The use of SNMR to determine the variability of permafrost in Adventdalen, Svalbard

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SUMMARY

Knowledge of the thickness and ice/water content of permafrost in arctic regions is critical for assessing the impacts of surface warming on environmental processes such as groundwater flow and the release of green house gasses from areas of degrading permafrost. In this study, we performed a geophysical survey using surface nuclear magnetic resonance (SNMR) and controlled source audio-magnetotellurics (CSAMT) to map the state of the permafrost in Adventdalen, Svalbard, a river valley in a coastal Arctic landscape. SNMR was used to determine the unfrozen water content at depths down to ~80 m. CSAMT was used to determine the total thickness of permafrost. In the parts of the valley above the marine limit (~80 m above sea-level) SNMR did not detect any unfrozen water content. However, the SNMR soundings along the valley up to several kilometers from the coast show a substantial signal due to unfrozen water content. The CSAMT observations suggest that permafrost thickens substantially along the ~12 km long transect from the coastal area inland. The electrical resistivities observed are relatively low, compared to mountain permafrost environments, which is most likely attributed to the high salinity of the pore water in our study area. Our study illustrates the ability of CSAMT and SNMR to map permafrost characteristics in saline environments. Future work enabling a more thorough interpretation needs more data on ice-content, the thermal state of the deeper permafrost, pore water salinities, and the geological development of the study area.

Key words: artic, coastal, permafrost, Svalbard, SNMR

INTRODUCTION

Permafrost is defined in terms of temperature as any Earth material that remains below 0ºC for two consecutive years (French, 2007). While it is typically assumed that the pore water in permafrost is frozen, permafrost soils may have a substantial unfrozen water content, for instance in coastal environments with saline intrusion (e.g., Overduin et al., 2012) or when the sediments are marine or littoral. Determining the thickness and ice/water content of coastal permafrost is critical for understanding the effects of climate change on artic environmental processes.

Research was performed in Adventdalen, Svalbard. This site is a sediment infilled, flat-bottomed river valley in a typical coastal Arctic high relief landscape with relatively warm continuous permafrost of -3˚C to -6˚C at 10 m depth (Christiansen et al., 2010) (Figures 1, 2). Near the coast in the Adventdalen Valley the permafrost is typically 80 to 100 m thick, while further up the valley the permafrost can reach a thickness of 200 m (Humlum, 2005).

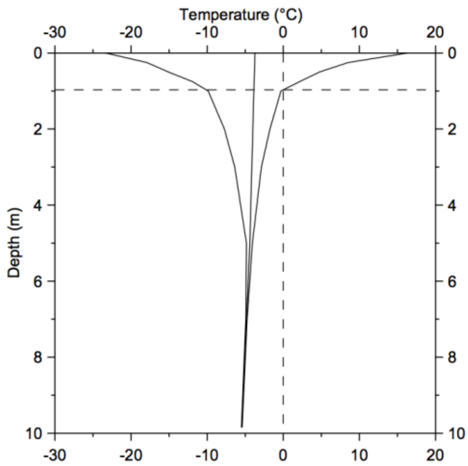

Figure 2: Ground thermal conditions from the lower part of the Adventdalen Valley for the year 1 September 2012 to 31 August 31 2013. The horizontal line denotes the interpolated depth of the active layer. (Figure from Gilbert, 2014 data from NORPERM.)

Geophysical measurements have previously been used to characterize the depth and distribution of permafrost. These geophysical investigations have mainly focused on electrical measurements made in alpine environments where permafrost is assumed to be frozen and with high resistivity (>~1000 Ω·m□in the absence of clay) and unfrozen ground has a low resistivity (<~500 Ω·m; Minsley et al., 2012). Examples include airborne electromagnetic measurements (e.g., Minsley et al., 2012), direct current resistivity (e.g., Hubbard et al., 2013), MT (e.g., Koziar and Strangway, 1978). However, in coastal environments both the frozen and unfrozen sediments can have low resistivity, e.g., <200 Ω · m as observed by Overduin et al. (2012) in Alaska and in Adventdalen by Ross et al. (2007), and thus the permafrost can have substantial unfrozen water content. This might imply the occurrence of active groundwater flow in near coastal Arctic aquifer systems, which would be supported by the presence of springs and pingos (Figure 1) the Adventdalen valley.

