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8 **Title:**
9 Combined geophysical measurements provide evidence for unfrozen water in permafrost in the
10 Adventdalen valley in Svalbard

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28

29 **Key Points:**

- 30
- 31 • Surface nuclear magnetic resonance and controlled source audio-magnetotelluric
32 measurements used to map permafrost in Adventdalen, Svalbard
 - 33 • Measurements provided direct *in situ* detection of unfrozen water in permafrost
 - 34 • Up to 10% unfrozen water content was detected using surface nuclear magnetic
35 resonance in measurements made below the marine limit

36 **Index terms** (up to 5): 0702 Permafrost, 0794 Instruments and techniques, 0925 Magnetic and
37 electrical methods (5109)

38

39 **Key words:** arctic, coastal, permafrost, Svalbard, SNMR, CSAMT

40 **Abstract**

41 Quantifying the unfrozen water content of permafrost is critical for assessing impacts of
42 surface warming on the reactivation of groundwater flow and release of greenhouse gasses from
43 degrading permafrost. Unfrozen water content was determined along a ~12 km transect in the
44 Adventdalen valley in Svalbard, an area with continuous permafrost, using surface nuclear
45 magnetic resonance and controlled source audio-magnetotelluric data. This combination of
46 measurements allowed for differentiation of saline from fresh, and frozen from unfrozen pore
47 water. Above the limit of Holocene marine transgression no unfrozen water was detected,
48 associated with high electrical resistivity. Below the marine limit, within several kilometers of
49 the coast, up to ~10% unfrozen water content was detected, associated with low resistivity values
50 indicating saline pore water. These results provide evidence for unfrozen water within
51 continuous, thick permafrost in coastal settings, which has implications for groundwater flow
52 and greenhouse gas release in similar Arctic environments.

53

54

55 **1 Introduction**

56 It is often assumed that permafrost, defined as any Earth material that remains below 0°C
57 for two consecutive years (French, 2007), indicates that the pore water is frozen. However,
58 permafrost in sediments may have a substantial unfrozen water content, for instance in coastal
59 environments with saline intrusion, when the sediment and original pore fluids are littoral or
60 marine in origin, or in warm permafrost, i.e., permafrost at or just below 0°C (e.g., Overduin et
61 al., 2012; Romanovsky & Osterkamp, 2000). While frozen ground is considered an impermeable
62 barrier for groundwater movement, partially frozen ground may allow for considerable flow,
63 which has significant implications for heat and mass transport processes (e.g., Bense et al., 2009;
64 Boike et al., 1998; Romanovsky & Osterkamp, 2000; Walvoord & Kurylyk, 2016). As such,
65 understanding the ice/water content of permafrost is critical for modelling permafrost evolution
66 and predicting the effect of climate change on the degradation of permafrost and consequent
67 impact on the carbon cycle and groundwater-surface water exchange processes (Bense et al.,
68 2012).

69 Currently, there is a lack of data documenting the unfrozen hydrogeologic characteristics
70 of permafrost, which severely limits the potential to accurately model hydrologic processes in
71 permafrost landscapes (Walvoord & Kurylyk, 2016). The thickness and location of permafrost is
72 typically determined from measurements of temperature or by modelling, which do not directly
73 relate to the unfrozen water content. Furthermore, in warm permafrost the unfrozen water
74 content can be substantial, up to ~20% of the total porosity for soils at -1°C depending on the soil
75 and pore-fluid composition (Romanovsky & Osterkamp, 2000). Cores collected from permafrost
76 environments are typically moved to freezers held at e.g. -12°C prior to analysis (Gilbert, 2014).
77 This may cause components of the core that were unfrozen at *in situ* conditions to freeze prior to

78 analysis making it difficult to quantify the unfrozen water content in the laboratory. In contrast,
79 geophysical measurements made in a borehole can provide *in situ* information about the physical
80 state of pore water (e.g., Kass et al., 2017; Minsley et al., 2016; Romanovsky & Osterkamp,
81 2000). Such measurements can provide the unfrozen water content; however, the data are limited
82 to borehole locations. To provide data for larger scale permafrost models, more spatial
83 information is needed.

