Modelling and Measurement of Radon and CO_2 Release from Thawing Permafrost Caused by Climate Change

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1. Introduction

Thawing of permafrost due to climate change is known to release gases - the climate drivers carbon dioxide (CO_2) and methane (CH_4), and carcinogenic radon (Rn).

Radon is a natural radioactive gas responsible for about 10% of lung cancer deaths globally, which is amplified by smoking (Rn-acquired lung cancer is 26 times more prevalent than in those who do not smoke), while smoking is 3 times more prevalent in sub-Arctic communities than the global average.

CO_2 and CH_4 are the main drivers of climate change and increased release of these gases from within and beneath the permafrost represent an undesirable positive feedback to climate forcing.

Gas transport is significantly reduced in permafrost, but now that permafrost is thawing due to climate change, the effect on the release of CO_2 and CH_4, and on domestic radon exposure is unknown.

This poster presents some of the first experimental porosity and fluid flow measurements and modelling of gas flows concomitant upon permafrost thawing.

2. Permafrost and Microstructure

Permafrost is a layer of frozen geological material which exists in a near-surface layer mainly in the arctic, where it accounts for 15% of all land in the Northern Hemisphere, but also in the Tibetan plateau and Himalayas (Figure 1). Permafrost varies in thickness from a few meters to over 1500 m. Some deeper permafrost (carbon-rich Yedoma) is over 100,000 years old.

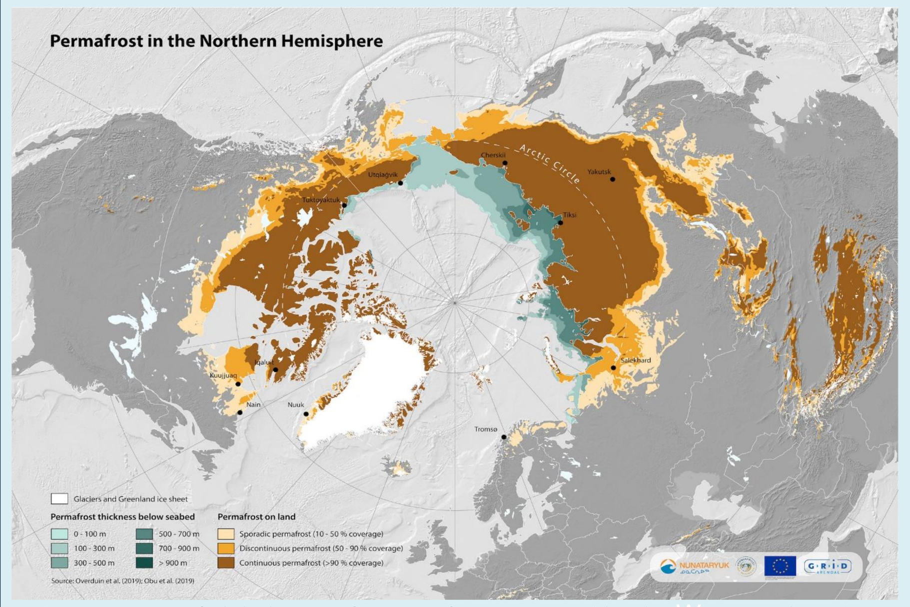


Figure 1. Map of global permafrost as of 2020 created by the Nunataryuk project (www.grida.no/resources/13519; Westerveld et al., 2023)

The Arctic is warming at a rate that is approximately 4 times faster than the global average since 1979. This Arctic Amplification (AA) phenomenon, has led to a warming by more than 3.1°C since 1979, compared to the global average of 0.817°C and is accelerating over time.