SNMR provides an additional approach for investigating permafrost environments. In theory, nuclear magnetic resonance (NMR) measurements are sensitive to both the frozen and unfrozen water content; however, the fast relaxation time of ice means that it cannot be detected using NMR equipment with long deadtimes, i.e., time between the excitation pulse and the first data point, such as SNMR (Kleinberg and Griffin, 2005). The SNMR measurement is thus only sensitive to the unfrozen water. Furthermore, due to the sensitivity of the SNMR signal to the subsurface electrical resistivity structure, electrical geophysical measurements are typically collected together with SNMR measurements. Previous studies have successfully demonstrated the use of SNMR to determine the thickness of taliks, a layer or body of unfrozen ground that occurs in permafrost, beneath frozen lakes and to determine the depth of permafrost in an alpine environment (Parsekian et al., 2013).

In this study we carried out a geophysical survey using CSAMT and SNMR to map permafrost occurrence in the Adventdalen Valley. The SNMR measurements were used to determine the unfrozen water content, whereas the CSAMT measurements, which are sensitive to changes in the electrical conductivity, were used to distinguish saline and fresh pore water and frozen and unfrozen soils.

METHODS

SNMR and CSAMT measurements were collected in Adventdalen, Svalbard, a river valley partly infilled with Holocene marine, deltaic, fluvial and periglacial sediments (Cable et al., in prep; Gilbert, 2014). SNMR and CSAMT soundings were collected both along the valley and across the valley as shown in Figure 1. Measurements were collected from March 23rd to April 2nd, 2014, during which time the ground was snow covered and the valley was accessible by snow mobile enabling effective surveys all over the landscape.

CSAMT measurements were collected at 13 locations using a Geometrics Stratagem EH4 with a frequency range from 11.7 Hz to 100 kHz. Information at depth was obtained by recording data from natural signals; information from shallow depths was obtained by recording data from a high frequency controlled source several hundred meters from the receiver. The electrodes were arranged with 40 m spacing. To ensure good electrical contact with the ground, a saline solution was poured over the electrodes prior to the collection of each MT dataset and supplemented as needed during the data collection. The MT data were inverted using IPI2win (http://geophys.geol.msu.ru/ipi2win.htm) to create a blocky 1D model at each receiver station.

SNMR measurements were collected at 14 locations using a 70x70 m square loop with the GMR system (Vista Clara Inc.). The remote location meant that the anthropogenic noise was limited to snow mobiles and a 50 Hz power line located along the road indicated in Figure 1. When possible, the snow mobile engines were turned off during the SNMR data collection and SNMR measurements were made away from the power line. Between 16 and 20 stacks were collected at each location. The pulse duration was set to 20 ms resulting in a maximum pulse moment of 14.19 A·s.

To account for variations in the magnetic field, the strength of this field was measured using a proton precession magnetometer during the SNMR measurements (Figure 3). The magnetic field varied from 54 674 nT to 54 819 nT with a declination of 7.5º and an inclination of 82º. The Larmor frequency, f_0, the frequency of the SNMR excitation pulse, is calculated from the magnitude of Earth's magnetic field, B_E, using $f_0 = \gamma_H B_E / 2\pi$, where γ_H is the gyromagnetic ratio for protons in water ($\gamma_H/2\pi$ = 42.577 MHz/T). The average Larmor frequency was 2332 Hz.

The SNMR data were processed using the GMR processing software (Walsh, 2008). The data were filtered with a 100 Hz bandpass filter. Individual records with high noise levels (primarily due to noise from snow mobiles) were removed prior to stacking the datasets. The filtered and stacked SNMR datasets were inverted using the GMR inversion software (Irons et al., 2012; Walsh, 2008). When possible, the SNMR data were inverted using the resistivity structure determined from a collocated CSAMT measurement; when there was no collocated CSAMT measurement at the SNMR location, the resistivity structure determined from the nearest CSAMT measurement was used.

