

Authors' response

“Geophysical mapping of palsa peatland permafrost” by Y. Sjöberg et al.

Reply to comments by Anonymous Referee #1

General comments:

This manuscript presents a joint application of GPR and ERT to map active layer depth and permafrost base at a palsa peatland at Tavvavouma, N-Sweden. The estimated depths are finally used for a simple calculation of permafrost thaw based on the Stefan equation. The study shows nicely the value of a combination of different geophysical measurement techniques to understand permafrost conditions in heterogeneous environments and the paper fits well into the scope of The Cryosphere.

Overall, I think the study is well suited for publication. However, I have a number of items which should be worked out to improve the clarity of the paper, some of them requiring major revisions. I would like to encourage the authors to do these revisions, and then I am looking forward to seeing this study published in TC.

We are grateful for the thorough review by Anonymous Referee #1 on our manuscript and the suggestions for how to improve it. Below are our responses (in italics) to the comments. A pdf version of the manuscript with tracked changes is also provided at the end of this document.

Major comments:

1. CMP velocity estimates (P 5144, L 23-29):

It is very reasonable to provide minimum and maximum values for the velocities of the various substrates, however, the description of the procedure to estimate representative, min and max values requires clarification: Add a figure showing the CMP measurements and discuss difficulties and “unrealistic velocities” in the interpretation of the results which needed to be compensated by literature measurements (Table 1).

Especially the sentence on P5144, L27-29 requires clarification.

The materials and velocities defined in Figure 2 and Table 1 need explanation: The chosen names for the materials are somewhat unfortunate (according to Fig 2, talik peat and talik mineral also belong to the active layer). The definitions/names could be more self-explaining by providing information about substrate, water content and freezing conditions (see text on P 5145) since these are the main factors determining the dielectric permittivity of the ground, e.g. one could use (i) dry peat on palsa and peat plateau surfaces, unfrozen (ii) (saturated (?)) peat in fens and under surface depressions, unfrozen (iii) (saturated (?)) talik mineral soils, unfrozen, (iv) frozen ground. The distribution of the different landforms which are related to distinct velocities should also be indicated along the x-axes of Figures 3 and 5 for better understanding.

Methods for velocity determination (Table 1): As far as I understand Table 1, velocity estimates were not only compiled from CMP measurements and literature information but also by relating GPR-measured travel times to active layer thicknesses measured with the steel rod or information from a soil core. Please expand Section 3.1 with related information. Also add information why exactly these values for representative, min and max were chosen

Section 3.1 (concerning the GPR velocity estimates) has been rewritten and expanded for clarification:

“Ground penetrating radar (GPR) can be used to map near surface geology and stratigraphy because of differences in dielectric properties between different subsurface layers or structures. An electromagnetic pulse is transmitted through the ground and the return time of the reflected pulse is

1 recorded. The resolution and penetration depth of the radar signal depends on the characteristics of
2 the transmitted pulse and the choice of antennas, which usually range between 10 to 1000 MHz.
3 Higher frequencies will yield a higher resolution but a smaller penetration depth, however, the
4 penetration depth will also depend on dielectric and conductive properties of the ground material.
5 Mapping of permafrost using GPR becomes possible due to the difference in permittivity between
6 unfrozen and frozen water.

7 In this study, measurements were made with a Malå GeoScience Proex GPR system using 200 MHz
8 unshielded antennas along T1 and T2. The transmitting and receiving antennas were held at a
9 constant distance of 0.6 m (common offset) and the sampling time window was set to 621 ns, with
10 recorded traces stacked 16 times. Measurements were made at every 10 cm along the length of these
11 two transects. Along T3 measurements were made using 100 MHz unshielded antennas with a 1 m
12 antenna separation and measurements made every 0.2 s while moving the antennas along the transect.
13 The sampling time window for T3 was 797 ns and traces were stacked 16 times. The GPR data were
14 processed for a time-zero correction, and with a dewow filter, a vertical gain, and a dynamic depth
15 correction for antenna geometry using the software ReflexW (version 6.1, Sandmeier, 2012,
16 www.sandmeier-geo.de).

17 The depths to the permafrost table and the interface between peat-mineral substrates were calculated
18 by converting the two-way travel time to known substrate transitions using estimated velocities for the
19 speed through three different substrate materials: dry peat, saturated peat, and saturated mineral
20 substrate (see Fig. 2 for conceptual sketch of these substrate layers and velocity profiles). To account
21 for uncertainty due to small scale heterogeneity of these ground materials, in addition to the optimal
22 velocity identified, the maximum and minimum likely velocities for each substrate were considered in
23 the GPR depth conversions. The velocity in dry peat (found in the active layer of palsas, hummocks,
24 and peat plateaus) was calibrated using the active layer thickness measurements made with a steel
25 rod. The minimum and maximum velocities were obtained by subtracting and adding one standard
26 deviation of these measured depths. For velocities in saturated peat, which was found in taliks such
27 as fens, the depths of saturated peat identified by coring with a 2 m steel pipe (see Figure 1 for
28 locations) were used. The velocity in pure water was used as the minimum velocity and the
29 representative velocity for dry peat was used as the maximum velocity for saturated peat. To obtain
30 velocities for unfrozen saturated mineral substrate, a common midpoint (CMP) GPR profile was
31 measured on a drained lake surface (point 6 in Figure 1) by moving the GPR antennas apart from
32 each other in 10 cm increments along the 15 m long transects (see Appendix A for a detailed
33 description). The CMP approach, thus, allows for imaging the same point in space with different
34 antenna offsets making it possible to back out material velocity estimates. CMP profiles were
35 analysed using semblance analysis (Neidell and Taner, 1971) in ReflexW software (version 6.1,
36 Sandmeier, 2012, www.sandmeier-geo.de). Due to inherent difficulties with CMP approaches
37 associated with heterogeneous ground substrate properties (Appendix A), the velocity estimates from
38 this analysis were complemented with literature values for the representative and minimum velocities.

39 The end product here is a range of plausible substrate velocities accounting for potential uncertainties
40 such that any resultant interpretation about subsurface conditions and interface locations can be
41 considered robust. These are expressed as what can be considered a 'representative' velocity bounded
42 by a maximum and a minimum velocity (Table 1)."

43
44 Considering the above rewrite and since a velocity for only one material (maximum velocity
45 in saturated mineral substrate) was obtained from the CMP analyses, we have chosen to not
46 expand on the description of the CMP analysis in section 3.1 as per the referee comment.
47 Instead, an appendix (Appendix A) has been added, which describes the CMP analysis in
48 more detail and also contains a figure including the CMP radargram and a semblance plot.
49 This way, we believe that the CMP methods can be described thoroughly for the interested
50 reader without expanding too much on the methods section for this detail. In addition, the
51 names for the subsurface materials have also been changed as suggested. Also, as the
52 winter data has been removed (see later comment reply below), velocities in frozen ground
53 are no longer used and have therefore also been removed from Table 1 and Figure 2.

1 *Finally, simple line graphs have been added to Figure 3 and 4, showing the surface*
2 *topography and landforms along the transects. In Figure 5 the extents of the taliks (as*
3 *interpreted from GPR data) have been marked and an explanation for which velocities were*
4 *used for depth conversions in and outside of taliks has been added to the caption.*
5

6
7 2. Resistivities for permafrost identification (P 5146, L 22 – P 5147, L10):

8 This section is somewhat confusing. I expect, the authors define a lower (1000 Ohm.m) and
9 an upper (1700 Ohm.m) for the transition from unfrozen to frozen conditions while all
10 resistivities > 1700 Ohm.m indicate permafrost. However, the paragraph reads as if there is a
11 range in resistivities (i.e. 1000-1700 Ohm.m) for identification of permafrost and all values
12 above are no permafrost again. Please clarify.

13
14 *We have reworded this paragraph for clarity. Simply, all resistivity values < 1000 Ω m were*
15 *interpreted as unfrozen ground and the values between 1000 and 1700 Ω m represent a*
16 *range of uncertainty for the location of the interface between frozen and unfrozen sediments.*
17

18 3. Calculation of thaw rates:

19 The authors carry out a very simple calculation of permafrost thaw for the investigated site,
20 which of course, is afflicted with considerably uncertainty. The study would strongly benefit if
21 the authors would provide an estimate for this uncertainty as they do nicely for the GPR and
22 ERT measurements.

