Replies to referee comments (RC1)

RC1: 'Comment on egusphere-2024-1044', Wojciech Dobiński, 26 Apr 2024 reply

Mapping of submarine permafrost remains an important scientific issue despite the increasing number of works published in this field. Undersea permafrost is much more difficult to access empirically and requires the use of a new, original methodological approach. Systematic research covers only the last few decades, so the recognition of undersea permafrost and especially the active layer is still imperfect and requires a lot of scientific effort. The presented article addresses both of these issues: substantive and methodological, contributing to this important topic with new, original research.

The authors try to present a number of scientific and methodological findings that may certainly be of great cognitive value to the growing number of undersea permafrost researchers. With this very general sentence I want to express my rather positive opinion about this work. I think it will be more interesting to present some comments and suggestions that would help improve this article. I will present them generally in this review, which is also significantly supplemented by detailed comments attached to the text of the article in the PDF version, in the form of notes

1. In the title, the authors rightly bring to the fore the substantive issue, i.e. determining the extent of permafrost in the studied area. I think it would be good to maintain this order in the structure of the entire work. However, in some chapters methodological issues come to the fore, such as limitations in the application of the method, difficulties in field work, uncertainty of some results, etc. This is an understandable and honest approach to the issue, but it slightly weakens the scientific result of the article. I would rather reverse this order.
   We agree. The order will be changed in the revised version.

   An extremely important issue is to clearly define what is actually the subject of the authors' research. Just saying it's about permafrost degradation is not enough and not very original. Although the definition of permafrost applies to its terrestrial and undersea occurrence to the same extent, in the undersea environment the situation becomes much more complicated, for example because permafrost is not a purely climatic geological formation (subaerial). Therefore, in my opinion, a chapter is needed that characterizes the differences in the occurrence of terrestrial and submarine permafrost. This is even more important because a clear definition of the subject of research has important methodological consequences, i.e. in the interpretation of research results. This is not a difficult issue. In the published articles of the team of prof. Angelopoulos it is clearly presented.
   We agree and have added to the introduction:
   "The occurrence of terrestrial permafrost is linked to the air temperature regime. In regions with a mean annual air temperature near the ground below 0 °C, permafrost can form. This can be the case in polar regions (latitudinal permafrost) as well as in mountainous regions (altitudinal permafrost). Deep permafrost (several 100 m) can last over centuries, even when mean annual air temperatures have risen above 0 °C. In contrast, subsea permafrost is bound to more specific conditions: The vast majority of subsea permafrost is relic terrestrial permafrost that has been inundated

due to the sea level rise after the Last Glacial Maximum (LGM). Heat transfer from sea water thaws the permafrost from the top downwards; geothermal heat thaws it from below. Where relic permafrost is thick (several 100 m), subsea permafrost can last over millennia. These conditions are met, for example, on the large Siberian Shelf, where subsea permafrost extends several 100 km offshore, representing the largest subsea permafrost occurrence on Earth (Overduin et al. 2019; Obu et al. 2019). On a smaller scale, subsea permafrost can also be found along the Canadian coast, for example offshore of the Tuktoyaktuk Coastlands."

Overduin, P., Schneider von Deimling, T., Miesner, F., Grigoriev, M., Ruppel, C., Vasiliev, A., Lantuit, H., Juhls, B., and Westermann, S.: Submarine permafrost map in the Arctic modeled using 1-D transient heat flux (supermap), J. Geophys. Res-Oceans, 124, 3490–3507, https://doi.org/10.1029/2018jc014675, 2019.

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmüller, B., Kholodov, A., et al.: Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale, Earth-Science Reviews, 193, 299–316, 2019.

2. Ice-bearing permafrost (IBP) is not the same as permafrost (PF) in general. IBP is to PF as a part is to the whole. In this context, it is important to comment on the issue of cryotic permafrost in your work. This would be a very interesting and necessary statement.
   Yes, it is important to distinguish between the two. To make it more clear (see comments below) we address it in the introduction by modifying the text to say: "Such lowering of the freezing point can result in ice-free permafrost (unfrozen), which is distinct from permafrost containing ice, termed ice-bearing permafrost (IBP). The lowering of the top of the permafrost, whether defined as the (0 °C isotherm or the top of ice-bearing permafrost, is referred to as permafrost degradation."

3. Regarding the method used. Of course, I agree that, just like on land, also in the case of undersea permafrost, its detection is associated with a sudden increase in resistance. It is worth noting, however, that this applies only to IBP but not to PF in general. A big problem arises when it comes to the issue of the cryotic state, especially present in sedimentary material saturated with salt water. This requires clarification and a broader discussion. In this respect, the conclusions chapter should also be clarified.
   We agree that the unfrozen but cryotic state (<0 °C) cannot be resolved with ERT. In our study the focus is on a nearshore environment that is subject to coastal erosion, where the terrestrial sediments are cemented by ice-bearing permafrost. Therefore, we want to resolve the boundary between unfrozen and frozen sediment, rather than the 0°C isotherm. The resistivity of unfrozen sentiment increases with decreasing temperature and can increase by orders of magnitude at the freezing point of the sediment which is determined by salt concentration in the porewater. We have changed the 2nd-last paragraph of the introduction from:

“Marine electrical resistivity tomography (ERT) has been used to detect subsea permafrost (Angelopoulos, 2022). The method relies on the high resistivity contrast between frozen fresh water saturated sediment (i.e. former terrestrial permafrost) and unfrozen salt water saturated sediment (i.e. degraded permafrost) and uses a floating electrode cable dragged by a boat for current injection and voltage measurements. As opposed to terrestrial ERT surveys where electrode positions are fixed, a flexible cable in a marine ERT survey relies on potentially varying electrode positions. Previous studies have accounted for deviating electrode positions only by visually assessing the cable straightness from the boat during the measurements (cf. Overduin et al., 2012, 2016; Angelopoulos et al., 2019).”

to:

“Marine electrical resistivity tomography (ERT) has been used to detect subsea permafrost (Angelopoulos, 2022). The method relies on the high resistivity contrast between frozen fresh water saturated sediment (i.e. former terrestrial permafrost) and unfrozen salt-water saturated sediment (i.e. degraded permafrost). In this case the transition from ice-free to ice-bearing permafrost and the from saline to freshwater pore solution result in a compound effect, increasing the resistivity by orders of magnitude.
To measure sub-bottom resistivity, a floating electrode cable is dragged by a boat for current injection and voltage measurements. As opposed to terrestrial ERT surveys where electrode positions are fixed, a flexible cable in a marine ERT survey relies on potentially varying electrode positions. Previous studies have accounted for deviating electrode positions only by visually assessing the cable straightness from the boat during the measurements (cf. Overduin et al., 2012, 2016; Angelopoulos et al., 2019).”