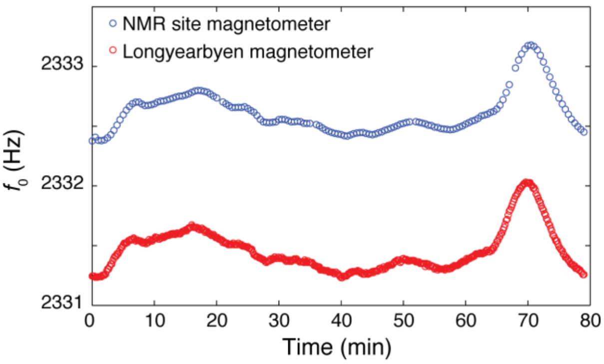

Figure 3. An example demonstrating typical f_0 variations observed during SNMR data collection. f_0 was calculated from B_E at the NMR-5 site for measurements made on March 28th, 2014. Shown for comparison is f_0 calculated from B_E measured using a permanent magnetometer located in nearby Longyearbyen (Tromsø Geophysical Observatory; http://flux.phys.uit.no/geomag.html).

RESULTS

The results from the CSAMT measurements at three measurement locations along the down valley profile are shown in Figure 4. The inverted resistivity images show a trend towards higher resistivities at the top of the valley. We note that near the coast, the resistivity is low, reaching a minimum of < 1 Ω · m. Although electrical measurements from mountain permafrost environments often show very high resistivity (e.g., Minsley et al., 2012), these values are consistent with direct current electrical resistivity measurements collected from a saline permafrost environment in Barrow, Alaska, USA (Overduin et al., 2012) and previously at the Adventdalen site (Harada and Yoshikawa, 1998).

The results from the SNMR measurements at three measurement locations are shown in Figure 4. For the measurements in the lower valley near the coast, the resolution matrix showed that the depth of investigation was much shallower than would typically be expected for a 70 m square loop (~50 m below the surface); the shallow depth of investigation is due to the low resistivity and the high magnetic field inclination. The depth of investigation reached a maximum of ~80 m for the measurements collected at the top of the valley. Near the coast a clear signal from unfrozen water was observed in the SNMR data, with maximum unfrozen water contents ranging from 5 to 10% in each sounding. No unfrozen water content was detected in the SNMR measurements collected above the upper marine limit (NMR-7 in Figure 4). The base of the permafrost was not observed in any of the SNMR datasets.

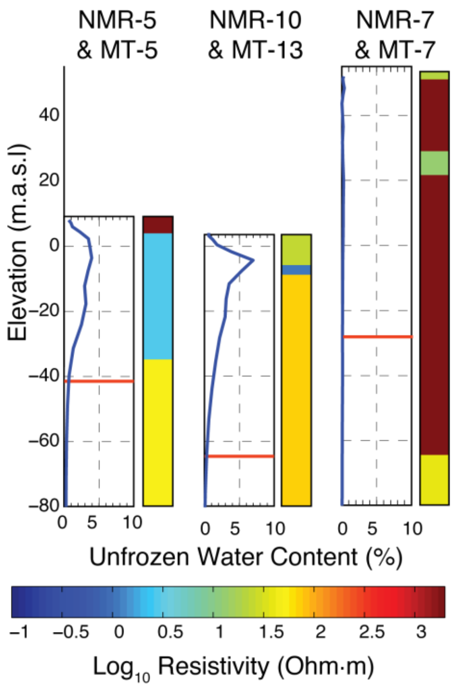

Figure 4. Inverted SNMR and CSAMT depth profiles for data collected in Adventdalen, Svalbard. Horizontal red lines indicate the approximate depth of investigation of the SNMR measurements.