23
24 *We have added a range of likely thermal conductivity values (minimum and maximum of 2*
25 *and 3 W/m/K, respectively, for this material) to account for some of the uncertainty in this*
26 *estimate. This leads to a range of thaw rates from 6 to 8.5 cm/year*
27

28 4. Figures 3-5:

29 P 5166 - 5168, Fig 3 - Fig 5: For ease of interpretation: Please add information about the
30 different landforms along the x-axes (e.g. on top) of these two figures. Also indicate positions
31 of sediment cores. If possible, it would also be helpful to have the topography included in the
32 radargrams and ERT sections.

33
34 *Simple line graphs have been added to Figure 3 and 4, showing the surface topography and*
35 *landforms along the transects. Since not all sediment cores were taken along the transects*
36 *presented in this paper, they cannot all be included in these figures. We have added the*
37 *sediment cores that were taken along these transects to the figures. In Figure 5 the extents*
38 *of the taliks (as interpreted from GPR data) have been marked and an explanation for which*
39 *velocities were used for depth conversions in and outside of taliks has been added to the*
40 *caption.*
41

42 Specific comments:

43 P 5138, L 19-20: I don't understand this sentence. What are areas "climatically marginal to
44 permafrost" and why do the peatlands occur there "due to the thermal properties of peat"?
45 Please clarify and provide a reference for this type of distribution.

46
47 *We have rephrased this sentence: "They often occur in sporadic permafrost areas, protected by*
48 *the peat cover, which insulates the ground from heat during the summer (Woo, 2012)."*
49

50 P 5138, L 22: Please clarify: ": : and therefore permafrost is sensitive: : "; and "In addition,
51 permafrost distribution and thawing: : :"
52

53 *Reworded to: "In the sporadic permafrost zone the permafrost ground temperature is often close to*
54 *0°C, and therefore even small increases in temperature can result in thawing of permafrost."*
55

1 P 5138, L26: better: "Due to these interactions, peatlands are often: : :"

2
3 *This has been changed as suggested.*

4
5 P 5139, L 12: What is meant by "condition"? Thermal state? Please clarify.

6
7 *This part of the sentence has been removed.*

8
9 P 5139, L 20: Suggestion: replace "modeling" by "models"

10
11 *Done.*

12
13 P 5142, L 19-20: What exactly should be observed during wintertime conditions?
14 Please add explanation/examples. Or: since the wintertime measurements have not been
15 evaluated, I'm wondering if it is necessary to mention them at all.

16
17 *Our original idea was to use wintertime GPR measurements to try to identify the base of the*
18 *permafrost, since the penetration depth of the GPR should theoretically be greater in frozen*
19 *compared to wet conditions. However, the winter images were extremely difficult to interpret,*
20 *likely due to large variability in ice content, leading to scattering of the radar signal. We agree*
21 *that the manuscript is improved by excluding the GPR winter data, which does not add any*
22 *relevant information on permafrost distributions. As such, we have removed these data and*
23 *their analysis in this revision.*

24
25 P 5142, L 24 – P 5143, L 7: Please add information at which lengths [from : : : m to
26 : : : m] along the profile the different landforms (thermokarst depressions, fen, stream, palsa)
27 were located.

28
29 *Done.*

30
31 P 5144, L 1-7: Please provide information about types of antenna used (manufacturer,
32 shielded/unshielded, : : :). Also add information about measurement setup (length of traces in
33 ns, stacks, : : :).

34
35 *This information has been added.*

36
37 P 5144, L 7: What was this correction aimed for? Please explain.

38
39 *The receiving antenna is located at a set distance (0.6 or 1.0 m) from the transmitting*
40 *antenna the reflected radar signal has travelled at an angle through the ground and the two-*
41 *way travel time does not represent the straight vertical distance to the reflector. This dynamic*
42 *correction was to adjust travel times for this geometrical error. The sentence has been*
43 *slightly reworded.*

44
45 P 5144, L 15-16: How do these CMP measurements contribute to the velocities listed in
46 Figure 2 and Table 1? Please clarify using same nomenclature for profiles. See also major
47 comment about CMP velocities.

48
49 *See reply to major comment on CMP velocities.*

50
51 P 5145, L 5-9: Select another name for "active layer velocities". The talik peat and talik
52 mineral velocities are active layer velocities as well. If the talik velocities are all assumed to
53 be saturated or wet, this should be stated in the text.

54
55 *The velocities have been renamed.*

1
2 P 5145, L 23: replace “pore size” by “porosity”
3

4 *Done.*
5

6 P 5145, L 23 – 25: Here also the ice content should be added since the transition from water
7 to ice is most responsible for the increase in resistivity.
8

9 *Done.*
10

11 P 5146, L1-2: Add information about instrument used for ERT measurements and
12 measurement settings.
13

14 *Done*
15

16 P 5146, L 5, L 9: suggestion: use “inversion” or “inverse modelling”
17

18 *Done.*
19

20 P 5146, L 9: add reference for Res2dinv
21

22 *Done.*
23

24 P 5148, L 11: better: “sandy soil” or “sand”
25

26 *Done.*
27

28 P 5149, L 8-12: I suggest to either add some winter radargrams and related interpretation to
29 the paper or remove this paragraph completely.
30

31 *Winter data has been removed.*
32

33 P 5149, L 14: suggestion: replace “results from the ERT data modelling” by “inverted
34 resistivity sections”
35

36 *Done.*
37

38 P 5150, L 18-19: In the range of the ERT uncertainty, the taliks are almost at the same
39 depth.
40

41 *This sentence has been slightly reworded to clarify this.*
42

43 P 5164, Tab. 2: Where does 17.3 m as maximum value for the permafrost base result from?
44 The 1000 Ohm.m for the permafrost base is not reliable as the DOI value is >
45 0.1 at this depth of the profile. In addition, this value does not correspond to the 25 m
46 maximum depth provided on P 5150, L 8.
47

48 *The 17.3 m depth is the maximum depth of the permafrost base (at 1700 Ohmm) along T2,*
49 *where DOI<0.1 (found at ca 250 m along x-axis in fig 4 and 5). The 25 m maximum depth*
50 *(mentioned in the original text at P 5150, L8) is the deepest point along all transects where*
51 *there is permafrost and DOI<0.1, however, the base of the permafrost has not been reached*
52 *via probing at this depth and location.*
53

P 5166, Fig. 3: I know it is difficult because of the different velocities for unsaturated, saturated and frozen conditions but it would be nice to have a depth axis added to Fig 4 especially for better comparison with Fig 5.

The idea of this figure is to show the GPR data without interpretations and therefore depth transformations have not been done. It is possible to make these transformations to the images using the velocities corresponding to interpreted ground material distributions, but those images are in our opinion more difficult to read and interpret. We have added a line graph showing the topography above each of the GPR images. Interpreted depths from the GPR data are instead provided as lines in Figure 5.

P 5167, caption Fig 4: please correct: DOI < 0.1

Done.

P 5168, Fig. 5: I expect that in the ERT permafrost boundary the uncertainty for the transition from unfrozen to frozen conditions is indicated. I suggest to rename this coding to “ERT permafrost table uncertainty”. Also indicate in the figure caption that the lower permafrost boundary cannot clearly be identified as shown by the high DOI values displayed in Fig 4. Probably it is also reasonable to add the depth of the DOI =0.1 line to Fig. 5 as lower limit of permafrost identifiability.

The “ERT boundary” has been renamed to “ERT boundary uncertainty” and the caption changed as suggested by the reviewer. As the DOI=0.1 line crosses the lines showing GPR data interpretations at many places, adding this line makes the figure less clear, especially for the shallow (< ca 1 m) soil depths. We have added a sentence to the caption to highlight that the data for DOI>0.1 is not shown and that all permafrost boundaries can therefore not be identified and believe that will help make the figure more clear.

Technical corrections:

P 5138, L 3: offer “a” possibility

P 5138, L 5: remove “surface”

P 5138, L 14: remove “out”

P 5138, L 16: pan-Arctic

P 5139, L 12: to date

P 5139, L 21: important “for” regions

P 5139, L 23: Giesler

P 5140, L 18: remove “surface”

P 5140, L 21: complementary

P 5142, L 16: slightly

P 5144, L 4: measurements

P 5144, L 8: depths

P 5144, L 14: offsets

P 5145, L 21: suggestion: write “lateral and vertical direction”

P 5146, L 7: replace “that” by “where”

P 5147, L 20: delete “the”

P 5147, L 20: delete one “v”: Tavvavuoma

P 5148, L 19: delete “out”

P 5149, L 1: transects

P 5149, L 1: correct: “At” the beginning : : :

P 5149, L 21: suggestion: replace “counter to this” by “in contrast”

P 5151, L 5: delete “out”

P 5152, L 19: delete “out”

P 5154, L 15: pan-Arctic

P 5164, Tab. 2: align “Representative” (*this has to be done by the typesetters!*)

- 1 P 5164, Fig. 1: add degrees to longitude axis
- 2
- 3 *All technical comments have been corrected for in the revised manuscript.*

Reply to comments by Anonymous Referee #2

This is a manuscript describing measurement of permafrost and talik using ground penetrating radar and electrical resistivity tomography geophysics. The methods applied here are well-tested and largely appear to have been deployed in an acceptable manner.