Angelopoulos, M.: Mapping subsea permafrost with electrical resistivity surveys, Nature Reviews Earth & Environment, 3, 6–6, https://doi.org/10.1038/s43017-021-00258-5, 2022.

Overduin, P. P., Westermann, S., Yoshikawa, K., Haberlau, T., Romanovsky, V., and Wetterich, S.: Geoelectric observations of the degradation of nearshore submarine permafrost at Barrow (Alaskan Beaufort Sea), J. Geophys. Res.-Earth, 117, https://doi.org/10.1029/2011jf002088, 2012.

Overduin, P. P., Wetterich, S., Günther, F., Grigoriev, M. N., Grosse, G., Schirrmeister, L., Hubberten, H.-W., and Makarov, A.: Coastal dynamics and submarine permafrost in shallow water of the central Laptev Sea, East Siberia, Cryosphere, 10, 1449–1462, https://doi.org/10.5194/tc-10-1449-2016, 2016.

Angelopoulos, M., Westermann, S., Overduin, P., Faguet, A., Olenchenko, V., Grosse, G., and Grigoriev, M. N.: Heat and salt flow in subsea permafrost modeled with CryoGRID2, J. Geophys. Res.-Earth, 124, 920–937, https://doi.org/10.1029/2018jf004823, 2019.

I also have a few minor comments:

1. I think it is more important to present at what depth the IBPT is located, not only under the water surface, but also under the seabed.
   See comment on lines 9-11.

2. It seems to me necessary to present and comment on many more profiles analogous to the one shown in Fig. 4. The reader should be able to compare. It doesn't have to be an extensive description.
   (see next answer)

3. It would be very interesting for substantive and methodological reasons to see several ERT profiles with DOI isolines shown on its interpretation.
   The paper becomes excessively long if we include all ERT profiles and descriptions in the text. We have chosen to synthesize results in a map form. To address this concern, however, we have added a supplement to the paper showing the other ERT profiles and their evaluation.

4. I think it would be very interesting to speak about the active layer that usually accompanies the occurrence of permafrost. This is a relatively difficult issue and there are few publications in this field, but that is why it is worth mentioning at least briefly on this occasion.
   Thanks for this suggestion. The terrestrial active layer (AL) is a well-known and crucial characteristic of permafrost on land, since most ecological, hydrological, biochemical, and pedogenic processes occur within it. The classical definition of the AL is "a layer of ground that undergoes annual thawing and freezing in areas underlain by permafrost" (ACGR, 1988; van Everdingen, 1998). This layer shows significant seasonal temperature variability, with its thickness ranging from a few centimeters to over 20 meters depending on environmental conditions. In glacial environments, the AL may contain liquid water or be entirely absent. Dobiński (2020) suggests a broader definition, proposing that the AL, like permafrost, should be defined based on its thermal state rather than phase transition.
   In submarine environments, the use of AL was extended to include sediments beneath the seabed, such as in the Beaufort Sea. It undergoes seasonal thawing and freezing influenced by overlying sea ice. One key study of the characteristics of the AL and shallow subsea permafrost was undertaken by Osterkamp et al. (1989) near Prudhoe Bay, Alaska. This study involved field and laboratory investigations, including drilling, sampling, and temperature measurements, along a line extending from the North Prudhoe State #1 well. Soil samples from the top 2 meters of sediments were analyzed to understand salt and water (re)distribution and its impact on permafrost. Brine infiltration and salt redistribution significantly impact the timing and extent of freezing and thawing processes, making the AL crucial for the stability and evolution of subsea permafrost.

   Since our focus is the submarine permafrost environment, we have added one sentence in the introduction:
   "The seasonal presence of cryotic and/or frozen sediment at the seabed can be

considered an active layer and has been observed in the Beaufort Sea near Prudhoe Bay, Alaska (Osterkamp et al., 1989)."

ACGR (Associate Committee on Geotechnical Research): Glossary of permafrost and related ground ice terms, Permafrost Subcommittee National Research Council of Canada, Technical Memorandum 142, 1988.

Van Everdingen, R. O.: Multi-Language Glossary of Permafrost and Related Ground-Ice Terms in Chinese, English, French, German, Icelandic, Italian, Norwegian, Polish, Romanian, Russian, Spanish, and Swedish, International Permafrost Association, Terminology Working Group, 1998.

Dobinski, W.: Permafrost, Earth-Science Reviews, 108, 158–169, https://doi.org/10.1016/j.earscirev.2011.06.007, 2011.

Osterkamp, T., Baker, G., Harrison, W., and Matava, T.: Characteristics of the active layer and shallow subsea permafrost, J. Geophys. Res-Oceans, 94, 16 227–16 236, https://doi.org/10.1029/JC094iC11p16227, 1989.

As I mentioned, the text also contains comments and some (not all) highlights that are the result of quite significant controversies. I hope they will be helpful in improving this interesting work.

Line 3: how do you know this? if science is an activity that provides certainty based on evidence, then it has no right to express an opinion about the future
The statement is based on Whalen et al. (2022) who extrapolated shoreline retreat based on the accelerated retreat rates since the year 2000 at 284 transects along the Island. For formatting reasons, we cannot add a reference to the abstract, but have added it at the appropriate location in the introduction.

