Response to RC2 Comments for

Placing constraints on submarine permafrost extent along the U.S. Beaufort Shelf using thermodynamic modeling

Ms. No: EGUSPHERE-2025-5529

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RC2: This study integrates numerical modeling with geophysical data to constrain the distribution of subsea permafrost along the U.S. Beaufort Shelf. The work provides valuable insights into the spatial distribution of subsea permafrost and the factors controlling it. I recommend that the authors address the following comments prior to publication

Author Response: We thank Dr. You for the thoughtful review of our manuscript and for recognizing the value of integrating thermodynamic modeling with geophysical observations to investigate submarine permafrost distribution along the U.S. Beaufort Shelf. We appreciate the constructive feedback and have carefully considered each comment. Below, we provide detailed responses and outline how the manuscript will be revised accordingly.

Reviewer Comment: Figure 3: The detailed bathymetry plot is not necessary. What are the numbers along the cable path?

Author Response: We will reconsider the presentation of the detailed bathymetry panel in Figure 3 and evaluate whether it can be simplified or removed to improve figure clarity. The numbers shown along the cable path represent distance markers along the fiber optic cable transect. We will clarify this more explicitly within the figure caption and labeling in the revised manuscript.

Reviewer Comment: Table 1: Should wet thermal conductivity be treated as a function of porosity? Is a constant value assumed across all depths? In addition, since bulk thermal conductivity is a key parameter, I recommend that the authors clearly describe the thermal conductivity model used in the manuscript.

Author Response: We appreciate this constructive comment and agree that the treatment of thermal conductivity should be described more clearly. In the simulations, dry thermal conductivity values are prescribed for each lithology, while effective bulk thermal conductivity is calculated internally within PFLOTRAN HYDRATE mode as a function of porosity and phase saturations. In the revised manuscript, we will expand this section to more clearly describe the thermal conductivity formulation and the assumptions associated with its implementation.

Reviewer Comment: Please add references for Archie constants for sand-rich and clay-rich sediments. Does the choice of Archie constant consider the effects of local elevated salinity?

Author Response: The Archie constant values used for the sand-rich and clay-rich intervals were taken from King et al. (1988), which reported representative values based on laboratory resistivity measurements of frozen sediments. In the revised manuscript, we will provide the explicit reference for these parameter choices.

The Archie constant itself was not varied as a function of salinity. Following King et al. (1988), the effects of elevated salinity are instead reflected through changes in pore-water resistivity associated with salt exclusion during freezing and increased electrolyte concentration in the remaining unfrozen water. We will clarify this distinction more explicitly in the revised manuscript.

Reviewer Comment: “Each model was initialized with a pressure of 0.5 MPa and a temperature of 1◦C”: This is not clear? Are pressure and temperature assumed to be uniform throughout the entire domain, or do these values correspond specifically to seafloor conditions?

Author Response: The initial conditions of 0.5 MPa and 1C were applied uniformly throughout the entire model domain and were intended only as numerical initialization conditions at the start of the simulation. Following initialization, the imposed boundary conditions rapidly establish physically realistic hydrostatic pressure and thermal gradients throughout the domain. This brief transient adjustment period is non-consequential to the final simulation results. In the revised manuscript, we will clarify this initialization procedure more explicitly.

Reviewer Comment: Line 210: temperature gradient should depend on geothermal heat flux.

Author Response: Based on this comment, we see that the relationship between the initialized temperature gradient and geothermal heat flux should be clarified. The prescribed geothermal heat flux boundary condition ultimately controls and determines the thermal gradient within the model domain, while the initialized temperature gradient simply provides a preliminary starting condition prior to equilibration. In the revised manuscript, we will revise this section to more clearly distinguish between the initialization conditions and the long-term thermally equilibrated state governed by the imposed heat flux.

Reviewer Comment: Boundary condition: Boundary condition for salinity is not clear. What is the value of salinity when the section is exposed to air and when it is submerged?

Author Response: Thanks for identifying this ambiguity. In the current simulations, salinity remains fixed according to the prescribed pore water scenario and is not varied dynamically between exposed and submerged conditions. We agree that the manuscript does not currently describe this assumption clearly enough. In the revised manuscript, we will clarify the treatment of salinity boundary conditions and revise the wording surrounding the transient boundary condition implementation to avoid implying that salinity evolves dynamically with sea level exposure.