I think the manuscript is a bit light on substantial results and interpretations, but it is nice to see new applications of geophysics to image permafrost. This manuscript is clearly within the scope of The Cryosphere and should be suitable for publication after moderate revisions.

We are grateful for the constrictive comments by Anonymous Referee #2 on our manuscript. Below are our replies (in italics) to the reviewer's comments. A pdf version of the manuscript with tracked changes is also provided at the end of this document.

Page 4, Line 20: I am not convinced that vulnerability was thoroughly estimated in this study. Based on the results presented, on case of warming was tested in a back-of-the envelope model using one example permafrost thickness based on one measurement from an ERT line. This resulted in an estimate of 175 years to thaw under the warmer climate scenario (along with hand-waving order of magnitude uncertainty), but I do not believe this is comprehensive enough to be considered a vulnerability estimate.

This sentence has been rephrased to avoid confusion with estimations of vulnerability.

Page 8, Lines 11-20: I have some concerns with this application of CMP geometry for estimating velocity. Since CMP data is not displayed in a figure it is difficult to assess the quality of the dataset and effectiveness of this application. My first concern is that relatively low frequency 100 MHz and 200MHz antennas were used in a case where the reflector may have been as little as 50cm from the surface (in the case of the active layer). This could have resulted in waveguide behavior or refractions that would have made traditional CMP analysis unreliable. I suggest that a CMP dataset and associated semblance plot is provided by the authors.

Section 3.1 (concerning the GPR velocity estimates) has been rewritten for clarification (see response to referee #1). As a velocity for only one material (maximum velocity in saturated mineral substrate) was obtained from the CMP analyses we have chosen to not expand on the description of the CMP analysis in section 3.1. Instead, an appendix (Appendix A) has been added describing the CMP analysis in more detail and containing a figure including the CMP radargram and a semblance plot. To clarify, the CMP analysis was not used to obtain signal velocities in the upper soil layers, such as the active layer. The shallowest reflector used was found at circa 1.75 m depth.

Page 12, Line 17: “: : :thought experiment: : :” This seems to be a ‘back of the envelope’ calculation, not a thought experiment. I suggest reconsidering use of the term “thought experiment” throughout the manuscript.

We have changed the wording throughout the manuscript as suggested.

Page 13, Line 8: The lack of reflections is surprising (particularly from taliks that should have had clear contrasts in physical properties throughout the winter). I suggest that either winter data is included or all mention of the winter data is removed from the manuscript.

Winter data have been removed from the manuscript. The lack of clear deeper reflections in the winter images was most likely due to high scattering of the radar signal in the frozen active layer which could have had high variability in ice content (for example due to ice lens formation).

Page 15, Line 6: How is the 15.3 m average thickness calculated? Based on previous remarks in the manuscript, the ERT imaged 15.8 m to more than 25 m.

The average depth at which the permafrost base was found (with DOI<0.1) was 15.8 m and the average thickness of the active layer was ca 0.5 m, which yields an average permafrost thickness of 15.3 m for the locations where both the permafrost table and base could be observed. Of course, along most of the transects the uncertainty was too great (i.e., DOI>0.1) and the permafrost base was too deep to be identified by our methods, at most >25 m. Only the locations where the permafrost base could be identified were used to calculate the average thickness of permafrost.

Page 15, Line 22-25: The estimated ice fraction calculation should be presented earlier in the manuscript and in more detail to help the reader understand what goes into the calculation and what it means.

We have added the equation for how excess ice fractions (EIFs) were calculated to this section ($EIF = \text{palsa height} / \text{permafrost thickness}$). The aim of this study was not to estimate EIFs and our data for most parts of the transects are not well suited for this as it was collected for other purposes. Therefore we do not feel it relevant to expand this part of the manuscript beyond a simple comparison in the discussion section. We do however think that it is an interesting comparison to make in the discussion on ground ice and permafrost distributions in these types of landscapes, as it provides some insight to how this site compares to similar sites in (for example) Canada. Our belief is that with the clarification of this simple equation for EIFs and the (previously) presented data from our site the reader should be able to get a better understanding of the permafrost and possible ground ice distributions in Tavvavuoma without needing further clarifications in the other sections of the manuscripts, as this would fragment the focus of the paper. We have rephrased this paragraph for clarity.

Page 16, Line 10-12: Another reason for this could be that the authors did not calculate the uncertainty in this estimate. I suggest a sensitivity analysis and uncertainty quantification to help place these thaw advance estimates better into context.

We have added a range of likely thermal conductivity values to account for some of the uncertainty in this estimate.

Page 18, Line 10: "...provide orthogonal views..." Perhaps I just don't understand what the authors intend the word "orthogonal" to mean in this case, however looking at Figure 1, no geometrically orthogonal lines we measured so I don't know what this is referring to. I suggest rewording for clarity.

We have reworded this sentence.

Figure 3: Depth axes should be carefully calculated and displayed on this figure.

The idea of this figure is to, as clearly as possible, show the GPR data and its visible reflections before further interpretations. By converting the time axis to depth, using the varying velocities for the different ground materials, these images get distorted so that some of the reflections are more difficult to see (see response to previous referee). As such, rather than add depth axes to these figures we have complemented these figures with line plots of the surface topography to provide a better context of the images for the reader. Depth converted GPR data interpretations are instead provided in figure 5.

Figure 5: Where does the GPR uncertainty estimate come from? Just the potential variability in velocity?

1
2 *The uncertainty estimates come from the different estimated velocities (minimum,*
3 *representative, and maximum) of the radar signal through the different ground materials (see*
4 *for example Table 1 and section 3.1). The caption has been reworded to clarify this.*
5

Geophysical mapping of palsa peatland permafrost

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Abstract

Permafrost peatlands are hydrological and biogeochemical hotspots in the discontinuous permafrost zone. Non-intrusive geophysical methods offer a possibility to map current permafrost spatial distributions in these environments. In this study, we estimate the depths to the permafrost table ~~surface~~ and base across a peatland in northern Sweden, using ground penetrating radar and electrical resistivity tomography. Seasonal thaw frost tables (at ~0.5 m depth), taliks (2.1 – 6.7 m deep), and the permafrost base (at ~16 m depth) could be detected. Higher occurrences of taliks were discovered at locations with a lower relative height of permafrost landforms indicative of lower ground ice content at these locations. These results highlight the added value of combining geophysical techniques for assessing spatial distributions of permafrost within the rapidly changing sporadic permafrost zone. For example, based on a ~~simple thought experiment~~back-of-the-envelope calculation for the site considered here, we estimated that the thickest permafrost could thaw ~~out~~ completely within the next two centuries. There is a clear need, thus, to benchmark current permafrost distributions and characteristics particularly in under studied regions of the pan-~~A~~arctic.

1 Introduction

Permafrost peatlands are widespread across the Arctic and cover approximately 12 % of the arctic permafrost zone (Hugelius et al. 2013, Hugelius et al. 2014). They often occur in ~~areas~~ climatically marginal to sporadic permafrost areas, protected due to the ~~thermal properties~~ of peat cover, which insulates the ground from heat during the summer (Woo, 2012). In the

1 sporadic permafrost zone the permafrost ground temperature ~~in these peatlands~~ is often close
2 to 0°C, and therefore ~~sensitive to even small fluctuations increases in climate temperature can~~
3 ~~result in thawing of permafrost.~~ In addition, ~~p~~Permafrost distribution and thawing in these
4 landscapes is influenced by several factors other than climate, including hydrological,
5 geological, morphological and erosional processes, that often combine in complex
6 interactions (e.g., McKenzie and Voss, 2013; Painter et al., 2013; Zuidhoff, 2002). Due to
7 ~~complex these~~ interactions, ~~between these factors these~~ peatlands are often dynamic with
8 regards to their permafrost thermal structures and extent as the distribution of permafrost
9 landforms (such as dome shaped palsas and flat-topped peat plateaus) and talik landforms
10 (such as hollows, fens and lakes) vary with climatic and local conditions (e.g., Sannel and
11 Kuhry, 2011; Seppälä 2011; Wramner, 1968). This dynamic nature and variable spatial extent
12 has potential implications across the pan-Arctic as these permafrost peatlands store large
13 amounts of soil organic carbon (Hugelius et al., 2014; Tarnocai et al., 2009). The combination
14 of large carbon storage and high potential for thawing make permafrost peatlands
15 biogeochemical hotspots in the warming Arctic. In light of this, predictions of future changes
16 in these environments require knowledge of current permafrost distributions and
17 characteristics, which is sparse in today's scientific literature.