Whalen, D., Forbes, D. L., Kostylev, V., Lim, M., Fraser, P., Nedimovíc, M. R., and Stuckey, S.: Mechanisms, volumetric assessment, and prognosis for rapid coastal erosion of Tuktoyaktuk Island, an important natural barrier for the harbour and community, Can. J. Earth Sci., https://doi.org/10.1139/cjes-2021-0101, 2022.

Lines 9-11: it is worth giving the value below the seabed (e.g. in brackets)
The degradation starts with inundation, i.e. the change in permafrost table depth is not from the seabed, but from sea level at the time of inundation. At this particular point in time sea level and sea bed can be regarded as level. For this environment, subsidence (from subsea permafrost thawing) and seafloor erosion are contributing to increasing water depths further offshore. Post-glacial sea level rise is not so important for the inundation time periods we deal with here. Therefore, the depth of the IBPT in m below sea level gives a better estimate of the actual vertical permafrost degradation.

Line 17: this sentence is obvious and does not need references, but if there are - it doesn't matter

We would prefer to keep the reference.

Line 35: here it is necessary to specify what is actually being examined in the paper, and what their purpose is. Permafrost, according to the current definition, which must be used as the starting point, is something different than IBP

Good point. We aim to resolve the ice-bearing permafrost table, which can be below the 0 °C isotherm under saline conditions. ERT is sensitive to phase changes, i.e. to the IBPT, which is also the more relevant boundary in terms of coastal stability.

We added the following for clarification: "We refer to the ice-bearing permafrost table (IBPT) as the boundary between unfrozen and frozen sediment. Especially in saline environments, it is not necessarily concordant with the 0 °C isotherm, due to a lower freezing point. However, the IBPT as a physical boundary is a more useful target parameter in the context of subsea permafrost degradation coastal stability."

Line 39: as above

See reply above.

Lines 46-47: ERT both on dry land and underwater can be used to detect frozen, ice-rich sediments. This is not the same as what we call permafrost. It is necessary to discuss here the relationship between: permafrost, IBP, or correctly ice-rich sediments, and cryotic ground.

We agree, and have improved our definitions of terms (see reply above).

Line 52: If you treat IBP (sediments) interchangeably with the permafrost, which is incorrect, then the term melting, not thawing, is valid for its degradation, even though this issue has been discussed and resolved already.

We do not regard IBP and permafrost as interchangeable, as now clarified in the introduction. We agree that it is important to be precise in terminology - permafrost in this case is the bulk mix of sediment, ice, porewater, etc, which cannot be said to melt, only the ice within it. We have changed terminology to "The objective of this study is to better understand how coastal retreat and permafrost degradation have shaped subsea permafrost around Tuktoyaktuk Island based on…"

Line 68: What is it GSC? Geological Survey of Canada? If so, needs explanation when first time used. Please check other abbreviations used in the text accordingly

We added "Geophysical Survey of Canada" (GSC) with the first mention. We checked and corrected, where necessary, the other abbreviations.

Line 72-73: as above. What is the scientific significance of this information?

As above: The statement is based on Whalen et al. (2022) who extrapolated shoreline retreat based on the accelerated retreat rate since the year 2000 at 284 transects along the Island.

Whalen, D., Forbes, D. L., Kostylev, V., Lim, M., Fraser, P., Nedimovíc, M. R., and Stuckey, S.: Mechanisms, volumetric assessment, and prognosis for rapid coastal erosion of

Tuktoyaktuk Island, an important natural barrier for the harbour and community, Can. J. Earth Sci., https://doi.org/10.1139/cjes-2021-0101, 2022.

Lines 87-88: what is the accuracy of your measurements? in the discussion you provide the results with an accuracy of centimeters. On what basis?
The accuracy of the spacing between soundings is dependent on the accuracy of the GPS employed, which is given by the manufacturer at <3m (95%). As the measurements were taken in a regular manner on a straight boat path, and the coordinates also show straight paths and regular distances between soundings, the (relative) accuracy is probably much higher. The cm values in the discussion are not representing the accuracy of the measurements but only a means for comparison of the performance of the inversion of the synthetic data.

Line 102: it is necessary to justify why the top of the permafrost is identified with IBPT. Generally it is not correct with permafrost definition. If this is due to the limitations of the ERT method used, this also needs to be emphasized and clarified.
We agree, and have improved our definitions of terms (see replies above).

Lines 131-132: ok, but how does this relate to the definition of permafrost and cryotic state?
We expect the transition from unfrozen to frozen sediment to be quite abrupt. However, only the layered inversion type returns a defined layer boundary. In the smooth, blocky and sharp inversion the boundary needs to be inferred from the continuous resistivity distribution. Therefore, we compared three approaches.

Line 145: only dates should be in brackets, not authors names
Corrected.

Line 150: If the purpose of the chapter is to show research results, it is best to start it there. Writing about the methodology at the beginning suggests that the results are not interesting or questionable.
Good point. We have changed the order as suggested in the general comments at the top.

Line 152: why you write about uncertainty at the very beginning of this important chapter, it immediately makes the reader careful and critical. Better to leave it for last
Adopted (see above).

Line 167: as above.
Adopted (see above).

Lines 195 + 198: how this accuracy compares to the accuracy of field measurements (see above). Are you sure this accuracy reaches centimeters or is it just a computer calculation?
This is a good point and requires clarification. We have added to the description of the method:
"RMS values for this offset are given in units of meters. Although centimeter scale values for this derived value are retained for comparison between profiles, this does not imply centimeter-scale accuracy in IBPT depths estimates."

