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Interactive comment on "Geophysical mapping of palsa peatland permafrost" *by* Y. Sjöberg et al.

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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 as a separate file.

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. Since 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 as per the referee comment. Instead, an appendix (Appendix A) has been added, which describes the CMP analysis in more detail and also contains a figure including the CMP radargram and a semblance plot. This way, we believe that the CMP methods can be described thoroughly for the interested reader without expanding too much on the methods section for this detail. In addition, the names for the subsurface materials have also been changed as suggested. Also, as the winter data has been removed (see later comment reply below), velocities in frozen ground are no longer used and have therefore also been removed from Table 1 and Figure 2. Finally, simple line graphs have been added to Figure 3 and 4, showing the surface topography and landforms along the transects. In Figure 5 the extents of the taliks (as interpreted from GPR data) have been marked and an *explanation for which velocities were used for depth conversions in and outside of taliks has been added to the caption.*

Section 3.1 now reads as: "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, measurements were made with a Malå GeoScience Proex GPR system using 200 MHz unshielded antennas 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. Measurements were made at every 10 cm along the length of these two transects. Along T3 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, and with a dewow filter, a vertical gain, and a dynamic depth correction for antenna geometry using the software ReflexW (version 6.1, Sandmeier, 2012, 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 velocity identified, the maximum and

minimum likely velocities for each substrate were considered in the GPR depth conversions. The velocity in dry peat (found in the active layer of palsas, hummocks, and peat plateaus) was calibrated 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 these measured depths. For velocities in saturated peat, which was found in taliks such as fens, the depths of saturated peat identified by coring with a 2 m steel pipe (see Figure 1 for locations) 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 velocities for unfrozen saturated mineral substrate, a common midpoint (CMP) GPR profile was measured on a drained lake surface (point 6 in Figure 1) by moving the GPR antennas 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 imaging the same point in space with different antenna offsets making it possible to back out material velocity estimates. CMP profiles were analysed using semblance analysis (Neidell and Taner, 1971) in ReflexW software (version 6.1, Sandmeier, 2012, www.sandmeier-geo.de). Due to inherent difficulties with CMP approaches associated with heterogeneous ground substrate properties (Appendix A), the velocity estimates from this analysis were complemented with literature values for the representative and minimum velocities. The end product here is a range of plausible substrate velocities accounting for potential uncertainties such that any resultant interpretation about subsurface conditions and interface locations can be considered robust. These are expressed as what can be considered a 'representative' velocity bounded by a maximum and a minimum velocity (Table 1)."

2. Resistivities for permafrost identification (P 5146, L 22 – P 5147, L10): This section is somewhat confusing. I expect, the authors define a lower (1000 Ohm.m) and an upper (1700 Ohm.m) for the transition from unfrozen to frozen conditions while all resistivities > 1700 Ohm.m indicate permafrost. However, the paragraph reads as if there is a range in resisitivities (i.e. 1000-1700 Ohm.m) for identification of permafrost

and all values above are no permafrost again. Please clarify.

We have reworded this paragraph for clarity. Simply, all resistivity values < 1000 âĎęm were interpreted as unfrozen ground and the values between 1000 and 1700 âĎęm represent a range of uncertainty for the location of the interface between frozen and unfrozen sediments.

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

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

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

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

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

distribution.

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

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

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

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

This has been changed as suggested.

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

This part of the sentence has been removed.

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

Done.

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

Our original idea was to use wintertime GPR measurements to try to identify the base of the permafrost, since the penetration depth of the GPR should theoretically be greater in frozen compared to wet conditions. However, the winter images were extremely difficult to interpret, likely due to large variability in ice content, leading to scattering of the radar signal. We agree that the manuscript is improved by excluding the GPR winter data, which does not add any relevant information on permafrost distributions.

As such, we have removed these data and their analysis in this revision.

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

Done.

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

This information has been added.

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

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

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

See reply to major comment on CMP velocities.

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

The velocities have been renamed.

P 5145, L 23: replace "pore size" by "porosity"

Done.

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

Done.

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

Done.

P 5146, L 5, L 9: suggestion: use "inversion" or "inverse modelling"

Done.

P 5146, L 9: add reference for Res2dinv

Done.

P 5148, L 11: better: "sandy soil" or "sand"

Done.

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

Winter data has been removed.

P 5149, L 14: suggestion: replace "results from the ERT data modelling" by "inverted resistivity sections"

Done.

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

This sentence has been slightly reworded to clarify this.

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

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

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 by 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 P5139, 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, Fig. 1: add degrees to longitude axis

All these technical comments have been corrected for in the revised manuscript.

P 5164, Tab. 2: align "Representative"

This is a typesetting error which will have to be corrected in a later stage

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/8/C2848/2015/tcd-8-C2848-2015-supplement.pdf

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Interactive comment on The Cryosphere Discuss., 8, 5137, 2014.

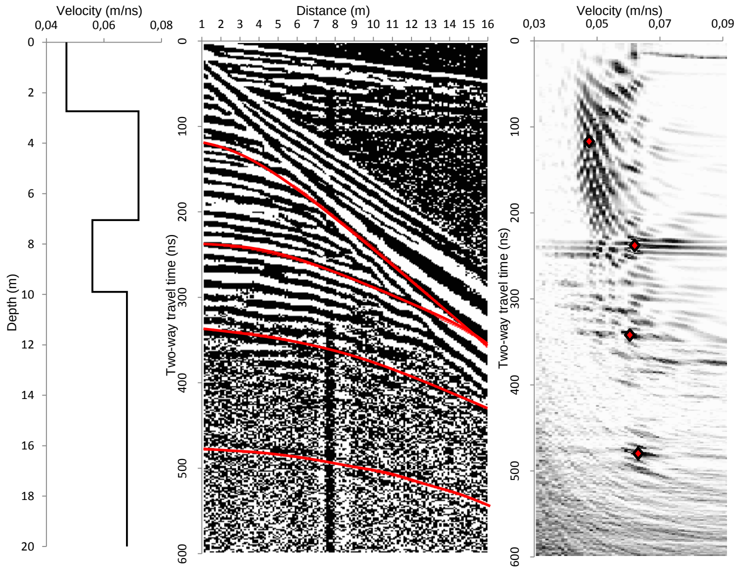

Fig. 1. Figure A1.