18 While most observations of permafrost ~~and its condition across the landscape to~~ date consist
19 of temperature measurements from boreholes, advances in geophysical methods provide a
20 good complement for mapping ~~the~~ permafrost distributions in space. Such techniques can
21 provide information about permafrost thickness and the extents and distribution of taliks,
22 which can usually not be obtained from borehole data alone. As the spatial distribution and
23 extent of permafrost directly influences the flow of water through the terrestrial landscape
24 (Sjöberg et al., 2013), adding knowledge about the extent and coverage of permafrost could
25 substantially benefit development of coupled hydrological and carbon transport modeling in
26 northern latitudes (e.g., Jantze et al., 2013; Lyon et al., 2010). This may be particularly
27 important ~~forte~~ regions where palsa peatlands make up a large portion of the landscape
28 mosaic and regional-scale differences exist in carbon fluxes (Geiesler et al., 2014).

29 Geophysical methods offer non-intrusive techniques for measuring physical properties of
30 geological materials; however, useful interpretation of geophysical data requires other types
31 of complementary data, such as sediment cores. Ground Penetrating Radar (GPR) has been

used extensively in permafrost studies for identifying the boundaries of permafrost (e.g., Arcone et al., 1998; Doolittle et al., 1992; Hinkel et al., 2001; Moorman et al., 2003), characterizing ground ice structures (De Pascale et al., 2008; Hinkel et al., 2001; Moorman et al., 2003), and estimating seasonal thaw depth and moisture content of the active layer (Gacitua et al., 2012; Westermann et al., 2010). Electrical Resistivity Tomography (ERT) has also been widely applied in permafrost studies (Hauck et al., 2003; Ishikawa et al., 2001; Kneisel et al., 2000), the majority of which focus on mountain permafrost. By combining two or more geophysical methods complementary information can often be acquired raising the confidence in interpretations of permafrost characteristics (De Pascale et al., 2008; Hauck et al., 2004; Schwamborn et al., 2002). For example, De Pascale et al. (2008) used GPR and capacitive-coupled resistivity (CCR) to map ground ice in continuous permafrost and demonstrated the added value of combining radar and electrical resistivity measurements for the quality of interpretation of the data. While some non-intrusive geophysical investigations have been done in palsa peatland regions (Dobinski, 2010; Doolittle et al., 1992; Kneisel et al., 2007; Kneisel et al., 2014; Lewkowicz et al., 2011), the use of multiple geophysical techniques to characterize the extent of permafrost in palsa peatland environments has not been employed.

In this study we use GPR and ERT in concert to map the distribution of permafrost along three transects (160 to 320 m long) in the Tavvavuoma palsa peatland in northern Sweden. Our aim is to understand how depths of the permafrost table–~~surface~~ and base vary in the landscape and, based on resulting estimates of permafrost thickness, to make a first order assessment of the ~~vulnerability-potential~~ thaw rate of this permafrost due to climate warming. Further we hope to demonstrate the added value of employing complementary geophysical techniques in such landscapes. This novel investigation thus helps contribute to our understanding of the current permafrost distribution and characteristics across palsa peatlands creating a baseline for future studies of possible coupled changes in hydrology and permafrost distribution in such areas.

2 Study area

Tavvavuoma is a large palsa peatland complex in northern Sweden at 68°28'N, 20°54'E, 550 masl (Fig. 1) and is a patchwork of palsas, peat plateaus, thermokarst lakes, hummocks and

fens. Ground temperatures and weather parameters have been monitored at the site since 2005 (Christiansen et al. 2010). Sannel and Kuhry (2011) have ~~analyzed~~analysed lake changes in the area and detailed local studies of palsa morphology have been conducted by Wramner (1968, 1973).

Tavvavuoma is located on a flat valley bottom, in piedmont terrain with relative elevations of surrounding mountains about 50 m to 150 m above the valley bottom. Unconsolidated sediments, observed from two borehole cores (points 1 and 2 in Fig. 1), are of mainly glaciofluvial and lacustrine origin and composed of mostly sands, loams and coarser grained rounded gravel and pebbles (Ivanova et al., 2011). The mean annual air temperature is -3.5°C (Sannel and Kuhry 2011), and the average winter snow cover in Karesuando, a meteorological station approximately 60 km east of Tavvavuoma, is approximately 50 cm although wind drift generally gives a thinner snow cover in Tavvavuoma (Swedish Meteorological and Hydrological Institute, www.smhi.se/klimatdata/meteorologi).

Permafrost occurs primarily under palsas and peat plateaus in Tavvavuoma, where the average thickness of the active layer is typically 0.5 m (Christiansen et al., 2010; Sannel and Kuhry, 2011). The mean annual temperature in permafrost boreholes (at 2 and 6.1 m depth) in the peatlands of Tavvavuoma range from -0.3°C to -0.4°C (Christiansen et al., 2010). However, no observations of the depth to the permafrost base have been presented for the area. Warming of the air temperature of about 2°C has been observed in direct measurements from the region over the past 200 years (Klingbjer and Moberg, 2003). In light of this warming, winter precipitation (mainly snow) in northern Sweden shows increasing trends over the past 150 years (Alexandersson, 2002). Further, permafrost is degrading across the region and northern Sweden (Sjöberg et al., 2013). For example, peatland active layer thickness in Abisko (located about 60 km south-west of Tavvavuoma) is increasing according to direct observation over the past 30 years (Åkerman and Johansson, 2008) and inference from hydrologic shifts over the past century (Lyon et al., 2009). This regional permafrost degradation has led to changes in palsas as well. Regionally, reductions in both areas covered by palsas and palsa height have been observed (Sollid and Sorbel, 1998; Zuidhoff, 2002; Zuidhoff and Kolstrup, 2000). In Tavvavuoma, both growth and degradation of palsas have been observed in detailed morphological studies during the 1960's and 1970's (Wramner, 1968; Wramner, 1973) and expansion and infilling of thermokarstic lakes have been observed

through remote sensing analyses (Sannel and Kuhry, 2011). Palsa degradation and infilling of lakes with fen vegetation have been the dominating processes during recent years (Sannel and Kuhry, 2011; Wramner et al., 2012).

3 Theory and methods

Measurements of permafrost extent and structure were made with both GPR and ERT between 20 August 2012 and 26 August 2012 along three transects covering the main permafrost landforms in the Tavvavuoma area (Fig. 1). The ERT transects were somewhat extended (i.e. slightly longer) compared to the GPR transects to increase the penetration depth along the overlapping parts of the transects. ~~These summer time measurements were targeted to capture the potential maximum active layer thicknesses in the region. In addition, GPR measurements were also made along the same transects between 22 March 2012 and 24 March 2012 to explore the winter time conditions. It was not possible to conduct winter time measurements with ERT due to large snow coverage and frozen surface conditions.~~

Transect T1 was 160 m long and crossed a peat plateau that was raised approximately 1.5 m above the surrounding landscape (Fig. 1). It further crossed two thermokarst depressions (centred at 45 and 130 m) within the peat plateau. Transect T2 was 320 m long, but the southern part covering about 180 m could not be measured with GPR during the summer campaign due to dense vegetation cover (mainly salix sp.). Transect T2 started ~~on-on~~ a peat plateau surface at the edge of a drained lake and continued north over a fen (110-180 m) and a small stream (140 m). The northern part, measured with both ERT and GPR, crossed a palsa (200 m) that was raised about 4 m above the surrounding landscape. This palsa has been described via a bore-hole profile (Ivanova et al. 2011, point 1 in Fig. 1). Transect T2 then continued across two fens (250 and 290 m) separated by a lower palsa (270 m). Transect T3 was 275 m long. It started on a relatively low palsa and stretched over a flat area covered by hummocks and thermokarst depressions.

