

Response to Reviewer 1

Seismic Evidence for Increasing Unfrozen Pore Water

Heterogeneity from Roadside to Coastal Arctic Tundra

Dear Reviewer,

Thank you for the careful and constructive review of our manuscript. We really appreciate your suggestions for improving the manuscript, and we have revised the manuscript accordingly. Below, we respond to each comment and summarize the corresponding changes.

1. Introduction

The Introduction does not sufficiently cover previous studies of unfrozen water and the different factors influencing its variation, including not only temperature but also sediment characteristics. Previous laboratory and field studies on unfrozen water content should be included to better highlight the importance of the present work and provide readers with a clearer overview of the state of the art. This would also help clarify the different factors controlling unfrozen water content.

*Factors other than temperature are discussed later in the Results and Discussion (for example, Section 3.4, lines 241–242, and Section 4.3), but it would be beneficial to introduce these factors earlier ... I would recommend considering, for example: Chuvilin, E., Sokolova, N., & Bukhanov, B. (2022). Changes in unfrozen water contents in warming permafrost soils. *Geosciences*, 12(6), 253.*

Response: We agree and have expanded the Introduction to introduce these controls earlier and with stronger literature support, including the suggested reference. The Introduction now discusses the dependence of unfrozen water content on specific surface area, grain size, and mineralogy (Anderson and Tice, 1972), as well as the effects of salinity and organic matter, and that salinity and organic (peat) content can substantially modify unfrozen water content, citing Chuvilin et al. (2022), Waseem et al. (2025), and Aleksyutina and Motenko (2016). We also added a field example directly relevant to our study area: cryopeg brines documented within permafrost near Utqiagvik remain liquid at temperatures well below 0°C because of solute-induced freezing-point depression, demonstrating directly that temperature alone does not fully determine phase partitioning (Iwahana et al., 2021).

Manuscript changes: New sentences added to paragraphs 1 and 2 of the Introduction, citing Anderson and Tice (1972), Chuvilin et al. (2022), Waseem et al. (2025), Aleksyutina and Motenko (2016), and Iwahana et al. (2021).

2. Study goal and motivation

The Introduction lacks a clear definition of the goal of the study, and the overall motivation is not fully developed ... Why exactly do we need to determine unfrozen water content? Why is knowledge of unfrozen water content important?

Response: We have added an explicit motivation paragraph explaining that unfrozen water content controls the mechanical strength, creep behavior, and hydraulic and thermal conductivity of permafrost, so that its increase with warming influences mechanical stability and heat/water transport and thereby contributes to processes associated with the subsidence, infrastructure vulnerability, and carbon mobilization mentioned earlier in the Introduction (citing Wang et al., 2025, and Gou et al., 2026, both of which concern the same field area and, in the case of Gou et al., 2026, the same road embankment as our Roadside site). We also clarify why temperature alone is insufficient: two locations at the same temperature can differ substantially in strength and thaw susceptibility depending on how much of their pore water remains unfrozen, which is why characterizing unfrozen water content itself, rather than ground temperature alone, is important for assessing spatial variations in permafrost mechanical stability, thaw susceptibility, and transport properties relevant to these impacts. In addition, we added an explicit goal statement at the opening of the final Introduction paragraph: “The goal of this study is to test whether seismically inferred unfrozen water content departs from a temperature- and laboratory-based reference in a spatially organized way along a transect extending from disturbed roadside to undisturbed coastal tundra.”

Manuscript changes: New paragraph added before the paragraph introducing geophysical methods; new opening sentence added to the final paragraph of the Introduction stating the study goal explicitly.

3. Methods

Instrument information, including the equipment name/model, precision, measurement limitations, and particularly any limitations associated with measurements in cold regions, should be provided in Section 2.2. There is methodological information currently presented in other sections ... It would be beneficial to review the manuscript and move the relevant methodological information into the Methods section.

Response: We added a new paragraph to Section 2.2 describing the DAS interrogator (Terra15; channel spacing, gauge length, sampling rate) and the geophone system (Geometrics Geode, 22 vertical-component 4.5 Hz geophones; spacing, sample interval, record length, triggering). We also addressed measurement limitations: geophone-ground coupling depends on spike penetration and local soil firmness, which can vary across the hummocky, locally water-saturated tundra surface (Krohn, 1984); general operational challenges of fiber-optic DAS in Arctic environments (cable coupling variability, noise sources, seasonal accessibility) have been documented in comparable tundra and glacier deployments elsewhere (Gajek et al., 2026). We also note that, as with all MASW surveys, the maximum resolvable

depth is fundamentally limited by receiver array length and the source's low-frequency content (Park et al., 1999), which we later quantify per site and sensor using sensitivity kernels (Sect. 3.2).

Because both surveys were conducted during the summer season, instrument performance under extreme low-temperature conditions was not a primary limitation for these measurements. We therefore focus on the acquisition and ground-coupling limitations most relevant to our surveys.

We also expanded the discussion of the maximum resolvable depth in Section 2.2. Because the 40 m depth used in the Neighborhood Algorithm inversion reflects the parameterization of the search rather than a depth directly constrained by the data, we added a paragraph quantifying, for each site and sensor, the depth range independently constrained by the observed dispersion curve, using the Rayleigh-wave phase-velocity sensitivity kernels already reported in the Supplement (Figure S8, Table S8). We define this sensitivity-based depth limit as the depth at which the frequency-integrated sensitivity falls to 10% of its maximum value, and use the resulting site-specific limits (and a common conservative 0–20 m interval for direct DAS–geophone comparisons) throughout the interpretation of anomaly depth extent in Sections 3 and 4.