Line 207: the amount of freezing, frozen material, may increase with depth. The permafrost boundary does not have to be sharp (table)
This is a good point. If the sediment prior to inundation is salt-free and not particularly coarse (e.g., silts, fine sands), then diffusion becomes the dominant mode of salt transport. Heat diffusion is faster than salt diffusion, which means that salt unlikely overtakes the 0 degree isotherm. In this case, the talik/IBP boundary is likely to be "abrupt."

We have added to the discussion "The sharpness of the transition from ice-free sediment to IBP over depth is unlikely to be the same everywhere. Certain sediment and porewater conditions facilitate a gradual transition: 1) clayey permafrost with high unfrozen water content, 2) a pre-existing cryopeg prior to inundation, 3) any environment in which salt keeps pace with heat diffusion, i.e., a subsea setting with significant convection. In any case, a long inundation period is generally required for a gradual transition to develop, and is unlikely in such a coastal setting. The two borehole logs showed a sharp transition on the sub-centimeter spatial scale (Dallimore et al., 2018)."

Dallimore, S., Fraser, P., Whalen, D., and Magen, C.: Field Report – Tuktoyaktuk Island – Permafrost Drilling Program, Tech. rep., Geol. Surv. of Can., 2018.

Line 211: What is interesting is not the BSL but how much is below the seabed. (In all results).
See reply above (comment on lines 9-11).

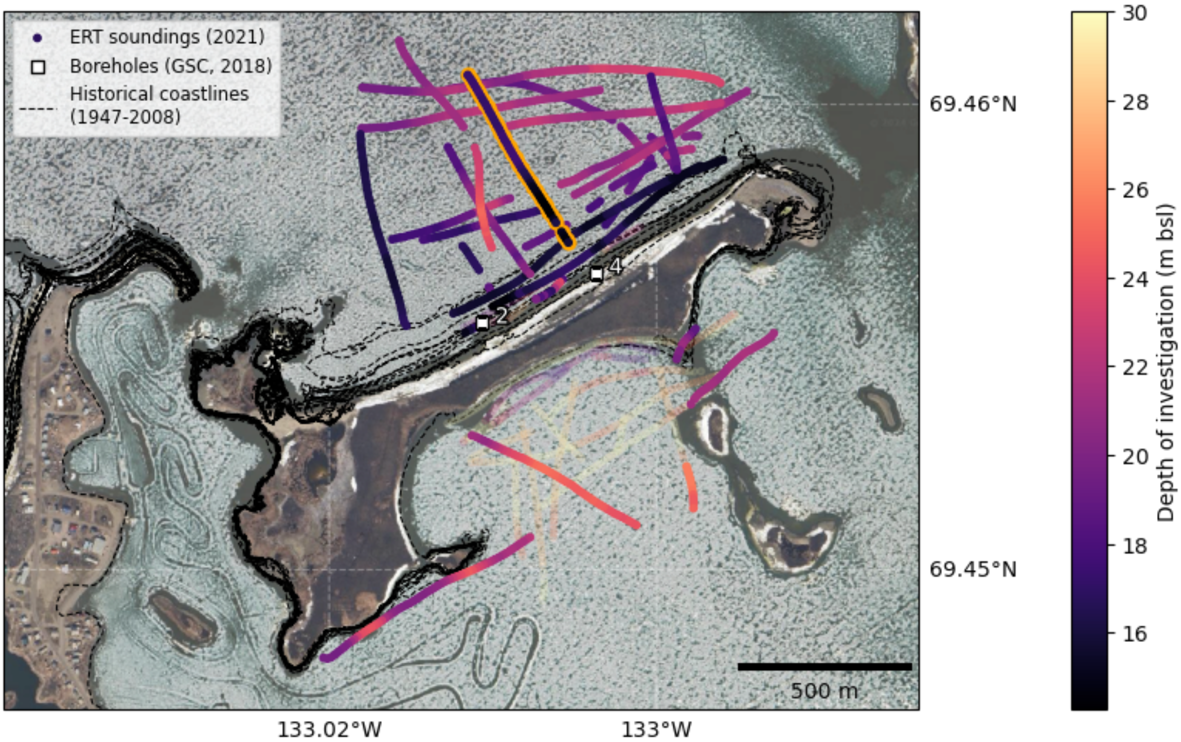
Line 218: nevertheless, it is necessary to show the reader more profiles in the form of figures for comparison
Yes, we agree (see answer to minor comments 2 and 3 above).

Lines 269-270: to my knowledge, the transition from unfrozen to frozen material can also be blurred, in the form of a zone. This complicates marking this boundary with ERT
Yes, the transition can potentially also be blurred under certain conditions - see reply above, line 207.

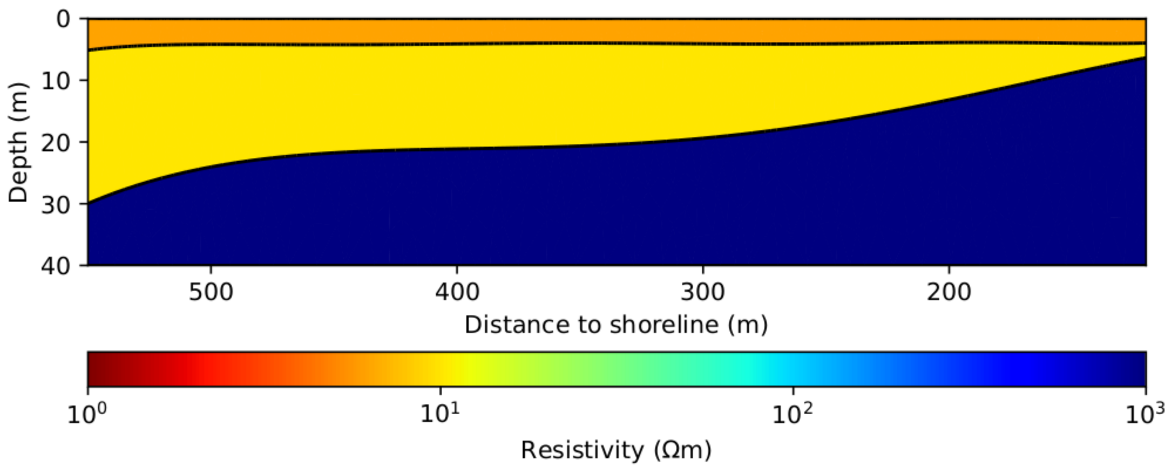
Line 333: No, this is not correct. It is possible exclusively by using thermometer.
We changed 'we were able to determine' to 'we were able to estimate'.