In addition to the geophysical investigations (details of which are described in the following sections), the depth to the permafrost table (the active layer) was probed every 2 meters along all transects using a 1 m steel rod. Sediment cores were retrieved at four points along T1 and two points along T3 down to 2 m. These cores were used to locate the depth to the peat-

mineral substrate interface and the depth to the permafrost table (at points 3, 4, 5, and 65 in Fig. 1). The topography was measured along the transects using a differential GPS with supplemental inclinometer observations along profiles where only ERT was used~~made using an inclinometer where only the ERT was used~~. The position of the transects was measured using a tape measure and marked at regular intervals to ensure that locations of GPR and ERT transects coincided.

3.1 Ground penetrating radar

Ground penetrating radar (GPR) can be used to map near surface geology and stratigraphy because of differences in dielectric properties between different subsurface layers or structures. An electromagnetic pulse is transmitted through the ground and the return time of the reflected pulse is recorded. The resolution and penetration depth of the radar signal depends on the characteristics of the transmitted pulse and the choice of antennas, which usually range between 10 to 1000 MHz. Higher frequencies will yield a higher resolution but a smaller penetration depth, however, the penetration depth will also depend on dielectric and conductive properties of the ground material. Mapping of permafrost using GPR becomes possible due to the difference in permittivity between unfrozen and frozen water.

In this study, ~~GPR~~-measurements were made with a Malå GeoScience ProEx GPR system using 200 MHz unshielded antennas on~~along~~ T1 and T2. The transmitting and receiving antennas were held at a constant distance of 0.6 m (common offset) and the sampling time window was set to 621 ns, with recorded traces stacked 16 times,~~with the transmitting and receiving antenna held at a constant distance of 0.6 m (common offset)~~. Measurements were made at every 10 cm along the length of these two transects. Along T3~~GPR~~ measurements were made using 100 MHz unshielded antennas with a 1 m antenna separation and measurements made every 0.2 s while moving the antennas along the transect. The sampling time window for T3 was 797 ns and traces were stacked 16 times. The GPR data were processed for a time-zero correction,~~using and with~~ a dewow filter, a vertical gain, and a normal-move out correction for ~~the distance between the transmitting and receiving antennas~~antenna geometry using the software ReflexW (version 6.1, Sandmeier, 2012, downloaded from www.sandmeier-geo.de).

The depths to the permafrost table and the interface between peat-mineral substrates were calculated by converting the two-way travel time to known substrate transitions using estimated velocities for the speed through three different substrate materials: dry peat, saturated peat, and saturated mineral substrate (see Fig. 2 for conceptual sketch of these substrate layers and velocity profiles). To account for uncertainty due to small scale heterogeneity of these ground materials, in addition to the optimal 'representative' velocity identified, the likely maximum and minimum velocities for each substrate were considered in the GPR depth conversions (Table 1). The velocity in dry peat (found in the active layer of palsas, hummocks, and peat plateaus) ~~were~~was calibrated ~~from~~using the active layer thickness measurements made with a steel rod. The minimum and maximum velocities were obtained by subtracting and adding one standard deviation of the measured depths, respectively. For velocities in saturated peat, which was found in taliks such as fens, the depths of saturated peat identified ~~from~~by coring with a 2 m steel pipe (points 3 and 5, Figure 1) were used. The velocity in pure water was used as the minimum velocity and the representative velocity for dry peat was used as the maximum velocity for saturated peat. To obtain ~~these substrate~~ velocities for unfrozen saturated mineral substrate, a common midpoint (CMP) GPR profiles ~~was~~ere measured on a drained lake surface (point 7 in Figure 1) ~~at two points. These were made~~ by moving the GPR antennae apart from each other in 10 cm increments along the 15 m long transects (see Appendix A for a detailed description). The CMP approach, thus, allows for reordering-imaging the same point in space with different antenna offsets making it possible to back out material velocity estimates. ~~The first CMP profile was recorded on a dry peat plateau surface and the second profile on a drained lake surface (points 6 and 7 in Fig. 1). These locations were chosen because they are relatively flat and have flat and uniform reflectors making them suitable for CMP measurements.~~ CMP profiles were analysed using semblance analysis (Neidell and Taner, 1971) in ReflexW software (version 6.1, Sandmeier, 2012, downloaded from www.sandmeier-geo.de).

~~The speed of the GPR signal was estimated through four different substrates (Table 1). These were, namely, the active layer, talik peat, talik mineral, and frozen ground (see Fig. 2 for conceptual sketch of these substrate layers and velocity profiles). As expected, small scale heterogeneity of these ground materials complicates the interpretation of the CMP results. To account for such uncertainty, in addition to the optimal velocity identified, the maximum and~~

1 ~~minimum likely velocities for each substrate were considered in the GPR depth conversions.~~
2 ~~Further, due to inherent difficulties with CMP approaches associated with heterogeneous~~
3 ~~ground substrate properties, unrealistic the velocity estimates from this analysis were~~
4 ~~complemented with literature defined values to define the for similar substrates representative~~
5 ~~and minimum velocities. The end product here is a range of plausible substrate velocities~~
6 ~~accounting for potential uncertainties such that any resultant interpretation about subsurface~~
7 ~~conditions and interface locations can be considered robust.~~

8 ~~The end product here is a range of plausible substrate velocities accounting for potential~~
9 ~~uncertainties such that any resultant interpretation about subsurface conditions and interface~~
10 ~~locations can be considered robust. These are expressed as what can be considered a~~
11 ~~'representative' velocity bounded by a maximum and a minimum velocity. The active layer~~
12 ~~velocities were used above the frost table on palsa and peat plateau surfaces that generally~~
13 ~~consist of relatively dry peat material. For unfrozen peat in fens and under surface depressions~~
14 ~~where there is a deepening of the permafrost table the talik peat velocities were used. The~~
15 ~~talik mineral velocities were used for unfrozen mineral sediments, which were assumed to be~~
16 ~~found only under talik peat. Finally, the velocities for frozen ground were used only when~~
17 ~~interpreting winter images. Since no local estimates could be made during the winter~~
18 ~~campaign, literature values for the minimum and maximum velocities were used for~~
19 ~~interpretations of the GPR data.~~

20 3.2 Electrical resistivity tomography

21 Direct-current electrical resistivity measurements are based on a measured potential
22 difference between two electrodes (ΔV) inserted with galvanic coupling to the ground and,
23 similarly, two electrodes where current is injected into the ground (I) with a known geometric
24 factor (k) depending on the arrangement of the electrodes. This gives a value of the apparent
25 resistivity (ρ_a) of the ground sub-surface as

$$26 \quad \rho_a = k \Delta V / I \quad (1)$$

27 During a tomographic resistivity survey numerous of these measurements are made in lateral
28 and vertical directions ~~both the lateral and vertical~~ (by increasing the electrode spacing). The
29 acquired data is subsequently ~~modeled~~ modelled to generate an image of the resistivity

1 distribution under the site. ~~Res2dinv v.3.59.64 by Geotomo software was used for the~~
2 ~~inversion modeling during this study.~~ Values of resistivity vary substantially with grain size,
3 porosity size, water content, ice content, salinity and temperature (e.g. Reynolds, 2011), thus,
4 the resistivity of permafrost also varies to a large degree. This makes electrical resistivity
5 tomography (ERT) techniques useful in detecting the sharp contrast between frozen and
6 unfrozen water content within sediments.

7 At the Tavvavuoma site, measurements of electrical resistivity were made with a Terrameter
8 LS from ABEM and an electrode spacing of 2 m for the T1 transect and 4 m for the T2 and
9 T3 transects. The Wenner array configuration for the electrodes was used due to its high
10 signal-to-noise ratio and for its accuracy in detecting vertical changes over other common
11 array types (Loke, 2010). For the ~~inversion-inverse~~ modeling the smoothness-constrained
12 least-squares method was applied (Loke and Barker, 1996). The inversion progress was set to
13 stop on the condition ~~that where~~ the change in root mean squared error from the previous
14 iteration was less than 5% (implying convergence of the inversion).- The software Res2dinv
15 (v.3.59.64, Geotomo Software, 2010) was used for the inverse modelingmodelling during this
16 study.

17 To assess the quality and reliability of the resistivity modeling for the Tavvavuoma site, the
18 depth of investigation (DOI) method (Oldenburg and Li, 1999) was used. This appraisal-
19 technique uses the difference between two inverted models where the reference resistivity
20 parameter is varied to calculate a normalized DOI-index map. From these values a depth at
21 which the surface data is no longer sensitive to the physical properties of the ground can be
22 interpreted. The method has previously been applied in permafrost studies (e.g., Fortier et al.,
23 2008; Marescot et al., 2003). To calculate the DOI-index we used a symmetrical two-sided
24 difference scheme where 0.1 and 10 times the average apparent resistivity of the resistivity
25 model was considered (respectively) for the initial reference resistivity parameter. Normalized
26 DOI values higher than 0.1 indicate that the model is likely not constrained by the data and
27 should be given little significance in subsequent model interpretation.