Reviewer Comment: Figure 6: What are the water depths where those wells are located?

Author Response: This is a good question to raise. We will look into this and include in the revised manuscript.

Reviewer Comment: Section 2.5: Since this study does not simulate carbon, I suggest revising this section to focus solely on water and salt for clarity.

Author Response: We agree that the current presentation of Section 2.5 includes unnecessary complexity given the scope of this study. In the revised manuscript, we will streamline this section to focus specifically on the water, ice, and salt processes relevant to the simulations presented here.

Reviewer Comment: Line 246: please double check the symbol for phase pressure. What is the dimension of each symbol? The “γα” term in Equation 3 and its expression in Line 247 is quite confusing.

Author Response: I believe the symbol error you are noticing results from a font inconsistency. We will ensure this is cleaned up in the revised manuscript. We also agree the “γα” term is confusing – we will further clarify this as well.

Reviewer Comment: Please describe how you quantify the impact of salinity on freezing temperature?

Author Response: The impact of salinity on freezing temperature is handled internally within PFLOTRAN HYDRATE mode through the coupled thermodynamic relationships between the water, ice, and dissolved salt phases. Specifically, salinity modifies the liquidus/freezing temperature term (TL) used within the exponential freezing curve formulation (Eq. 5), which governs the partitioning of pore water into liquid water and ice saturation as a function of temperature. As dissolved salt concentration increases, the calculated freezing temperature decreases, requiring colder temperatures to produce equivalent ice saturation. If this is not a sufficient answer, we can expand even further.

Reviewer Comment: Lines 332-347: Please describe what caused the discontinuity in permafrost distribution?

Author Response: The discontinuities in submarine permafrost distribution arise from the combined effects of elevated pore water salinity, geothermal heat flux, and lithologic heterogeneity, which together suppress ice saturation in portions of the offshore domain. In the heterogeneous borehole models specifically, clay-rich intervals retain larger fractions of unfrozen water at subfreezing temperatures, contributing to localized reductions in ice saturation and discontinuous permafrost geometries. Your comment points out that we need to clarify these controlling mechanisms more explicitly in the revised manuscript.

Reviewer Comment: A geothermal heat flux of 80 mW/m2 is quite high value. Is there any other evidence for the presence of such high geothermal heat flux there?

Author Response: We acknowledge that 80 mW m^{-2} represents a pretty high geothermal heat flux for the region. This value was selected as an upper-bound end-member based on the reported regional average of 66 ± 14 mW m^{-2} from Deming et al. (1992), placing 80 mW m^{-2} within the upper range of measured values. While direct evidence for localized elevated heat flux beneath the study transect remains limited, the use of this higher-end scenario was intended to explore the thermodynamic sensitivity of submarine permafrost extent to plausible variations in basal heat flow. We will clarify this rationale more explicitly in the revised manuscript.

Reviewer Comment: Figure 11: It would be helpful to indicate the well locations in the plot.

Author Response: The boreholes used to construct the heterogeneous model domains are not located directly along the PEMDATS transect, and their spatial relationship to the cable path is already shown in Figure 6. Because Figure 11 presents thermodynamic simulations projected along the cable transect rather than at the borehole locations themselves, we cannot realistically add them.

Reviewer Comment: Figure 12: Which baseline resistivity curve is used in the calculations? The curve corresponding to a constant *n* is not shown in Figure 12. In addition, I suggest overlaying the modeled results with the measured resistivity to further evaluate the model's performance.

Author Response: The baseline resistivity calculation uses the constant n = 3 case, representing a homogeneous sand assumption, while the variable-n curve applies lithology-dependent Archie constants based on the assigned sand- and clay-rich intervals. We will clarify this more explicitly in the Figure 12 caption and associated text.

We also agree that comparison with measured resistivity would be useful. We will look into adding this in the revised version of the manuscript.

Reviewer Comment: Section 3.4 is not well connected with the modeling study. Can you compare the predicted subsurface temperature with the DTS measurements?

Author Response: A direct comparison between the modeled subsurface temperature profiles and DTS measurements is the focus of an ongoing companion study, so we will avoid presenting that full analysis here. However, in the revised manuscript, we will clarify the purpose of Section 3.4 as providing modeled thermal constraints that can support DTS calibration and interpretation, and we will revise the text to better connect these temperature profiles to the broader modeling objectives.