Line 337: Or rather IBPT? this is not the same
Adopted.

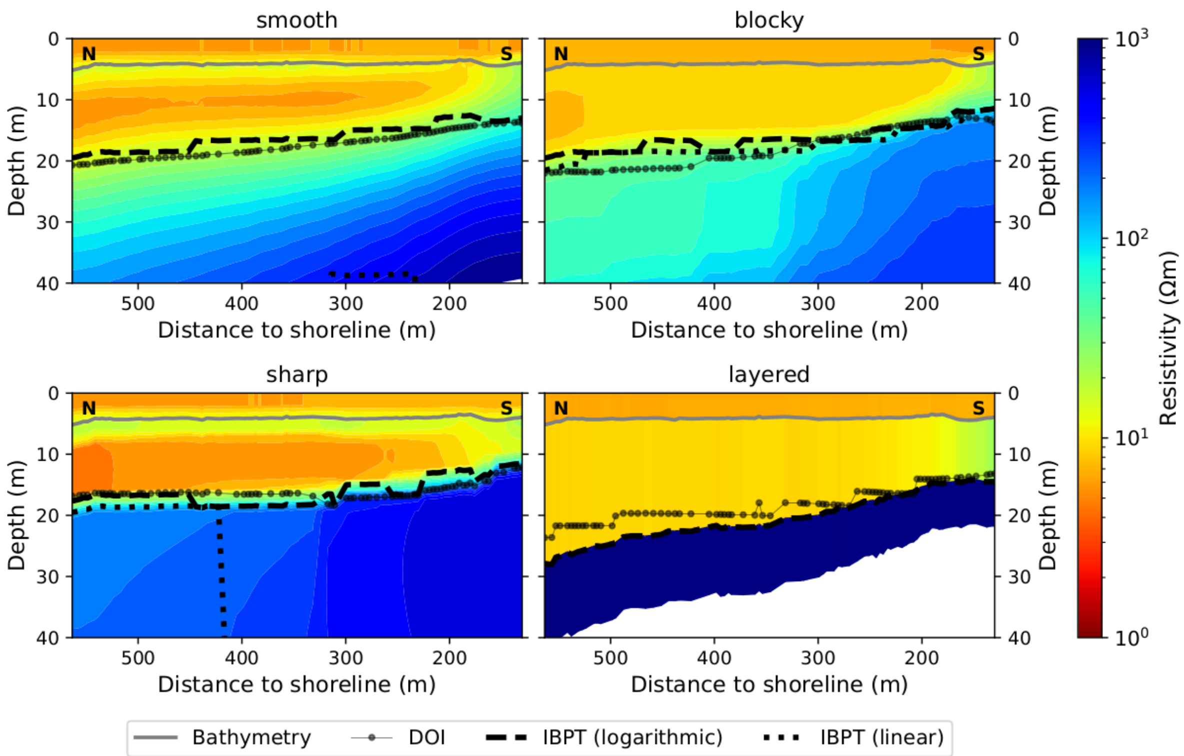
Supplement



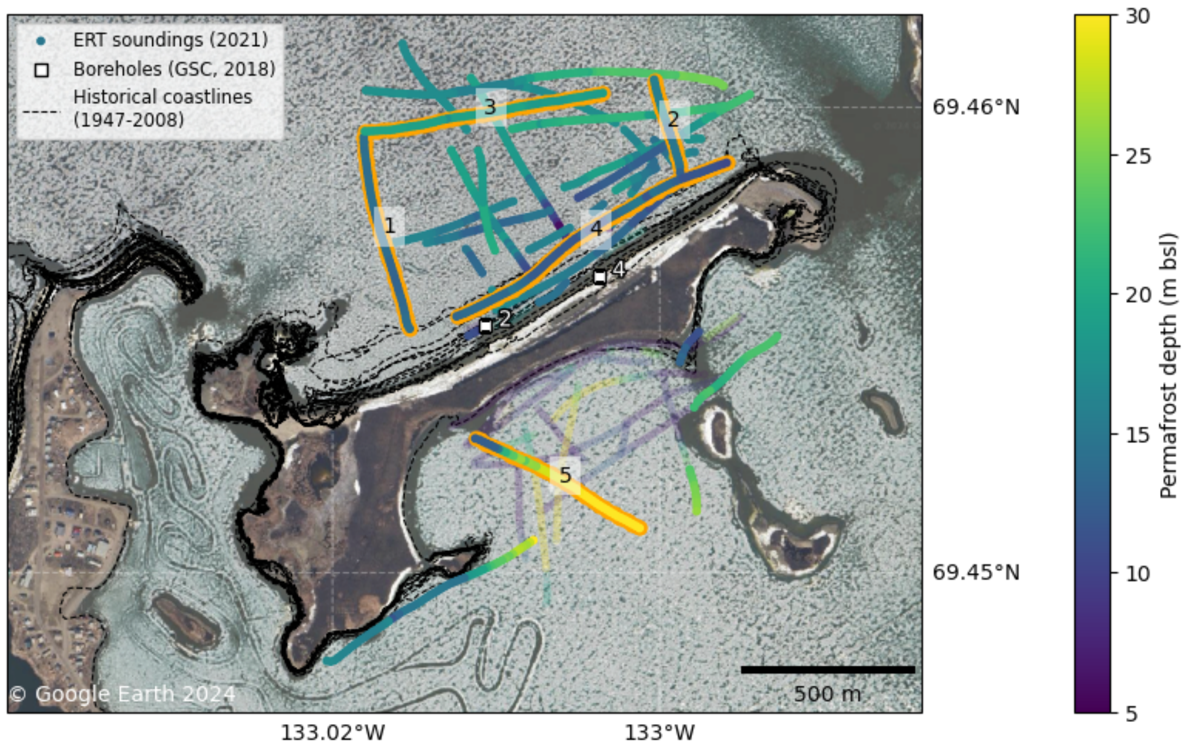
Supplement Figure 1: This figure shows a map of the ERT surveys conducted around Tuktoyaktuk Island (analogous to Fig. 5a). The survey lines are color-coded with the Depth of Investigation (DOI) in meters below sea level (m bsl). The DOI ranges from around 15 to almost 30 m bsl.