84 Surface-based geophysical measurements can be used to characterize the depth and
85 distribution of permafrost; an overview of large scale permafrost mapping can be found in
86 (Walvoord & Kurylyk, 2016). Geophysical investigations have primarily consisted of electrical
87 and electromagnetic measurements in environments where permafrost is assumed to be frozen,
88 including in mountainous and high-latitude settings. In these environments, permafrost has a
89 high resistivity ($> \sim 1000 \Omega\text{m}$ in the absence of clay) and unfrozen ground has low resistivity
90 ($< \sim 500 \Omega\text{m}$; Minsley et al., 2012). Examples include airborne electromagnetic measurements
91 (e.g., Minsley et al., 2012), direct current resistivity (e.g., Hilbich et al., 2008; Hubbard et al.,
92 2013), and magnetotellurics (e.g., Koziar & Strangway, 1978). In coastal environments and with
93 groundwater brines, the interpretation of electrical resistivity data becomes more complex as
94 both frozen and unfrozen sediments can have low resistivity, e.g. $< 200 \Omega\text{m}$ as observed by
95 Mikucki et al. (2015) in the McMurdo Dry Valleys in Antarctica, Overduin et al. (2012) in
96 Alaska, and by Ross et al. (2007) in the Adventdalen valley, Svalbard. This makes it difficult to
97 use electrical resistivity measurements alone to understand the physical state of pore water as
98 either frozen, partially frozen, or liquid.

99 Surface nuclear magnetic resonance (SNMR), which is sensitive to unfrozen water
100 content, is emerging as a geophysical method that, alongside electrical resistivity measurements,

101 can be used to investigate permafrost environments (Behroozmand et al., 2015; Parsekian et al.,
102 2013). Due to the impact of the subsurface electrical resistivity structure on the SNMR signal,
103 electrical or electromagnetic geophysical measurements are typically collected together with
104 SNMR measurements (Behroozmand et al., 2015). Previous studies have successfully
105 demonstrated the use of SNMR to determine the thickness of taliks, a layer or body of unfrozen
106 ground that occurs in permafrost, and to determine the depth of permafrost (Parsekian et al.,
107 2013).

108 In this study, we used controlled source audio magnetotelluric (CSAMT) and SNMR
109 measurements to map the physical state of permafrost and distinguish frozen from unfrozen
110 water in the permafrost in the Adventdalen valley in Svalbard at 78°N. The SNMR
111 measurements were used to determine the unfrozen water content, whereas the CSAMT
112 measurements, which are sensitive to changes in the electrical resistivity, were used in the
113 inversion of the SNMR measurements, and to distinguish saline from fresh pore water and frozen
114 from unfrozen ground. To the best of the authors' knowledge, this study is the first to
115 successfully employ CSAMT and SNMR to detect unfrozen water content within continuous
116 permafrost.

117

118 **2 Site description**

119 Field data were collected in the Adventdalen valley (hereafter only called Adventdalen)
120 in Svalbard at 78°N. This flat-bottomed river valley is partly infilled with Holocene marine,
121 deltaic, fluvial and periglacial sediments, in a typical coastal Arctic high relief landscape with
122 continuous permafrost of -3°C to -6°C at 10 m depth (Christiansen et al., 2010; Gilbert, 2018)
123 (Figures 1 and 2). Typically, the upper 3-4 m of sediment is aeolian with a relatively high

124 amount of syngenetic ground ice in the permafrost, all of which accumulated since 3 ka ago in
125 the middle of Adventdalen, after the underlying deltaic sediments became subaerially exposed
126 (Gilbert, 2018). Sediments below this depth are primarily deltaic with epigenetic permafrost and
127 a generally low ground ice content (Gilbert, 2018). The upper deltaic sediments consist of
128 approximately even amounts of silt and sand, with less than 5% clay, and were deposited in delta
129 top and delta front facies assemblages. The deepest studied sediments in one core below 35 m
130 are finer-grained with up to 10% clay and around 15 % sand; deposited in glaciomarine and
131 prodelta environments (Gilbert, 2014, 2018). Raised marine deposits, indicating the upper
132 Holocene marine limit, in Adventdalen, dated to ~10 ka, occur at 70 m a.s.l. in its outer part and
133 at 62 m a.s.l. in the inner part (Lønne & Nemeč, 2004; Lønne, 2005). Adventdalen features
134 typical periglacial landforms including pingos and ice-wedges. Thermal profiles from borehole
135 records show that in Adventdalen the permafrost is typically 80 to 100 m thick, and is assumed
136 to thin to 0 m at the shore. In the mountains surrounding the valleys the permafrost can reach a
137 thickness of 400 m (Humlum, 2005; Svensson, 1970). The active layer in Adventdalen is ~1m
138 thick (Figure 2; Christiansen, 2005).