28 To further validate the ERT interpretations, one shorter transect with 0.5 m electrode spacing
29 was conducted over a palsa. This was used to acquire a local resistivity values for the
30 interface between unfrozen and frozen sediments at the bottom of the active layer (surface of
31 the permafrost table). This value (1700 Ω m) allowed us to map permafrost boundaries in the

ERT images, with all resistivity values > 1700 Ωm interpreted as permafrost. However, as the resistivity of the ground varies with other sediment physical properties and the sediment distribution is complex at the site, the resistivity boundary value for permafrost will naturally vary along transects and with depth. For instance, sands generally have maximum values for the unfrozen state close to 1200 Ωm and for some gravels this can reach up to 3000 Ωm (Hoekstra et al., 1974). Finer sediments, such as clays and silts have lower values, ranging from ca 80 to 300 Ωm (Hoekstra et al., 1974). At our site sands dominate, but there is also evidence of loams. Lewkowicz et al. (2011) report a resistivity of 1000 Ωm at the base of permafrost under a palsa in similar, but somewhat finer, sediments conditions in southern Yukon. This value from Lewkowicz et al. (2011) was thus used as a possible minimum resistivity value for the permafrost boundary in the interpretations, while the local resistivity estimate (1700 Ωm) was used as a maximum and representative value. All resistivity values < 1000 Ωm were thus interpreted as unfrozen ground and the values between 1000 and 1700 Ωm represent a range of uncertainty for the location of the interface between frozen and unfrozen sediments. Again, the motivation here was to account for potential uncertainty allowing for robust interpretation.

3.3 Calculations of active layer and thaw rates

To help put the geophysical measurements and their potential implications for this peatland palsa region in context, the thickness of the active layer as well as first order estimate of long-term thaw rates were estimated using a simple equation for 1-D heat flow by conduction, the Stefan equation (as described by Riseborough et al., 2008):

$$Z = \sqrt{\frac{2\lambda I}{Ln}}, \quad (2)$$

where Z is the thaw depth, λ is thermal conductivity, I is the thawing degree day index (as described by Nelson and Outcalt, 1987), L is the volumetric latent heat of fusion and n is the saturated porosity of the ground substrate. As a talik is by definition unfrozen ground occurring in a permafrost area, the Eq. (2) was used to confirm that ~~the~~ ground identified as talik in Tavvavuoma through the GPR and ERT images did not correspond to locations of deeper active layer relative to surrounding ing positions (i.e. provide a confirmation that these sites would not freeze during winter).

Calculations of active layer depths in fens were made using as input a sinusoidal annual air temperature curve generated from the average temperature of the warmest and the coldest months of the year. The effect of the snow cover, which would give higher ground surface temperatures in the winter, was not explicitly taken into consideration in this simple calculation as we did not have any direct estimates of snow cover available for the transects. As such, these calculations are simply a first-order approximation. Representative properties for saturated peat were chosen, including a thermal conductivity of 0.5 W/m/K and a saturated fraction of 0.80 (Woo, 2012).

In addition, a first-order approximation of long-term thaw rates was carried ~~out-out-as-a~~ ~~thought-experiment~~. An instantaneous increase in air temperature of 2° C was assumed, which represents a warming within current climate projections for the 21st century, although at the low end of projections for Arctic warming (IPCC RA5, 2013). A ~~thermal conductivity of 3 W/m/K and a~~ saturated fraction of 0.50 ~~were-was~~ used to represent ~~a-sand-soil~~, slightly oversaturated with ice. To account for some of the uncertainty in this rough estimate, a range of likely minimum and maximum values for thermal conductivity (2 and 3 W/m/K, respectively) for this material, were used to estimate a range of thaw rates. The annual freezing degree days were subtracted from the annual thawing degree days, I in Eq. (2), and the amount of days necessary to thaw the estimated local thickness of permafrost was estimated. This is a simple estimate since, clearly, the Stefan equation is not designed to calculate long-term thaw rates nor does such an estimate consider any density dependent feedbacks and/or subsequent hydroclimatic shifts. Regardless, combined with estimates of permafrost thickness made in our geophysical investigation, the aim of this ~~thought~~ ~~experiment~~back-of-the-envelope calculation was to provide an order-of-magnitude estimate for the time it could potentially take permafrost to completely thaw~~-out~~ at this site to help place it in a pan-arctic context.

4 Results

4.1 GPR data

In the ~~summer~~-GPR images the permafrost table was clearly detectable under the palsa and peat plateau surfaces along all transects (Fig. 3). The interface between peat and mineral

substrates was only detectable in unfrozen sediments. Deeper reflections, interpreted as the permafrost table under supra-permafrost taliks, were found under the fens and surface depression in all transects. ~~At the~~ In the beginning of both transects T1 and T2, deep reflections that end abruptly were present in the images at about 250 ns and 150 ns, respectively. In T1, this corresponds to a wet fen bordering a lake and for T2 it corresponds to a fen bordering a stream. The proximity to these water bodies suggests that these are likely not reflections from the permafrost table. The base of the permafrost could not be detected at any point in the GPR images likely because of loss of signal strength at depth.

~~In the winter GPR images, interfaces between frozen and unfrozen ground (taliks) were not clearly separable from sedimentary layers. Several interfaces are visible in the images, however, indicating a complex layering of sediments and ground ice confirmed by described sedimentary profiles from the site (Ivanova et al., 2011). No further interpretations were made from winter images, however, due to the lack of clear reflections.~~

4.2 ERT data

The ~~results from the ERT data modelling~~inverted resistivity sections showed areas of high resistivity (1000-100000 Ωm) where permafrost could be expected due to the sharp contrast to surrounding surfaces. This suggests permafrost boundaries are detectable for both the extent of the horizontal distribution and the vertical extent to the base of permafrost (Fig. 4). The highest resistivity values were found under the peat plateau in T1 and under the palsas in T2 and T3. Low resistivity values were found under the fens in all transects. DOI values increase with depth for all transects allowing the permafrost base to be interpreted only along parts of T2. ~~Counter to this~~In contrast, under T1 and T3 the DOI rapidly increases under the peat plateau and hummocks. Due to the wide electrode spacing adopted (2 and 4 m), the permafrost table under the active layer is too shallow to be visible in the ERT data.

4.3 Geophysical interpretations

Permafrost occurs under the palsa and peat plateau surfaces along T1 and T2, as well as under the hummocks along T3 (Fig. 5). The active layer depths estimated from the GPR data closely matched the depths measured in the field (Table 2). This is expected since measured active layer depths ~~along T1 and T2~~ were used to derive the velocity of the radar signal in the dry

1 | peat in the active layer. The depth to the base of the permafrost could only be estimated with
2 | good confidence along parts of T2 and is on average 15.8 m from the ground surface and at
3 | least 25 m at its deepest point. Along transects T1 and T3 the deepest permafrost was found at
4 | 8.4 m and 23.4 m respectively; however, the permafrost base could not be identified with
5 | confidence below this depth.

6 | Potential taliks (Table 3 and Fig. 5) are numerous and occur in both wet fens, such as all taliks
7 | along T2, and relatively dry depressions in the terrain, such as all taliks along T1. The
8 | sediment cores used for estimating the GPR representative signal velocity in saturated-talik
9 | peat were taken in both a relatively dry location and in a wet fen, but the calculated velocities
10 | were nearly identical, indicating that the soil moisture at depth was similar at both locations.
11 | Most of T3 was underlain by taliks and these were found under both wet fens and drier
12 | surface depressions. The taliks range in depth from 2.1 m (T3f, numbering from Table 3 and
13 | Fig. 5) to 6.7 m (T1c) based on the GPR data and are slightly deeper, however within the
14 | range of uncertainty, based on the ERT results. From the ERT data, T1c is in fact interpreted
15 | as a potential through-going talik. Talik T1b was only detected from the ERT data, and taliks
16 | T3b – T3d appear as one large talik in the ERT data.