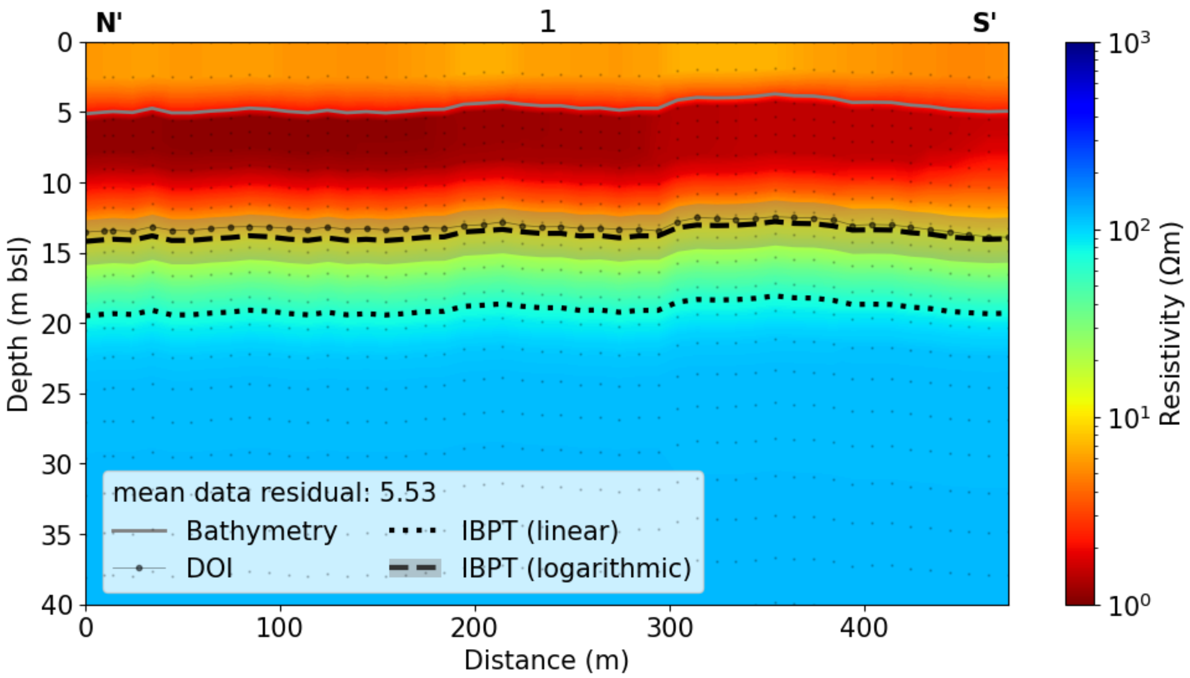
Supplement Figure 2: Synthetic model used to infer the most suited inversion technique for the specific setting. The model consists of 3 layers: The upper layer is representing the water body with a depth of 5 m and a resistivity of 6.1 Ohm m. The second and third layer have resistivities of 10 Ohm m and 1000 Ohm m, representing unfrozen and frozen sediment *respectively. The boundary between the two ranges between depths of 7 to 30 m and dips at varying angles, which is a plausible scenario for the IBPT in a profile perpendicular to the shoreline of Tuktoyaktuk Island.*



Supplement Figure 3: Comparison between the smooth, blocky, sharp and layered inversions of the synthetic model. The models show different transitions between the second and the third layer (unfrozen and frozen sediment in Supplement Fig. 2). The inferred IBPT as the highest vertical resistivity gradient in logarithmic space is close to the DOI in all four models. In the blocky model, the inferred IBPT is closest to the actual boundary in the synthetic model.