139 The average gravimetric ice content, determined in a 60 m continuous core extracted
140 from the UNIS-CO₂ borehole (Figure 1) and placed directly in a -12 °C freezer, generally ranges
141 from 20 to 40% (Gilbert, 2018). However, the near surface terrestrial sediments (from depths <
142 5m) can have gravimetric ice contents up to 160%, due to the presence of ice-wedges and/or the
143 formation of syngenetic permafrost in the terrestrial sediments (Gilbert, 2018).

144

145

146

147 **3 Geophysical methods**

148 SNMR and CSAMT measurements were collected both along and across Adventdalen
149 (Figure 1) from 23 March to 2 April 2013. During this time, the ground was snow covered, the
150 active layer was frozen (Figure 2), and the valley was accessible by snow mobile enabling
151 effective surveys across the entire valley bottom.

152 CSAMT measurements were collected at 13 locations using a Geometrics Stratagem EH4
153 system with a frequency range from 11.7 Hz to 100 kHz. Information at depth was obtained by
154 recording data from natural signals; information from shallow depths was obtained by recording
155 data from a high frequency 400 Am² controlled source several hundred meters from the receiver.
156 The electrodes were arranged with 40 m spacing. To ensure good electrical contact with the
157 ground, electrode sites were predrilled to approximately 20cm and a saline solution was poured
158 over the electrodes prior to the collection of each CSAMT dataset and supplemented as needed
159 during the data collection. The CSAMT data were inverted using IPI2win (Bobachev, 2002) to
160 create a blocky 1D model at each receiver station. Datasets with high noise (due to problems
161 with maintaining electrode contact in frozen ground) were discarded.

162 SNMR measurements, which are directly sensitive to hydrogen protons in water, were
163 collected at 15 locations using a 70x70 m square loop with the Vista Clara GMR system.
164 Although in theory SNMR measurements are sensitive to hydrogen in both ice and unfrozen
165 water (Kleinberg & Griffin, 2005), the fast relaxation time of ice means that it cannot be detected
166 using NMR equipment with long “deadtimes”, i.e., time between the excitation pulse and the
167 first data point, such as in SNMR instruments. The remote location meant that the anthropogenic
168 noise was limited to snow mobiles and a 50 Hz power line located along the road indicated in
169 Figure 1. When possible, the snow mobile engines were turned off during the SNMR data

170 collection and SNMR measurements were made away from the power line. Between 16 and 20
171 stacks were collected at each location. The pulse duration was set to 40 ms resulting in a
172 maximum pulse moment of 14.19 A·s.

173 To account for variations in the magnetic field, its strength was measured using a proton
174 precession magnetometer during the SNMR measurements. In Adventdalen the magnetic field
175 declination is 7.5° and the inclination is 82° . The total magnetic field strength varied from 54 674
176 nT to 54 819 nT across all measurement locations; the maximum variation during a single
177 measurement was 130 nT (for site SNMR04), while the average variation during individual
178 measurements was 41 nT. The Larmor frequency, f_0 , is calculated from the magnitude of Earth's
179 magnetic field, B_E , using $f_0 = \gamma_H B_E / 2\pi$, where γ_H is the gyromagnetic ratio for protons in water
180 ($\gamma_H / 2\pi = 42.577$ MHz/T). The SNMR excitation pulse is tuned to the Larmor frequency, which
181 allows for the selective excitation of hydrogen protons. The variation in the Larmor frequency
182 during the course of a single measurement ranged from 0.2 to 2.3 Hz for most SNMR profiles,
183 but was higher for SNMR03 (3.7 Hz) and SNMR04 (5.5 Hz); this variation is within the
184 acceptable range of frequency offsets for accurate inversion of SNMR data (Walbrecker et al.,
185 2011).

186 The SNMR data were first processed using the GMR processing software (Walsh, 2008)
187 and filtered with a 100 Hz bandpass filter. Individual records with high noise levels (primarily
188 due to snow mobiles) were removed prior to stacking the datasets. The filtered and stacked
189 SNMR datasets were inverted using an open-source NMR processing package (MRSMATLAB;
190 Müller-Petke et al., 2012). This package uses a QT inversion scheme, which simultaneously fits
191 all pulse moments, signal amplitudes, and relaxation times, to determine the water content and
192 relaxation time profiles (Müller-Petke and Yaramanci, 2010). The data were fit assuming that

193 relaxation started following the applied pulse, i.e., not accounting for relaxation during pulse
194 (RDP); this approach was used because, for signals with short relaxation times (< the length of
195 the applied pulse), accounting for RDP can result in over- or under-estimation of the total water
196 content (Grombacher et al., 2017; Walbrecker et al., 2009). Four-layer blocky inversion models
197 were used for all data sets. Uncertainty is shown by displaying models that fit the data
198 approximately equally well as the best fit, i.e., have a similar chi-squared statistic; 6 to 12
199 equivalent models are shown for each profile. When possible, the SNMR data were inverted
200 using the resistivity structure determined from a collocated CSAMT measurement; when there
201 was no collocated CSAMT measurement at the SNMR location, the resistivity structure
202 determined from the nearest noise-free CSAMT measurement was used.