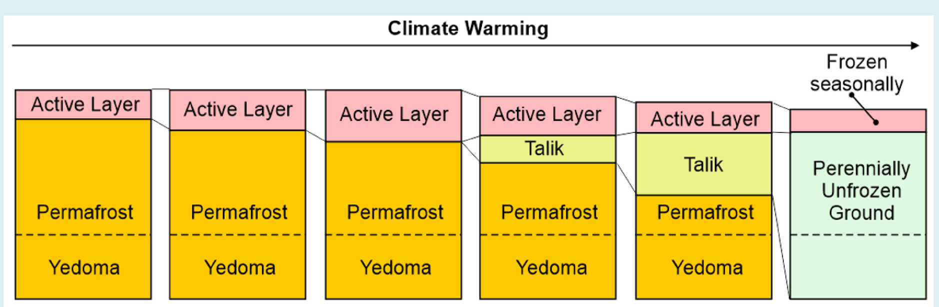
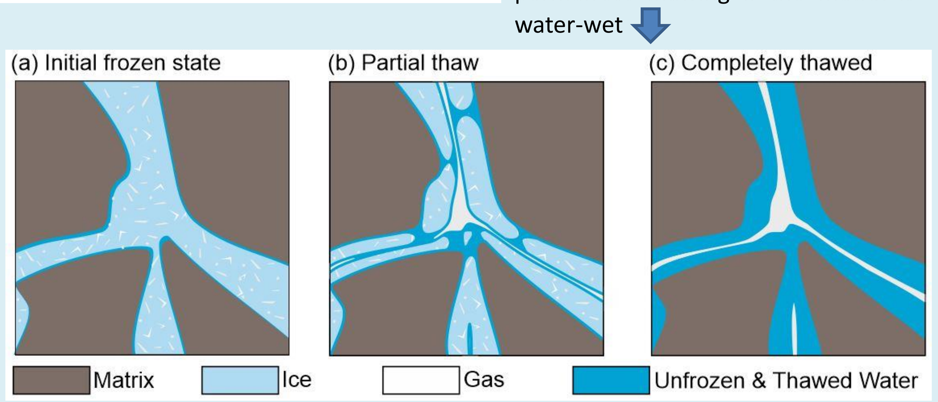


Figure 2. Climate change progressively thaws the permafrost, increasing the thickness of the Active Layer, which thaws and refreezes seasonally, and the thawed layer which seasonal cooling cannot refreeze (Talik)

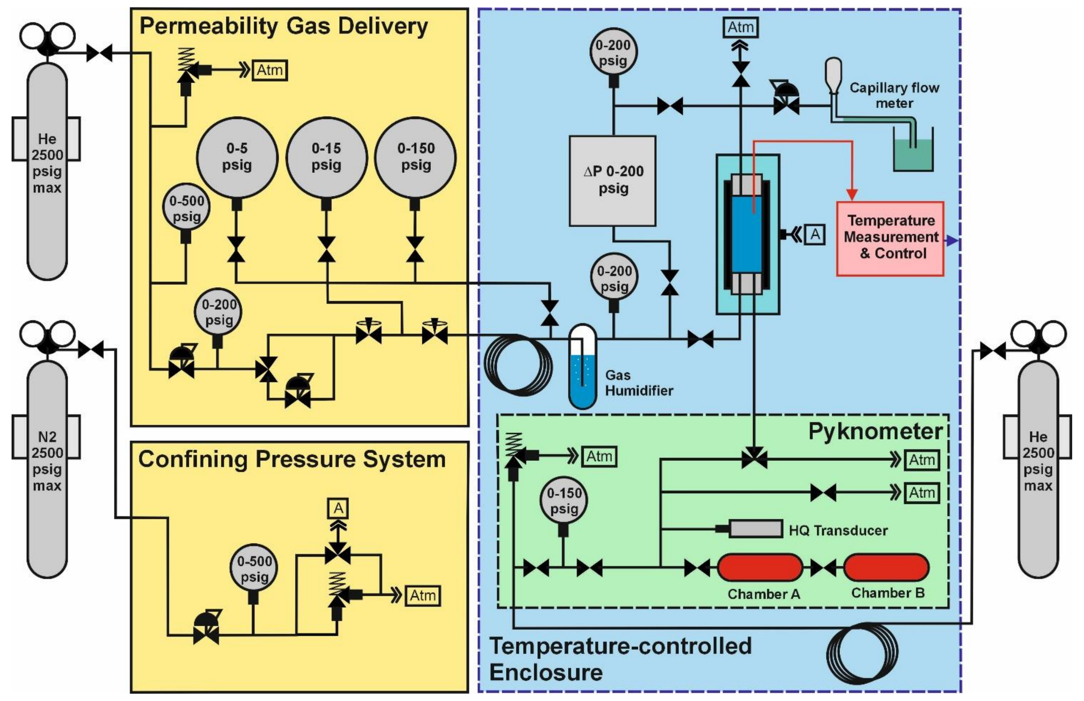
Figure 3. Phase distribution during permafrost thawing if the matrix is water-wet