17 | 4.4 Calculations of active layer and thaw rates

18 | The active layer depths calculated using the Stefan equation support the interpretation that
19 | identified taliks do not freeze during winter. The seasonal frost penetration depth was
20 | estimated to be 0.72 m which is about the same as the average peat depth along the transects
21 | and much less than the estimated minimum depth of the taliks (2.1 m). While a shallower peat
22 | depth would give a deeper frost penetration it is unlikely that the seasonal frost penetration is
23 | > 2.1 m in the area surrounding Tavvavuoma. This ancillary estimate confirms the
24 | aforementioned geophysical interpretation. Further, as a thought experiment, assuming a 2°C
25 | instantaneous temperature increase at the site, the a first order approximation of the long-term
26 | thaw rate was calculated to be 7-6 - 8.5 cm/year. At this rate, the time to completely thaw ~~out~~
27 | permafrost assuming the estimated average thickness along T2 (15.3 m) was calculated to be
28 | 175 - 260 years.

5 Discussion

5.1 Permafrost and talik distribution at Tavvavuoma

The spatial pattern of permafrost and taliks in Tavvavuoma is closely linked to the distribution of palsas, peat plateaus, fens and water bodies. This suggests that local factors, such as soil moisture, groundwater flow, ground ice content, sediment distributions and geomorphology, strongly influence the local ground thermal regime (see e.g. Delisle and Allard, 2003; McKenzie and Voss, 2013; Woo, 2012; Zuidhoff, 2002). The relative elevation of permafrost landforms, as well as permafrost resistivity values and sediment distributions suggest that there is a large variation in ground ice content in the area. Surface elevations of palsas and peat plateaus are highest along T2 and lowest along T3, indicating a higher ice content of the underlying ground along T2, which is likely related to differences in ground substrates between the transects. Coring (<2 m) across the site, as well as existing borehole descriptions (Ivanova et al., 2011) confirm that the ground contains a larger fraction of coarse glaciofluvial sand and gravel, which are not susceptible to frost heave, closer to T3 as compared to T2.

Lewkowicz et al. (2011) used the height of palsas and permafrost thickness, estimated by ERT, to calculate excess ice fractions (EIF =defined as the ratio of –palsa height to /permafrost thickness) in permafrost mounds in southern Yukon. InFor Tavvavuoma, the EIF at the top of the highest palsa at T2 is approximately 4 m high and underlain by 16 m thick permafrost at the highest point. This corresponds to an EIF of 0.25~~was 0.25~~, which is comparable to the these EIFs reported by Lewkowicz et al. (2011), which were generally ranging between 0.2 and 0.4. In contrast, along T3 the relative heights of permafrost landforms are lower and the permafrost is thicker for most of the transect. Similarly calculated EIFs along T3 were on average <0.03 and at maximum <0.09, but are likely lower in reality as the base of the permafrost is at a greater depth than what could be detected in our study. For T3 possible maximum EIFs were calculated using the greatest depths at which permafrost was found, since the permafrost base could not be identified from the data for T3. The calculated EIFs along T3 were on average <0.03 and at maximum <0.09, confirming that ground ice content is lower along this transect. The relatively low resistivity of the permafrost along T3 further supports interpretations for lower ice content in this permafrost. Permafrost

with low ice content is more susceptible to thaw, as less energy is needed for latent heat exchange. This provides a possible explanation for why taliks are more widespread along T3, as permafrost with a low ice content would have reacted more rapidly to warming in the area.

The calculated thaw rate of $6 - 8.57$ cm/year is considerably higher than the circa 1 cm/year deepening of the active layer observed in the region (Åkerman and Johansson, 2008) and inferred from hydrological records (Lyon et al. 2009). One possible reason for this is that these observations were made in the relatively ice rich top layer of peat, while for the calculations in this study a medium with higher thermal conductivity and lower ice content was used to represent the lower mineral sediment layer. The 2°C instantaneous step change in temperature could further have contributed to the higher thaw rates compared to the ones observed. As thawing is driven by gradients in heat it can be argued that permafrost thaw rates should increase with warmer air temperatures. Considering this, the calculated time of complete permafrost thaw-out of about 175 - 260 years can be considered reasonable in at least an order of magnitude. However, much more rapid palsa degradation has been observed in the region (Zuidhoff, 2002), due to block and wind erosion processes and thermal influence on palsas from expanding water bodies, and very rapid decay of palsa surface areas has been observed in both southern Norway and the Canadian Arctic (Payette et al., 2004; Sollid and Sorbel, 1998). The coupled erosion, hydrological and thermal processes are not represented in the Stefan equation but can be of great importance for permafrost thaw rates (McKenzie and Voss, 2013; Painter et al., 2013; Zuidhoff, 2002). There is clearly a need for quantification of the relative importance of these processes for permafrost thaw to better understand expected future changes in these environments.

5.2 On the complementary nature of the geophysical techniques

Several previous studies have shown the benefits of combining more than one geophysical technique for mapping permafrost (e.g. De Pascale et al., 2008; Hauck et al., 2004; Schwamborn et al., 2002), and also in this study the GPR and ERT data provided complementary information that allowed for interpretations that would not have been possible by using only one of the two datasets. Of course, combining multiple techniques for inference compounds our estimate uncertainties. To attain more precise estimates of depths to the different interfaces, deeper coring data would have been necessary for both more accurate

1 signal velocity estimates for the GPR and for local resistivity values of the ground materials.
2 The fact that ERT depth estimates are consistently higher than the GPR estimates suggest that
3 either the resistivity boundary value for permafrost is in fact lower than our local estimate, or
4 that GPR signal velocities are higher than the values used in this study. Since our local
5 permafrost resistivity estimate was made in peat at the permafrost table, which can have a
6 very high ice content compared to deeper sediment layers, it is a more likely explanation for
7 this discrepancy.

8 GPR and ERT yielded somewhat overlapping data but the two datasets have different
9 strengths and therefore complement each other well. The GPR data worked well for
10 identifying the permafrost table with high confidence, especially in the top 2 meters where
11 sediment cores could be easily obtained for validation and signal velocity estimates. This
12 suitability of GPR for identifying permafrost interfaces in the top 1-2 meters has been shown
13 in several studies (e.g. Doolittle et al., 1992; Hinkel et al., 2001; Moorman et al., 2003). ~~GPR~~
14 ~~was however not a suitable technique for detecting the permafrost base during winter, due to~~
15 ~~the high variability in ground ice content and sediment layering in this environment.~~ The ERT
16 data, using the setup in this study, does not yield data in the uppermost part of the ground and
17 also has higher uncertainty where resistivity contrasts are high (Fig. 4), which makes it less
18 well suited for the active layer and shallow taliks. With the ERT data it is, however, possible
19 to image relatively deep in the ground, where the GPR cannot penetrate. By combining both
20 GPR and ERT the active layer, the base of permafrost, and potential taliks could be identified
21 along at least parts of the transects, which could not have been achieved with good confidence
22 by either of the two methods alone.

24 6 Concluding remarks

25 Peat plateau complexes offer an interesting challenge to the Cryosphere community as they
26 are clear mosaics combining local-scale differences manifested as permafrost variations. As
27 such variation occurs both horizontally and vertically in the landscape, geophysical
28 techniques offer a good possibility to record current permafrost conditions across scales.
29 ~~Complementary~~ Further, by combining methods, such as GPR and ERT as demonstrated here,
30 ~~are necessary as they can provide orthogonal complementary and independent~~ views of the
31 permafrost extents can be acquired. The results of this study show a heterogeneous pattern of

permafrost extent reflecting both local and climatic processes of permafrost formation and degradation. To improve our understanding of landscape-permafrost interactions and dynamics will require a community effort to benchmark variability across the scales and environments within the pan-Arctic. This is particularly important in lesser studied regions and across the sporadic permafrost zone where changes are occurring rapidly.

Appendix A: CMP analyses

Common mid-point (CMP) analysis is a widely used method to estimate local GPR signal velocities through ground materials. By moving GPR transmitting and receiving antennas apart incrementally between measurements, the same point in space is imagined with different antenna offsets making it possible to back out material velocity estimates from the hyperbolic shape of the recorded reflectors. The measured reflectors must be relatively flat so that the signal moves through the same materials at the same depths independent of antenna offset.

In this study, a CMP profile was measured on a drained lake surface (point 7 in Figure 1). Coring down to 2 m with a steel pipe at this location revealed the existence of an unfrozen saturated peat layer down to 1.75 m depth and unfrozen mineral soils consisting of mainly sand and silt below that depth. The aim of the CMP measurement used in this study was to estimate material velocities for the deeper unfrozen saturated mineral substrate. As such, deeper here means materials below the observation depths of the permafrost probe (< 1 m) and coring with the steel pipe (< 2 m). For the CMP measurement, 100 MHz unshielded antennas were moved apart in 10 cm increments along a 15 m transect with a time window of 797 ns and 16 stacks of each trace.