CONCLUSIONS

Our study is the first to successfully map unfrozen water content in a coastal permafrost environment using SNMR and CSAMT. The SNMR measurements identified substantial unfrozen water content (>~5%) near the coast; the unfrozen water content decreased with distance from the coast. No unfrozen water was detected above the upper marine limit. The CSAMT measurements supported the SNMR results. Low resistivities were observed in the lower valley (near the coast); above the marine layer at the top of the valley, the resistivity was higher (>1000 Ω·m in some locations). The next steps in our work is to combine the results presented here with the thermal and geochemical data, particularly the pore water salinity, and the overall sedimentological model for Adventdalen, which is currently under development. Combining these datasets will allow us to develop a full assessment of the ice-content and thermal state of permafrost in Adventdalen, Svalbard.

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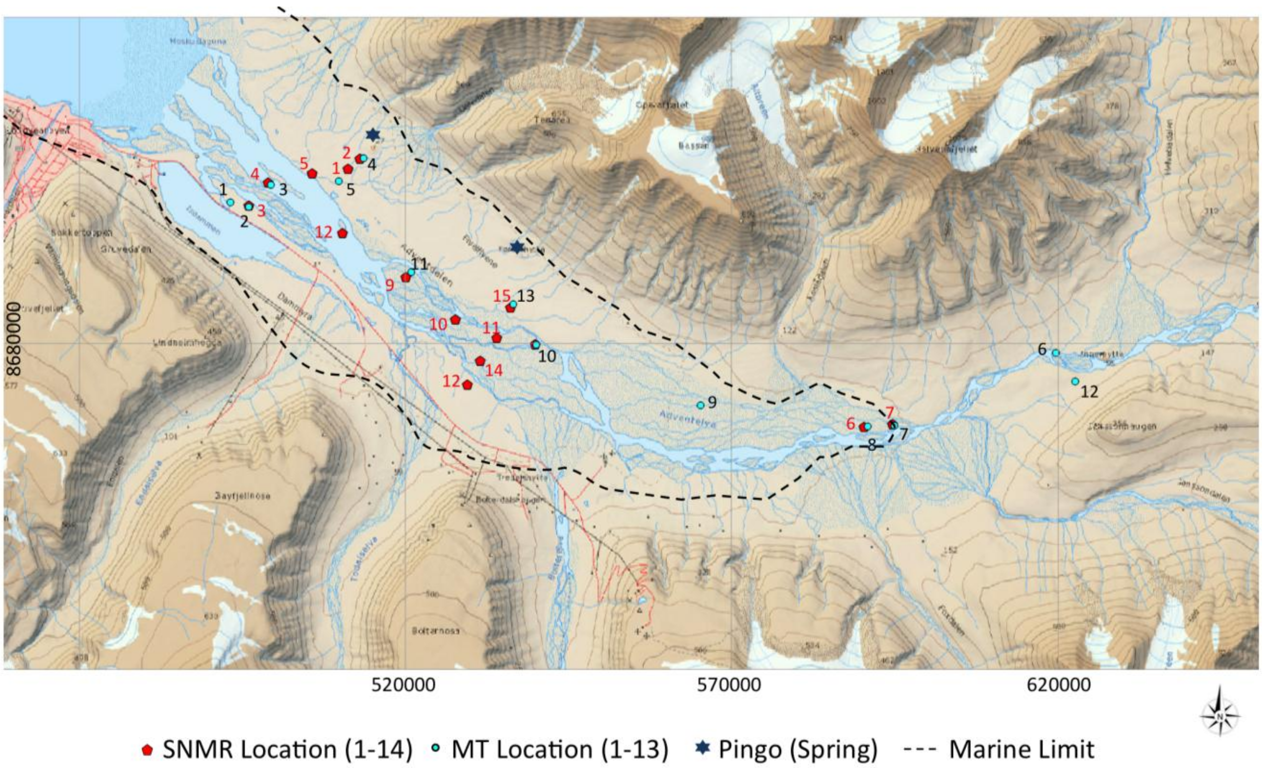

Figure 1: Location of the survey including MT and SNMR sites in the Adventdalen valley, Svalbard. The infrastructure of the valley is included. Map from the Norwegian Polar Institute; http://toposvalbard.npolar.no.