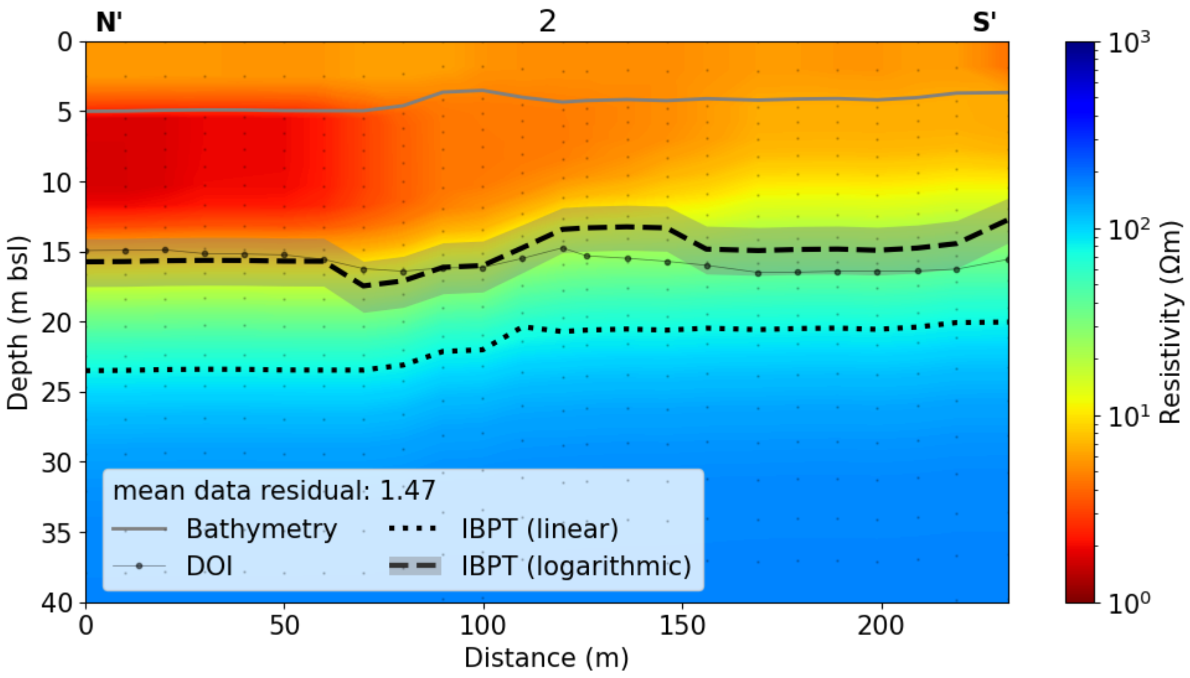


Supplement Figure 4: Overview map for supplemental profiles. The map shows all surveys conducted around Tuktoyaktuk Island and the inferred IBPT depth (as in Fig 5a). 5 profiles are highlighted that will be shown in the following.

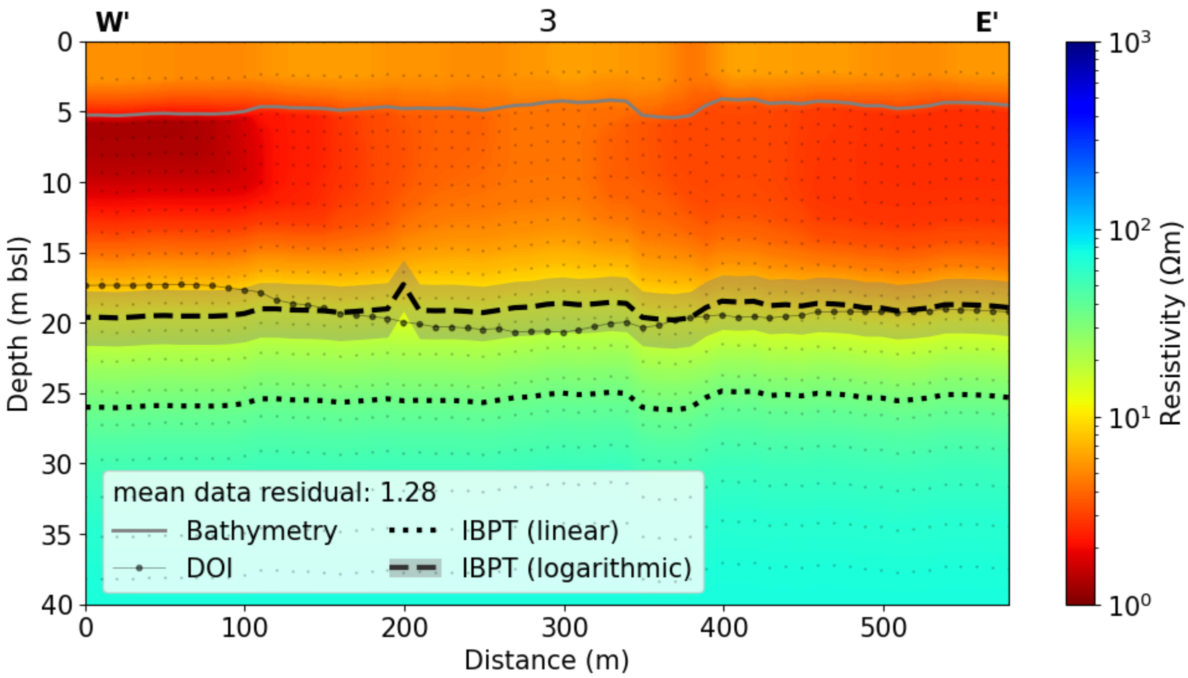


Supplement Figure 5: Inverted model of supplemental profile 1. The profile lies perpendicular to the northern shoreline and extends from North (offshore) to South (closer to the coast).

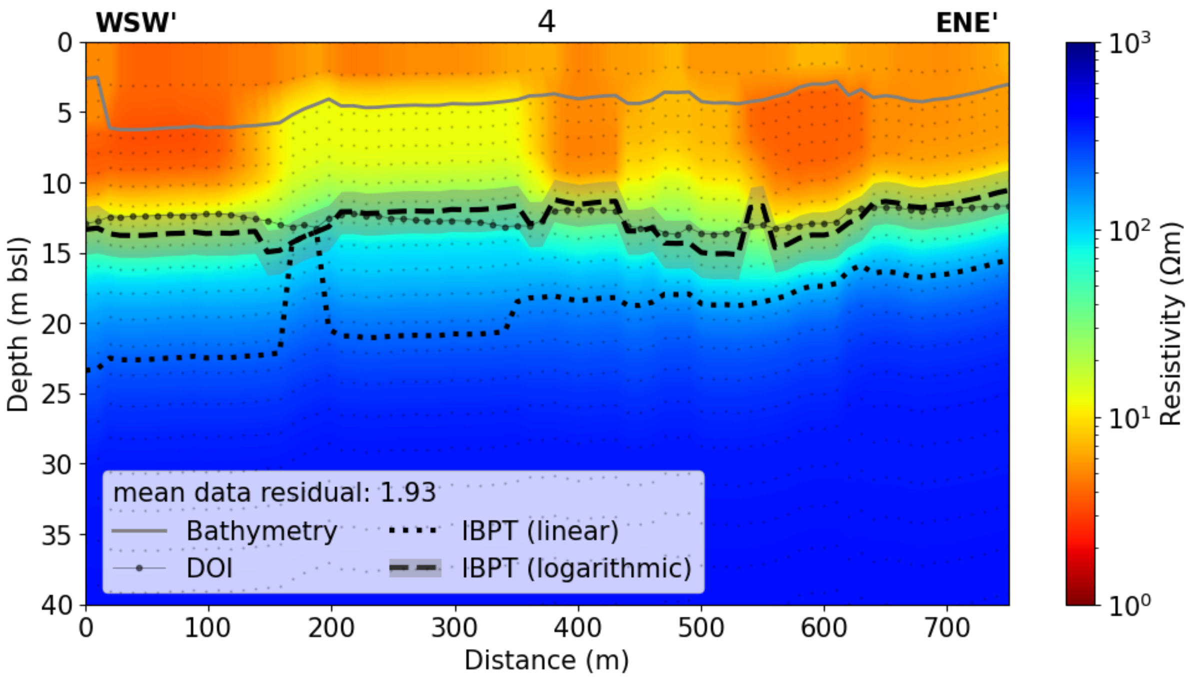
The water depth is around 5 m and the IBPT is inferred at around 14 m bsl, close to the DOI. Although the profile extends in North-South direction, and a dipping of the IBPT due to different inundation times along the profile is expected, the IBPT appears flat. However the fit of this inversion is rather poor, so the IBPT displayed here can be questioned.