203

204 **4 Results**

205 Results from the SNMR and CSAMT measurements are shown for the down-valley
206 profile in Figure 3 and the two across-valley profiles in Figure 4. The inverted resistivity images
207 show a trend towards higher resistivity at the top of the valley. Near the coast the resistivity is
208 low, reaching a minimum of $\sim 1 \Omega\text{m}$. A number of inversions of the CSAMT data show vertical
209 profiles with significant contrasts in resistivity, some with thin low resistive layers, e.g.
210 CSAMT13. These profiles represent a best fit to the data but, as in all inverse models, alternative
211 models with near equivalent misfit exist. Using CSAMT13 as an example, the best fit model
212 (RMS misfit 9.7%) contains a $1\Omega\text{m}$ layer between 9.4m and 12.2m, however, using the
213 equivalence modeling option in IPI2win a minimum resistivity of $0.7\Omega\text{m}$ between 10.1 and
214 12.2m and a maximum resistivity of $5.1\Omega\text{m}$ between 4.4m and 21.4m are computed (with RMS
215 misfits of 10.6% and 11.7%, respectively). Despite such variation in near equivalent models the

216 data confirm the presence of a shallow low resistivity layer, which we attribute to the presence of
217 unfrozen saline pore water.

218 The depth of investigation for the SNMR measurements, shown as a red line in each
219 inverted SNMR plot in Figures 3 and 4, is much shallower than typically expected for
220 measurements collected with a 70 m square loop, < 50 m below the surface in some locations.
221 The shallow depth of investigation is likely due to the low resistivity of the sediment near the
222 coast, and the high magnetic field inclination (Berhoozmand et al., 2015; Hertrich, 2008). In
223 Figures 3 and 4, the uncertainty associated with the inversion is shown by displaying models (as
224 thin grey lines) that fit the data approximately as well as the model of best fit.

225 Substantial variation can be seen in the water content in the down-valley profile. Near the
226 coast, a clear signal from unfrozen water was observed in the SNMR data, with maximum
227 unfrozen water contents ranging from 2 to 10% in each sounding. In SNMR12, SNMR10,
228 SNMR11 and SNMR08, the peak water content is in a single layer in the top 20 m below the
229 surface. No unfrozen water content was detected in the SNMR measurements collected near the
230 upper Holocene marine limit at ~62 m a.s.l. (Lønne & Nemeč, 2004; SNMR06 and SNMR07 in
231 Figure 3). The base of the permafrost, which would be indicated by higher unfrozen water
232 content at depth, was not observed in any of the SNMR datasets, as the measurements did not
233 penetrate below 80 m in the lower valley bottom. The relaxation times associated with the
234 unfrozen water content in the down-valley profile were short and ranged from 8 to 50 ms.

235 Less variation is seen in the across-valley profiles. In the across-valley profile 1, located
236 closer to the coast, all profiles show a maximum unfrozen water content between 3.5 and 10%,
237 with the exception of SNMR02, which was located on the northern side of Adventdalen and
238 shows no unfrozen water content. The resistivity sounding (CSAMT04) at the northern side of

239 the profile also indicates a more resistive subsurface in comparison to the valley center. The
240 modeled resistivities at CSAMT04 are, however, less than 30 Ωm , which may be attributed to
241 silt/clay contributions. For the across-valley profile 2, which is located further up the valley, less
242 unfrozen water was detected and little variation is seen across the valley (between 1.5 and 6%).
243 Again, the base of the permafrost was not observed in any of the SNMR datasets. As with the
244 mean log relaxation times in the down-valley profile, the mean log relaxation times associated
245 with the unfrozen water content in the across-valley profiles were short and ranged from 8 to 47
246 ms for across-valley profile 1 and from 11 to 42 ms for across-valley profile 2.