The measured CMP data was analysed in ReflexW (version 6.1, Sandmeier, 2012, downloaded from www.sandmeier-geo.de). The data were processed for a time-zero correction, a dewow filter, and a vertical gain. Semblance analysis (Neidell and Tanner, 1971) was used to identify appropriate reflectors from which velocities could be estimated. Using semblance analysis numerous velocities are used to correct the recorded reflectors for the increased travel distance for each offset. When the hyperbolic reflection becomes coherent in the CMP (i.e. a flat line) a high semblance value is obtained indicating that the correct velocity has been used.

.

Figure A1 shows the estimated velocity profile, recorded CMP radargram, and semblance plot for the CMP transect. Although a relatively flat reflector was identified for the CMP measurement, the results from the semblance analysis does not show one clear reflector and associated velocity at the identified depth of the peat-mineral interface. Instead, a wide range of possible velocities are shown in the semblance plot for the top ~200 ns, likely due to high heterogeneity in ground substrates and/or water content. Due to the difficulty in constraining the material velocities for the deeper layers using this method, these results were only used for estimating a probable maximum velocity in unfrozen mineral sediments (as this was higher than most literature values). This maximum velocity estimate was complemented with literature values for the representative and minimum velocities.

Author contribution

Ylva Sjöberg designed the study, carried out the GPR measurements and analysis, and did the main writing of the manuscript. Per Marklund carried out the ERT measurements and analysis and did the main writing for the sections on ERT methods and ERT results, as well as commented on the whole manuscript. Rickard Pettersson provided input on the geophysical techniques and analyses and commented on the whole manuscript. Steve Lyon provided input on the project design and commented on the whole manuscript, including language and style.

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1 Table 1. Velocities used for converting two-way travel times to depth in GPR data.

Material	Velocity (m/ns)	Method/Source
Active layer <u>Dry peat</u> – representative	0.049	Calibration against every second field measurements ⁱ of active layer depths
Active layer <u>Dry peat</u> - min	0.046	Representative estimate minus one standard deviation of field measurements ⁱ
Active layer <u>Dry peat</u> - max	0.052	Representative estimate plus one standard deviation of field measurements ⁱ
Talik-Saturated peat – representative	0.036	Calibration against coring (point 3 and 5, in Fig. 1)
Saturated Talik peat - min	0.033	Velocity in pure water (Davis and Annan, 1989)
Saturated Talik peat - max	0.049	Representative estimate for active layer <u>dry</u> peat
Saturated Talik mineral – representative	0.060	Velocity in sand and clay from Davis and Annan (1989)
Saturated Talik mineral - min	0.053	Calculated from Joseph et al. (2010) for saturated loams and sands
Saturated Talik mineral - max	0.073	Highest estimated velocity from CMP analysis
Frozen ground – min	0.110	Minimum for permafrost from Hinkel et al. (2001)
Frozen ground – max	0.160	Velocity in pure ice from Evans (1965)

2 ⁱ Field measurement using a 1 m steel rod

3

Table 2. Range of interpreted depths (m) of active layer, peat-mineral interface, and permafrost base averaged along transects at Tavvavuoma.

	T1			T2			T3		
	Min ⁱ	Representative ⁱⁱ	Max ⁱⁱⁱ	Min ⁱ	Representative ⁱⁱ	Max ⁱⁱⁱ	Min ⁱ	Representative ⁱⁱ	Max ⁱⁱⁱ
Active layer									
<i>Observed</i> ^{iv}		0.51			0.52			0.56	
<i>GPR</i>	0.50	0.53	0.57	0.48	0.51	0.54	0.52	0.56	0.59
Peat-mineral interface									
<i>GPR</i>	0.77	0.84	1.14	0.68	0.74	1.01	0.63	0.69	0.93
Permafrost base									
<i>ERT</i>		-	-		15.8	17.3		-	-

ⁱ GPR: using the estimated minimum velocity (Table1). ERT: using 1000 Ωm resistivity boundary (talik).

ⁱⁱ GPR: using representative estimate velocity (Table 1). ERT: using 1700 Ωm resistivity value.

ⁱⁱⁱ GPR: using the estimated maximum velocity (Table 1). ERT using 1000 Ωm resistivity boundary (permafrost base).

^{iv} Depth from manual field measurement using a steel probe.

1 Table 3. Estimated depths (m) of taliks. Numbering is the same as in Fig. 5.

Talik max depth	GPR minⁱ	GPR representativ eⁱⁱ	GPR maxⁱⁱⁱ	ERT minⁱ	ERT representativ eⁱⁱ
T1a	2.4	2.7	3.4	2.5	3.1
T1b	-	-	-	1.6	2.8
T1c	6.0	6.7	8.3	> 4.7	> 4.7
T2a	5.4	6.1	7.6	5.4	6.9
T2b	5.3	6.0	7.4	6.9	8.8
T3a	5.3	5.9	7.4	5.8	7.8
T3b	5.7	6.4	8.0	6.3	8.2
T3c	5.1	5.7	7.0	4.8	7.9
T3d	3.1	3.5	4.4	-	4.0
T3e	4.6	5.2	6.4	5.4	7.2
T3f	2.0	2.1	2.2	-	3.8
T3g	3.7	4.1	5.2	5.0	6.8

2 ⁱ GPR: using the estimated minimum velocity (table1). ERT: using 1000 Ωm resistivity
3 boundary (talik).

4 ⁱⁱ GPR: using representative estimate velocity (table 1). ERT: using 1700 Ωm resistivity
5 value.

6 ⁱⁱⁱ GPR: using the estimated maximum velocity (table 1). ERT using 1000 Ωm
7 resistivity boundary (permafrost base).

8

Figure 1. Location of the study site (inset), investigated transects, existing boreholes (Ivanova et al., 2011, points 1 and 2), coring points, and points of CMP measurements (described in section 3.1 and Appendix A). (Aerial photograph from Lantmäteriet, the Swedish land survey, 2012.)

Figure 2. Conceptual sketch of typical distribution of ground substrates and associated estimated velocities for a palsa and talik ground profile.

Figure 3. Elevation profiles and GPR images for T1, T2, and T3 with selected reflections marked as examples of interfaces that were identified for this study. Landforms are indicated on top of elevation profiles along T1 and T2 (Tk.D = thermokarst depression) together with coring points in T1 (a = point 3 in Figure 1, and b = point 4 in Figure 1) and T3 (d = point 6 in Figure 1) as well as the 10 m borehole in T2 (c = point 1 in Figure 1). No landforms are indicated along T3 after the first palsa (0-25 m) due to the complex micro topography of hummocks and thermokarst depressions along this transect.

Figure 4. Elevation profiles and ERT results for T1, T2, and T3. DOI \leq 0.1 (black lines) indicates that the model is well constrained by the data. Landforms are indicated on top of elevation profiles along T1 and T2 (Tk.D = thermokarst depression) together with coring points in T1 (a = point 3 in Figure 1, and b = point 4 in Figure 1) and T3 (d = point 6 in Figure 1) as well as the 10 m borehole in T2 (c = point 1 in Figure 1). No landforms are indicated along T3 after the first palsa (0-25 m) due to the complex micro topography of hummocks and thermokarst depressions along this transect.

Figure 5. Interpreted permafrost distribution along T1, T2, and T3. Uncertainty intervals come from the range of estimated signal velocities for GPR (Table 1) and from the range of resistivity values (1000-1700 Ω m) used for identifying the permafrost boundary for ERT. In sections marked GPR Talik (red dotted line) GPR depth conversions have been made using

1 saturated peat velocities down to the peat-mineral interface (green line) and then using
2 saturated mineral substrate velocities down to the permafrost table (blue line). In the
3 remaining parts of transects the dry peat velocities have been used down to the permafrost
4 table. No interpretations of ERT data with DOI > 0.1 are have been made and therefore the
5 permafrost base is only visible along parts of T2. Note the differences in scale in the x-
6 direction between figures and the vertical exaggeration.

7
8 Figure A1. Estimated velocity profile, recorded CMP radargram, and semblance plot for the
9 CMP transect measured on the drained lake surface. The semblance plot shows more likely
10 velocities in darker shades of grey with the velocities from the reflectors (red lines in
11 radargram) used for generating the velocity profile indicated by black and red diamonds.