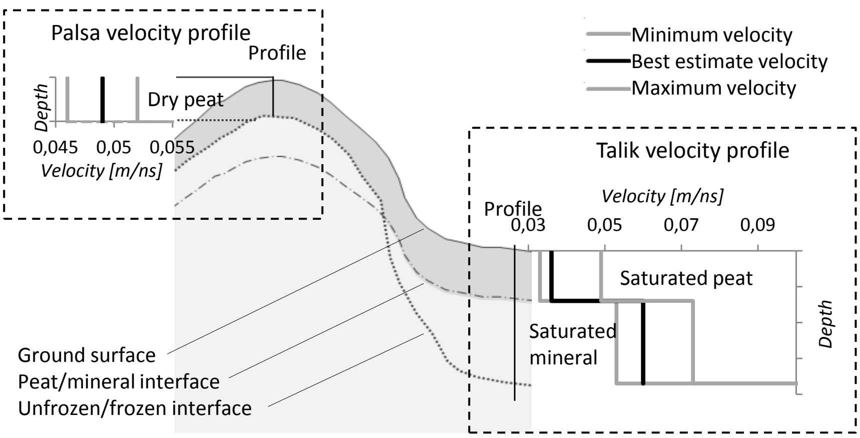

Fig. 2. Figure 2.

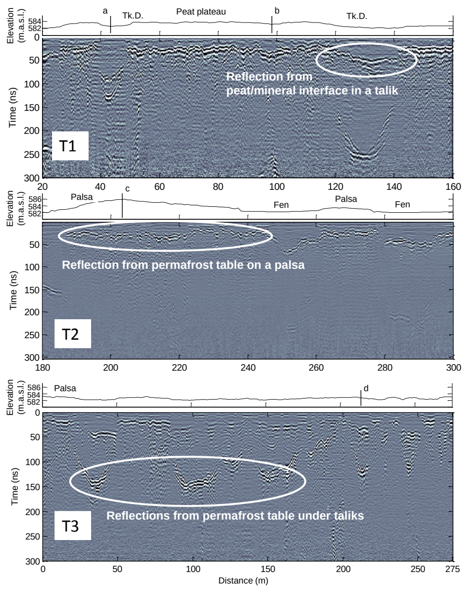

Fig. 3. Figure 3.

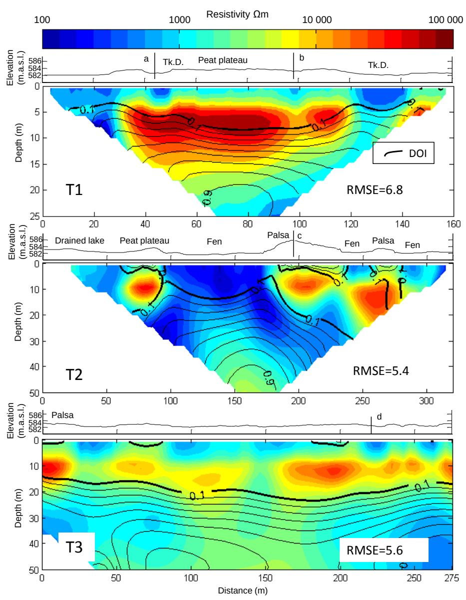

Fig. 4. Figure 4.

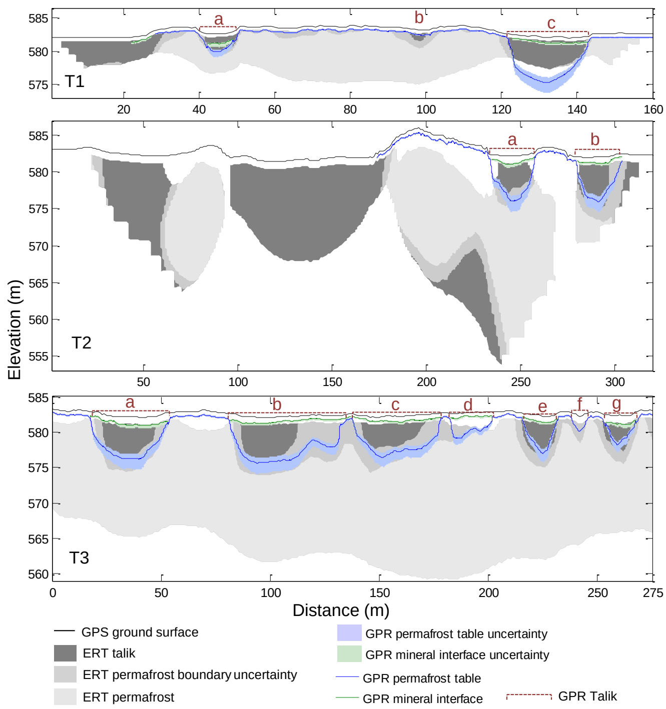

Fig. 5. Figure 5.