247

248 **5 Discussion**

249 Based on the temperature profiles collected in the boreholes in Adventdalen (Figure 2), it
250 would be assumed that the pore water within the permafrost is frozen; however, the SNMR
251 results show that the permafrost near the coast contains unfrozen water. The SNMR profiles
252 suggest that the unfrozen water content is as high as 10%. The low resistivity values associated
253 with the unfrozen water content further suggests that the pore water is saline, depressing the
254 freezing point of the pore water. The SNMR results shown were collected sufficiently far from
255 the power lines and contain very little noise (SNMR 13 was collected near the power lines and
256 had high noise levels, but was not used in our interpretation), and we can thus be confident in our
257 findings. We note, however, that the exact shape of the unfrozen water content profiles (Figures
258 3 & 4) is affected by the inversion approach and thus some features, such as the thickness of the
259 layer of higher water content in SNMR03, cannot be determined exactly, as indicated by the
260 models showing uncertainty.

261 Furthermore, we note that SNMR inversions are strongly affected by the subsurface
262 resistivity structure. The threshold for when the subsurface resistivity affects the SNMR
263 inversion is a function of loop size; when the resistivity falls below this threshold, i.e., 70 Ωm for
264 this study, it will impact the SNMR inversion (Braun & Yaramanci, 2008). Thus, for the SNMR
265 data collected near the coast with low resistivity value, errors in the resistivity structure can
266 impact the resulting SNMR profile. If the true resistivity is lower than determined here, then the
267 SNMR profile would have a shallower depth of investigation and a larger maximum water
268 content. Similarly, if the true resistivity is higher than determined here, then the SNMR profile
269 would have deeper depth of investigation and a smaller maximum water content. Examples
270 demonstrating the potential effect of errors in the resistivity structure are shown in Figure S1 for
271 SNMR profiles SNMR03 and SNMR12.

272 Additionally, the unfrozen water content profiles provide a generalized overview of the
273 subsurface that does not capture the complexity associated with small-scale periglacial
274 subsurface landforms such as ice layers (Gilbert, 2018) and ice-wedges. However, the results
275 shown here do provide a conceptual overview of the patterns and distribution of the unfrozen
276 water content in Adventdalen, at the scale of a coastal valley in a typical Arctic setting.

277 The relatively shallow depth of investigation observed in the SNMR measurements (< 50
278 m below the surface in some locations), will limit future use of SNMR to image the permafrost
279 base in Adventdalen. In a typical survey the pulse length (to a maximum of 40 ms, the pulse
280 length used in this study) and loop size can be enlarged to increase the depth of investigations.
281 We thus recommend that in future applications of SNMR in Adventdalen, the loop size be
282 increased.

283 The resistivity values measured near the coast were very low (with a minimum of ~1
284 Ωm). Although electrical measurements from permafrost environments can show very high
285 resistivity (e.g., Minsley et al., 2012), the values measured in our study are consistent with direct
286 current electrical resistivity measurements collected from a saline permafrost environment in
287 Barrow, Alaska, USA (Overduin et al., 2012) and previously in Adventdalen by Harada and
288 Yoshikawa (1998), who observed a resistivity of $7.5\Omega\text{m}$ at a depth of 30 m, and Ross et al
289 (2007), who observed resistivities from ~10 to $400\Omega\text{m}$ associated with two pingos (Hytté and
290 Longyear Pingos). More recently, based on electrical resistivity imaging, Kasprzak et al. (2017)
291 postulated the existence of unfrozen saline pore water near coastal zones in southern Svalbard.
292 From our SNMR measurements we are able to confirm that such low resistivity values can
293 indeed be attributed to the existence of unfrozen saline pore fluid.

294 The results from the SNMR and CSAMT data, showing unfrozen water content
295 associated with low resistivity in substantial quantity and significant depths, are consistent with
296 the sedimentological and cryospheric paleoenvironmental interpretations of the formation and
297 evolution of permafrost in Adventdalen (Gilbert, 2018). Comparing the unfrozen water content
298 detected by SNMR to laboratory measurements of the ice content in the 60 m CO_2 core from
299 Adventdalen (location shown in Figure 1), which is in the range of 20 to 40% (Gilbert, 2014), we
300 conclude that the permafrost in the lower Adventdalen is partially unfrozen. This assessment is
301 consistent with the epigenetic origin of the permafrost, which developed after delta progradation
302 down-valley filled Adventdalen with sediments following deglaciation since the early Holocene
303 (Gilbert, 2018). Permafrost formation commenced and extended down-fjord through
304 Adventdalen, when the fluvio-deltaic fjord-fill was subaerially exposed, and only the top
305 syngenetic part of the permafrost below contained excess ice in a suite of cryofacies indicating

306 ground-ice segregation and segregation intrusion (Gilbert, 2018). The lack of excess ice further
307 down valley indicates that the source of moisture was limited to the saline pore water of the
308 sedimentary deposits with no significant replenishment (Gilbert, 2018).