Thawing of permafrost (Figure 2) increases the gas fraction and the connectedness of the gas fraction leading to increased permeabilities. A water-wet matrix ensures that gas-filled space occurs in the middle of pores and becomes well-connected. Throughgoing pathways of gas can become efficient corridors for gas transport even when the permafrost is only partially thawed.

3. Permafrost Samples and Experiment

Synthetic samples of permafrost have been used because (i) they provide a high degree of homogeneity *cf* natural samples, (ii) difficulty in obtaining natural samples with the wide range of initial ice fractions required, and (iii) difficulty transporting permafrost samples internationally. Sixteen (16) permafrost samples were made by combining Ottawa sand, sieved and water-soaked peat, and grated ice made from rainwater in approximately the preferred volumetric proportions in a length of polymer sleeving of 1.5 inch (38.4 cm) nominal diameter. A laboratory-designed and built helium pycnometer (range 0% to over 40%, accuracy ±0.1%, but ±2% in this application) has been combined with modules needed to measure Klinkenberg permeability.



Measurements were made for both the thawing cycle, starting at -18°C and progressing in nominal steps of either 1°C or 0.5°C until +5°C, and the freezing cycle, using approximately the same temperature points in reverse order. Each thawing/freezing step was considered complete after 1 hr stability. This usually took several hours to attain.

Figure 5. The partly disassembled experimental rig.

4. Permafrost Phase Fractions & Experimental Permeability

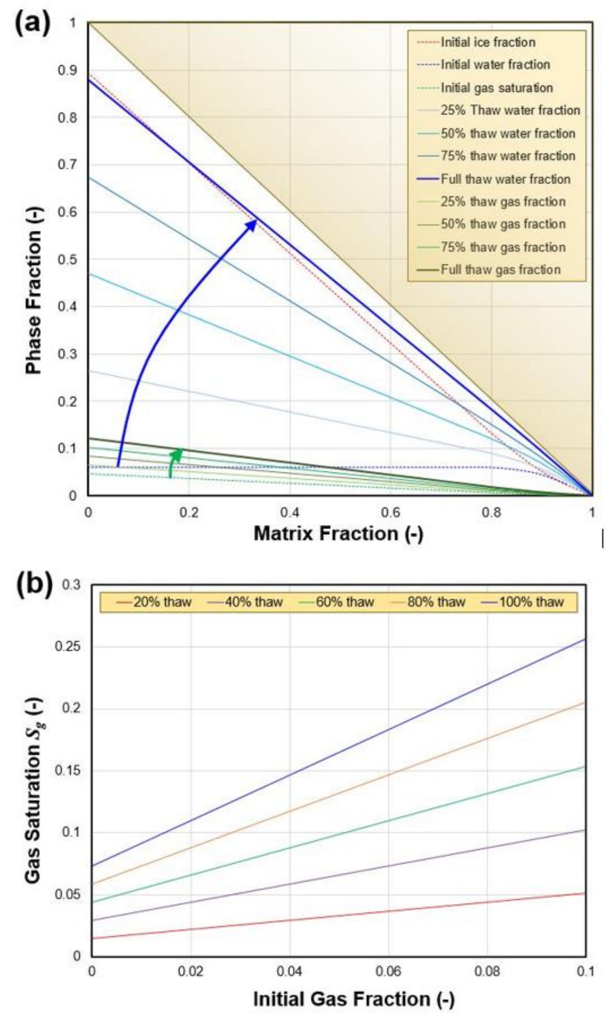


Figure 6. Modelled (a) Relative phase fractions for initial conditions and various degrees of thawing as a function of the matrix fraction. Blue and green arrows show water and gas fractions as thawing progresses, respectively (χ_{wi} =0.06 and ε_g = 0.05). The shaded zone represents permafrost matrix a. (b) Gas saturation S_g resulting from various degrees of thawing as a function of the gas fraction present in the initial ice.

