Comments on "Osmosis Drives Explosions and Methane Release in Siberian Permafrost" by Morgado et al. 2024

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Abstract

This commentary addresses the model proposed by Morgado et al. (2024) in their paper, "Osmosis Drives Explosions and Methane Release in Siberian Permafrost." The model explores the role of osmotic pressures in explaining the formation of gas escape craters in the Western Siberian permafrost. While it presents a novel perspective on permafrost dynamics under climate change, three significant challenges primarily related to thermodynamics and process rates are discussed. These include the need to consider freezing point depression due to salinity changes, and the kinetics of cryopeg expansion and hydrate dissociation. Addressing these factors could enhance the model's accuracy and applicability for understanding permafrost destabilization.

Plain Language Summary

This commentary evaluates a new model by Morgado et al. (2024), which explains how osmosis — the movement of water due to salt concentration differences — could cause explosions and methane release in Siberian permafrost. The model suggests that as freshwater enters salt-rich areas underground, pressure builds up, potentially leading to explosions. However, this commentary highlights that the model needs to consider how salt affects water's freezing point and the speed of certain processes. Improving these aspects could make the model more reliable for predicting changes in permafrost due to climate change.

Key points

- The freezing point depression due to salinity in cryopegs is crucial and must be included to accurately model volume expansion.
- The rapid expansion rate of cryopegs modeled by Morgado et al. (2024) appears unrealistic given their long-term stability.
- The kinetics of methane hydrate dissociation is complex and must be thoroughly evaluated to determine the feasibility of pressure build-up.

From a thermodynamic standpoint, the environmental stability of liquid water bodies (cryopegs) within permafrost is inherently governed by the delicate balance between temperature, pressure, and salinity. The unique characteristics of permafrost ground layers, often formed over millennia, imply a form of thermal inertia that resists rapid changes. In this context, the cryopeg's salinity not only affects its freezing point but also plays a critical role in determining its phase stability under various thermal conditions. These changes are rigidly bound by thermodynamic controls that impose conditions under which methane hydrates and saline cryopegs exist within permafrost environments, highlighting the impact of temperature and pressure variations on phase stability. As external temperature fluctuations due to seasonal variations and long-term climate change influence the permafrost, the cryopegs must adjust their internal salinity and pressure to maintain equilibrium. However, the interaction between cryopeg salinity and the thermal gradient within permafrost layers introduces complex feedback mechanisms. For instance, the inflow of freshwater, as proposed for osmotic processes, could lower the salinity and thereby alter the cryopeg's freezing point, necessitating additional thermal input to maintain a liquid state.

The recently published paper "Osmosis Drives Explosions and Methane Release in Siberian Permafrost" by Morgado et al. (2024) proposes a new and interesting model to explain the physical process that may have resulted in the gas escape craters that have formed in the Western Siberian Yamal and Gydan peninsulas. Their discussion on the transport of liquid water along grain contacts in permafrost is particularly noteworthy, giving rise to a range of physical processes that may affect the dynamics of the permafrost and its internal structures at a time of rapid climate change. The study further establishes a link between atmospheric warming and the expansion of the active layer, correlating these changes with deeper physical alterations in the permafrost. Specifically, the paper posits that osmotic pressure differences drive the expansion of saline and liquid cryopegs by transporting freshwater from the active layer, thereby inducing stress, fracturing, hydrate dissociation, and ultimately rupture. While the modeling in the paper is thorough, three challenging aspects warrant attention two associated with the rates of the modeled processes, and one on the thermodynamics of cryopegs. The thermodynamic issue is particularly significant and will be addressed.

In the model, the water pressure difference between the saline cryopeg and the surrounding liquid water within permafrost grain boundaries drives water into the cryopeg, thereby increasing the volume and pressure. The relationships between water inflow, cryopeg expansion, and pressure evolution are well supported. In the paper different initial salinities are modelled, ranging from 1 to 60 g/L (0.02 to 1.02 M NaCl). Higher salinities lead to larger pressure differences and volume changes, with the highest salinity (1.02 M) leading to a cryopeg volume increase of nearly three times the original volume within less than a year. The overpressure achieved during this time is ~6 bar. As the volume increases, the model also tracks a concomitant reduction in salinity due to the inflow of freshwater.

The challenge with the model is that the freezing point depression as a function of salinity is not taken into account. A cryopeg will be in thermal equilibrium with the surrounding permafrost ice, and the salinity of the cryopeg will be determined by this thermal equilibrium. Figure 1 illustrates the temperature-pressure relationships in the salt-H_2O-CH_4 system as described by Dickens and Quinby-Hunt (1997), where the freezing point depression is seen as the shift of the univariant Ice-Liquid saline water-Vapor (I-Lw-V) curve to lower temperatures. For example, a 2 M NaCl solution has a freezing point of approximately -6 °C. It is nearly a linear relation between salinity and freezing point in the range of interest for this study, and reduction from 1 M NaCl to 0.33 M would lead to a change in freezing point from -3 to -1 °C. Assuming the cryopeg remains in thermal equilibrium with the permafrost, only a 2 °C heating of the permafrost itself could facilitate such a cryopeg expansion and salinity reduction. The base-case temperature in the model is –5.85 °C, but it is unclear how this relates to the freezing points of the modeled cryopeg, given the low salinities that are well below the 2 M solution required to maintain the cryopeg in a liquid state. Including the adjustment for freezing point depression and the thermal state of the entire system including the cryopeg and surrounding permafrost will reduce the potential for volume expansion and stress generation, and this should be considered in a future development of the model.