309 These results will also help predict permafrost degradation under the influence of
310 ongoing climate warming in polar regions (Hansen et al., 2014; Isaksen et al., 2007). This is
311 particularly important since unfrozen sediments can delay deep freezing, impact the sediment
312 structure, permit groundwater upwelling to surface water bodies and/or may affect microbial
313 activity thereby impacting greenhouse gas emissions (Grosse et al., 2011; Shur et al., 2005).

314

315 **6 Conclusions**

316 This study is the first to successfully map unfrozen water content in a coastal permafrost
317 environment in the Arctic using SNMR and CSAMT. The SNMR measurements identified
318 substantial unfrozen water content (up to ~10%) in the lower valley, near the coast in
319 Adventdalen, Svalbard; the unfrozen water content decreased with distance from the coast as the
320 age of the permafrost increased. No unfrozen water was detected above the upper marine limit.
321 The CSAMT measurements supported the SNMR results. Low resistivities were observed in the
322 lower valley; above the marine limit in the upper part of the valley, the resistivity was higher
323 ($>1000 \Omega\text{m}$ in some locations).

324 The results of this study clearly demonstrate the utility of combining SNMR and CSAMT
325 measurements to map the unfrozen water content in continuous permafrost. Combining the
326 results presented here with thermal and geochemical data, including the pore water salinity, as
327 well as the overall sedimentological and cryostratigraphical model for Adventdalen will allow
328 development of a full assessment of the ice-content and thermal state of permafrost in

329 Adventdalen, Svalbard. Such a model is necessary to understand groundwater flow and its
330 impact on periglacial features, such as pingos, and will allow us to quantify the potential release
331 of greenhouse gasses.

332

333

334

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342 (<https://doi.org/10.17635/lancaster/researchdata/212>). Permafrost thermal data from
343 Adventdalen is available online through the NORPERM database at the Geological Survey of
344 Norway (http://geo.ngu.no/kart/permafrost_svalbard/?lang=English).

345

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478 **Figure Captions**

479 **Figure 1:** Terrain model of the Adventdalen valley showing the locations of the CSAMT and
480 SNMR measurements. The road is shown as a light brown line. The model is from the
481 Norwegian Polar Institute; <http://toposvalbard.npolar.no> (Norsk Polarinstitut, 2017). The inset is
482 from Google Earth.

483

484 **Figure 2:** Annual ground thermal conditions in the permafrost in the Adventdalen valley. Data
485 are from the valley bottom borehole AS-B2 for the hydrological year 1 September 2012 to 31
486 August 2013. The black lines show the maximum and minimum average daily temperature
487 during this year; the red lines show the maximum and minimum average daily temperature
488 during the study period 23 March to 2 April 2013; the horizontal line denotes the interpolated
489 depth of the active layer (NORPERM, 2016).

490

491 **Figure 3:** Inverted SNMR and CSAMT depth profiles of unfrozen water content and resistivity
492 for the down-valley profile (locations as shown in Figure 1) for data collected in Adventdalen,
493 Svalbard. Horizontal red lines indicate the approximate depth of investigation of the SNMR
494 measurements. Labels above the profiles indicate which CSAMT measurement was used in the
495 inversion of the SNMR data, but only collocated or independent CSAMT measurements are
496 shown. The thin grey lines on the SNMR profiles indicate the uncertainty in the inversion and
497 are models that fit the data approximately as well as the model of best fit (thick blue line). The
498 spacing between the measurements made in the upper-valley indicates that these measurements
499 were made further apart (not to scale).

500 **Figure 4:** Inverted SNMR and CSAMT depth profiles of unfrozen water content and resistivity
501 for the across-valley profiles (locations as shown in Figure 1) collected in Adventdalen,

502 Svalbard. Horizontal red lines indicate the approximate depth of investigation of the SNMR
503 measurements. Labels above the profiles indicate which CSAMT measurement was used in the
504 inversion of the SNMR data, but only collocated CSAMT measurements are shown. The thin
505 grey lines on the SNMR profiles indicate the uncertainty in the inversion and are models that fit
506 the data approximately as well as the model of best fit (thick blue line).

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