar, H. Reeves, and S. Donohue, 2020, Four-dimensional electrical resistivity tomography for continuous, near-real-time monitoring of a landslide affecting transport infrastructure in British Columbia, Canada: Near Surface Geophysics, 18, 337–351.

Kass, M. A., T. P. Irons, B. J. Minsley, N. J. Pastick, D. Brown, and B. K. Wylie, 2017, In situ nuclear magnetic resonance response of permafrost and active layer soil in boreal and tundra ecosystems: The Cryosphere, 11, 2943–2955.

Keating, K., A. Binley, V. Bense, R. L. Van Dam, and H. H. Christiansen, 2018, Combined geophysical measurements provide evidence for unfrozen water in permafrost in the Adventdalen valley in Svalbard: Geophysical Research Letters, 45, 7606–761

REFERENCES PAPERPILE TEMP

Botnen, S. S., S. Mundra, H. Kauserud, and P. B. Eidesen, 2020, Glacier retreat in the High Arctic: opportunity or threat for ectomycorrhizal diversity? FEMS Microbiology Ecology, **96**.

Bradley, J. A., A. M. Anesio, and S. Arndt, 2017, Microbial and Biogeochemical Dynamics in Glacier Forefields Are Sensitive to Century-Scale Climate and Anthropogenic Change: Frontiers of Earth Science in China, **5**, 26.

Bradley, J. A., A. M. Anesio, J. S. Singarayer, M. R. Heath, and S. Arndt, 2015, SHIMMER (1.0): a novel mathematical model for microbial and biogeochemical dynamics in glacier forefield ecosystems: Geoscientific Model Development, **8**, 3441–3470.

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Holmes, J., J. Chambers, P. Meldrum, P. Wilkinson, J. Boyd, P. Williamson, D. Huntley, K. Sattler, D. Elwood, V. Sivakumar, H. Reeves, and S. Donohue, 2020, Four‐dimensional electrical resistivity tomography for continuous, near‐real‐time monitoring of a landslide affecting transport infrastructure in British Columbia, Canada: Near Surface Geophysics, **18**, 337–351.

Kass, M. A., T. P. Irons, B. J. Minsley, N. J. Pastick, D. Brown, and B. K. Wylie, 2017, In situ nuclear magnetic resonance response of permafrost and active layer soil in boreal and tundra ecosystems: The Cryosphere, **11**, 2943–2955.

Keating, K., A. Binley, V. Bense, R. L. Van Dam, and H. H. Christiansen, 2018, Combined geophysical measurements provide evidence for unfrozen water in permafrost in the adventdalen valley in Svalbard: Geophysical Research Letters, **45**, 7606–7614.