The second challenge pertains to the rates of the processes leading to the cryopeg expansion. Expanding the volume three-fold in less than one year seems remarkably rapid, considering the long stability and persistence of the cryopegs since the formation of the permafrost ca. 80 – 90 ky BP, as stated in the paper. The long-term stability is likely due to the thermal equilibrium of the liquid brine bodies with the surrounding permafrost governed by the salinity-temperature relation and a low rate of expansion. The progression of changes in the thermal state of the active layer to cryopegs deeper in the permafrost may therefore be unlikely to induce as rapid of an expansion as suggested.

The third challenge involves the dissociation of hydrates, leading to overpressure and rupture. It is not clear to what extent hydrate dissociation is a kinetic process, and how much the dissociation kinetics is a function of the pressure build-up from the dissociation process itself. The maximum achievable pressures are again constrained by the temperature of the system according to the Ice-Hydrate-Vapor (I-H-V) curve in Figure 1. However, the specific overpressures that could be achieved from hydrate dissociation in Morgado et al.'s (2024) model are not provided. The study only offers data on pressure and stress increases resulting from cryopeg expansion.

The presented model of osmosis-driven methane release in the Siberian permafrost is based on an interesting concept, which expands the knowledge of climate-relevant processes. The transport of liquid water along ice-grain contacts in permafrost and the derived model for the expansion of cryopegs and methane hydrate destabilization are promising for the understanding of further permafrost dynamics. The challenges in this comment suggest the consideration of thermodynamic and kinetic processes to improve and extend the applicability of the presented model in the future.

References

Dickens; G, R., Quinby-Hunt, M. S., 1997.. Methane hydrate stability in pore water: A simple theoretical approach for geophysical applications. Journal of geophysical research, Vol.102(B1), p.773-783, DOI: 10.1029/96JB02941

Morgado, A. M. O., Rocha, L. A. M.,Cartwright, J. H. E., & Cardoso, S. S. S.(2024). Osmosis drives explosions andmethane release in Siberian permafrost.Geophysical Research Letters, 51,e2024GL108987. https://doi.org/10.1029/2024GL108987

Figure

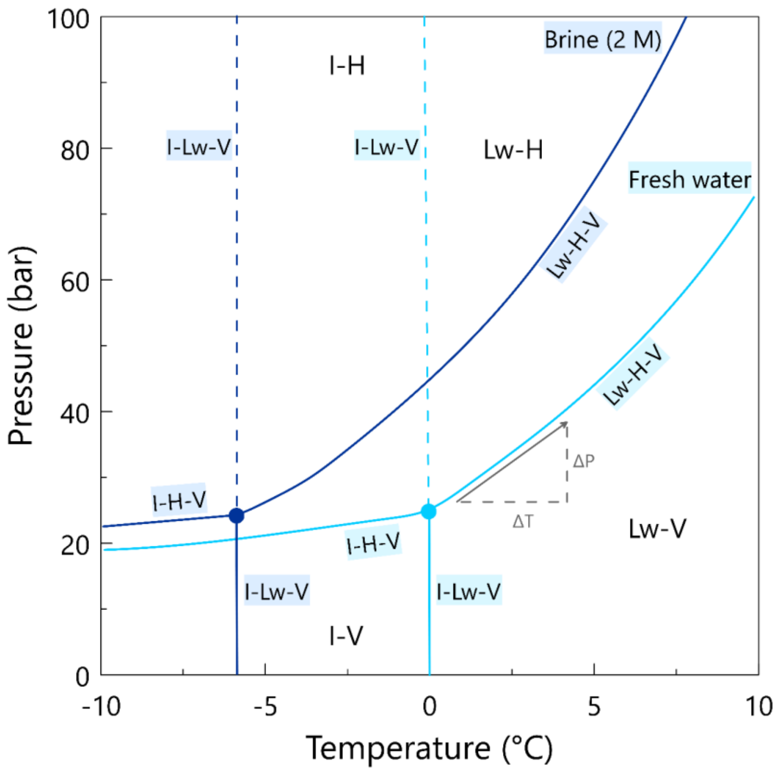

Figure 1. The diagram contextualizes the thermodynamic conditions under which methane hydrates and saline cryopegs exist within permafrost environments, highlighting the impact of temperature and pressure variations on phase stability. The diagram includes the Ice-Hydrate-Vapor (I-H-V) and Liquid Water-Hydrate-Vapor (Lw-H-V) curves, as well as the freezing-point depression represented by the Ice-Liquid Water-Vapor (I-Lw-V) univariant curve. The temperature-pressure (T-P) relationships are based on the data from Dickens and Quinby-Hunt (1997).