- Upon thawing gas fraction increases and is a function of the initial gas saturation in inclusions in the ice
- Gas fractions may remain less than 0.25 but the gas is well-connected to make flow pathways.

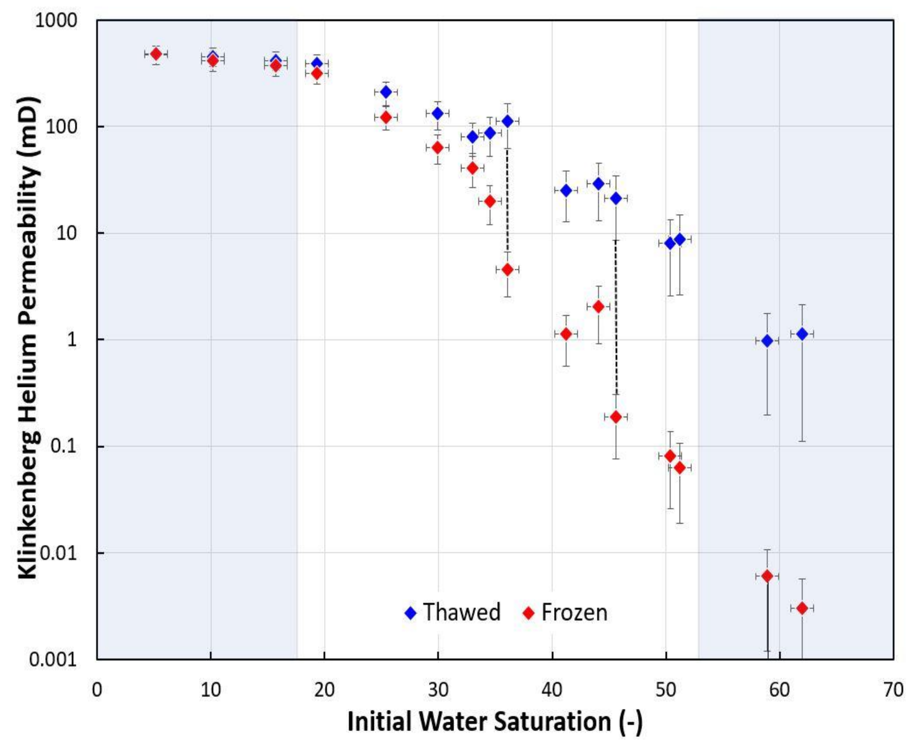


Figure 7. Klinkenberg humidified helium gas permeabilities as a function of initial water saturation for fully frozen (-18°C, red) and fully thawed samples (+5°C, blue) for 16 synthetic permafrost samples.

- Frozen permafrost samples have smaller permeabilities than when thawed.
- The permeabilities of both the thawed and frozen samples decrease with increasing initial water fraction (and hence with ice fraction).
- Samples with initially high water fraction have a large difference between the frozen and thawed permeabilities (over two orders of magnitude), becoming progressively less until it is almost the same at an initial water saturation of 5%.
- Data shares similarity with results obtained by Chuvilin et al. (2021).
- Non-grey data in Fig 7. can provide permeability as a function of temperature.