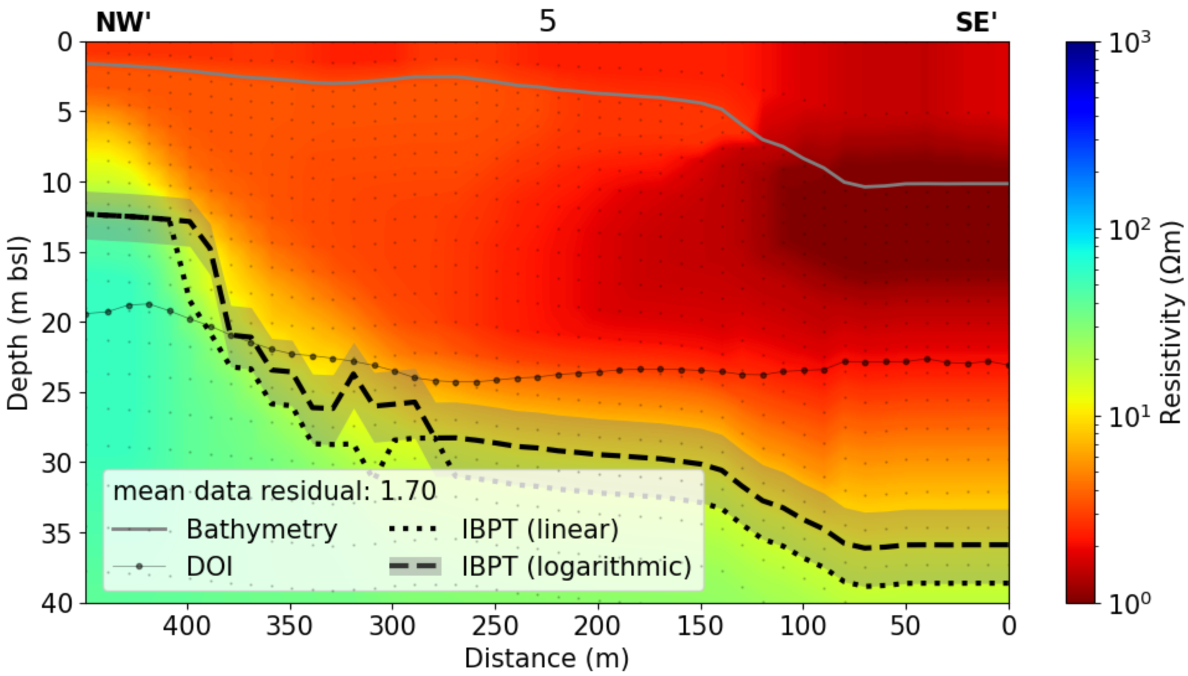
Supplement Figure 6: Inverted model of supplemental profile 2. The profile lies perpendicular to the northern shoreline and extends from North (offshore) to South (closer to the coast). The water depth is around 4 to 5 m and the IBPT is inferred at around 13 to 17 m bsl, close to the DOI. The dipping of the IBPT from South to North is not as pronounced as for the profile shown in Fig. 4 in the paper.



Supplement Figure 7: Inverted model of supplemental profile 3. The profile lies parallel to the northern shoreline and extends from West to East at around 500 to 700 m from the coast. The water depth is around 5 m and the IBPT is flat at around 20 m bsl, close to the DOI. Compared to profile 4 Supplement Fig. 8, the IBPT is more than 5 m deeper as profile 3 lies further offshore.



Supplement Figure 8: Inverted model of supplemental profile 4. The profile lies parallel to the northern shoreline and extends from (West-North-) West to (East-North-) East at around 150 *m from the shore. The water depth is varying between 3 and 7 m and the IBPT is inferred between 12 and 16 m bsl, close to the DOI. Changes in Bathymetry and IBPT may appear more abrupt in comparison to the other profiles, as this is the longest profile and thus more compressed. The IBPT is shallower than in profile 3, as it lies closer towards the shore.*



Supplement Figure 9: Inverted model of supplemental profile 5. The profile lies south of Tuktoyaktuk Island and extends from North-West (close to the coast) to South-East (towards the Harbor basin). The water depth ranges from 2 m close to the coast to around 10 m. The IBPT ranges from 12 m bsl close to the coast to around 35 m bsl where the water is deeper. A significant stretch of the IBPT lies several meters below the DOI, where the sensitivity is very low and the IBPT depth should be treated with caution. However we expect a deeper IBPT south of Tuktoyaktuk Island due to deeper water and slower coastal retreat rates that imply longer inundation times at similar distances from the coast and thus a longer period of subsea permafrost degradation.