Manuscript changes: New paragraph added to Section 2.2 (equipment specifications and limitations); new paragraph added to Section 2.2 quantifying sensitivity-kernel-based depth resolution per site and sensor, referenced throughout the interpretation in Sections 3–4.

The site description in Section 2.1 contains information about the geophysical methodology but does not provide enough information about the sites themselves. It would be valuable to include sediment composition based on core data from previous research ... Information on ice content would also be useful ... What are the road conditions and road material? Is the road elevated? Is there ponded water near the measurement locations? Are there other site characteristics that may be important for interpreting unfrozen water content?

Response: We added a new paragraph to Section 2.1 describing sediment composition and ice content at each site, drawing on permafrost cores collected at the same five locations (boreholes S1–S5, corresponding to Roadside and Tundra 1–4, respectively; Wang et al., 2025). These cores show a general downward transition from organic-rich peat and clayey or sandy silt near the surface to ice-rich silty sand at depth, with the Roadside core comparatively ice-poor and the tundra cores, particularly Tundra 2 through Tundra 4, containing thicker ice-rich intervals. We also specify that the Roadside site lies along a gravel embankment road adjacent to the NOAA facility (Tourei et al., 2024; Gou et al., 2026). The general presence of ponded and lake-covered surfaces along the coastal part of the transect was already noted in Section 2.1 (polygonal ground, ice-wedge networks, ponded or wet areas, and thermokarst lakes); we did not add site-specific claims about ponded water at individual measurement locations, since we do not have precise positional data to support such a claim.

Manuscript changes: New paragraph added to Section 2.1 (sediment composition, ice content, and road characteristics per site).

Figure 1a: It would be useful to include higher-resolution satellite imagery for each study site to show local landscape variations.

Response: Higher-resolution imagery and local acquisition geometry for each of the five sites are provided in Figure S1. We have now added a sentence to the Figure 1 caption directing readers explicitly to Figure S1.

Figure 1b: From which borehole was this temperature profile obtained? Please identify and mark the borehole on the map.

Response: The borehole (B1) is now labeled on the map in Figure 1a and identified in the Figure 1 caption.

Figure 1c: Are any of the water-content measurements associated with the boreholes shown in Figure 1a? ... please include the borehole names/numbers on the map and corresponding labels on the graph ...

Response: The permafrost coring boreholes are now labeled S1–S5 on the map in Figure 1a, and the sample codes already shown in the Figure 1c legend (e.g., S3-5, S4-2) follow the same S{borehole}-{sample} naming convention, so each curve can now be traced back to its borehole location on the map.

Figures 1d and 1e: Are these examples from a specific study site? If so, please indicate which site they represent.

Response: Both panels are from the Roadside site; this is now indicated in the figure and stated explicitly in the caption.

In Section 2.2, it would be beneficial to clearly describe which sites were investigated in each year.

Response: We clarified in the opening sentence of Section 2.2 that both surveys were acquired at all five sites: the geophone survey in August 2022 and the DAS survey in August 2024.

Figure 2: Please increase the size of all text in the figure ...

Response: We regenerated Figure 2 with larger axis labels, legends, and tick numbers throughout.

Figures 2a, 2c, and 2g: Are these examples from a specific site?

Response: Panels (a)–(e) and (g) are from the Roadside site; panel (f) shows the load-bearing rock-physics relationship, which is generic and applied uniformly across all sites. This is now labeled in the figure and stated in the caption.

4. Conclusions

Lines 335–337: The influence of salinity and sediment characteristics on unfrozen water content has been well studied experimentally. However, ... a direct and unique relationship between V_s and S_w cannot be established without accounting for other sediment properties and state variables. I suggest revising this statement to more clearly distinguish what is already established experimentally from what remains unresolved ...

Response: We agree that the original phrasing could be read as implying that the influence of these controls on unfrozen water content was unresolved, when it is well established experimentally. We revised the closing of the Conclusions to separate the two issues explicitly: salinity, organic matter content, sediment properties, hydrology, cryostructure, and degradation-related changes are stated as established experimentally as controls on unfrozen water content (citing Chuvilin et al., 2022, and Wang et al., 2025), while what remains unresolved is (i) their relative contributions at this specific site, and (ii) more fundamentally, that because V_s responds simultaneously to porosity, ice–water partitioning, salinity, sediment texture, and organic content, no unique mapping from V_s to S_w exists without assuming values for the other properties.

Manuscript changes: Closing paragraph of the Conclusions revised.

5. Organic matter

There is no discussion of the potential influence of organic matter on unfrozen water content, although organic-rich sediments are also present in Utqiaġvik ...

Response: We agree this was a gap and added a new paragraph to Section 4.3 (following the paragraph on salinity and other controls). Controlled laboratory experiments on silt-clay soils with varying peat content but similar grain size, mineralogy, and salinity show that unfrozen water content at a given subzero temperature can increase substantially with organic matter content (Chuvilin et al., 2022); increasing water retention with peatification has also been documented experimentally (Motenko et al., 2024) and characterized directly in organic turfy soils using nuclear magnetic resonance (He et al., 2023). We note explicitly that the specific influence of organic matter was not explored quantitatively in the construction of our reference, and that isolating its contribution from the other controls discussed would require dedicated core-based measurements of organic content and unfrozen water content at each site.

Manuscript changes: New paragraph added to Section 4.3.

We thank the reviewer again for these suggestions. The limitations and scope are much clearer now, and the comments have strengthened the physical motivation of the work. We appreciate the time and effort of the reviewer to provide such constructive comments.

Sincerely,

Guilherme Zakarewicz

On behalf of all co-authors.