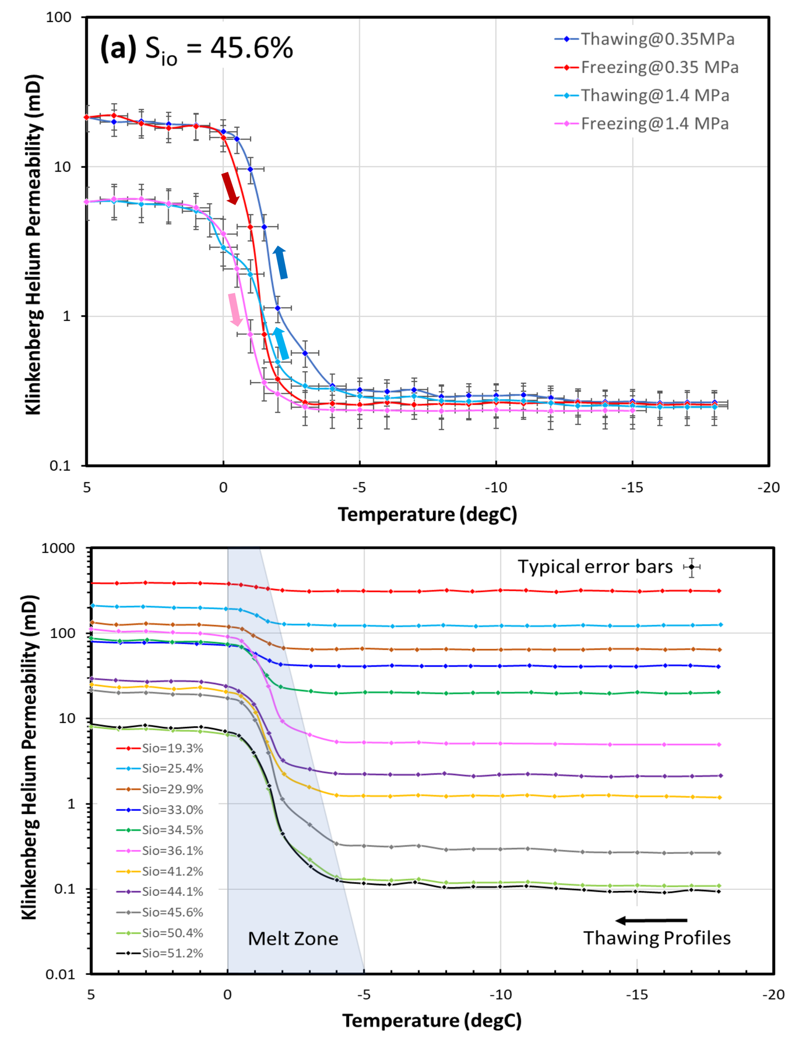


Figure 8. Progressive change in Klinkenberg-corrected humidified helium gas permeabilities as a function of temperature from frozen (-18°C) to fully thawed samples (+5°C) and vice versa for 11 permafrost samples with initial water saturation of (a) 45.6% for 2 confining pressures, and (b) thawing profiles for all samples.

- Thaw and permeability change is restricted to the temperature range 0°C>T>-5°C.
- Sudden, large changes in permeability are possible when the temperature of the permafrost changes by only a few degrees Celsius.
- Confining pressure increases causes compaction effects, reducing the thawed permeability.

5. Permafrost Poroperm

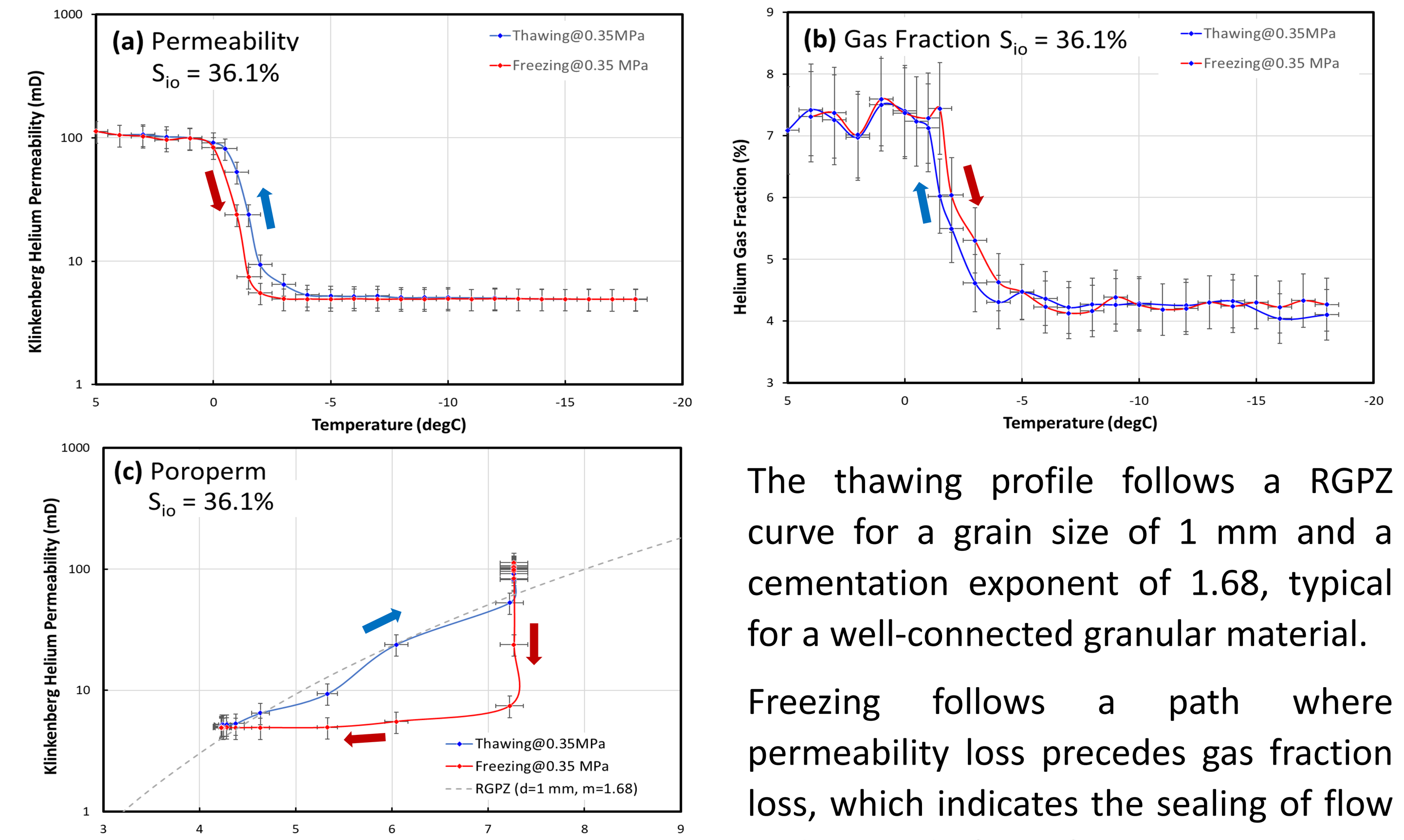


Figure 9. (a) Permeability measurements during freezing and thawing can be used with (b) porosity measurements to produce (c) a poroperm plot.

The thawing profile follows a RGPZ curve for a grain size of 1 mm and a cementation exponent of 1.68, typical for a well-connected granular material.

Freezing follows a path where permeability loss precedes gas fraction loss, which indicates the sealing of flow pathways before freezing progresses further.

6. Radon Flow Modelling

Brief application to modelling (see Glover and Blouin, 2022) calculates Rn concentrations in a basement in thawing permafrost for different thawing rates. The result is that the 200 Bq/m³ safety threshold is breached for over 4 years in most cases where thawing takes less than 15 years.

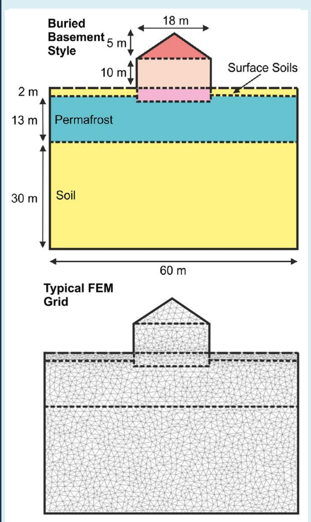


Figure 10. Model soil/ permafrost/house model (top), and tesselated for FEM flow modelling (bottom).

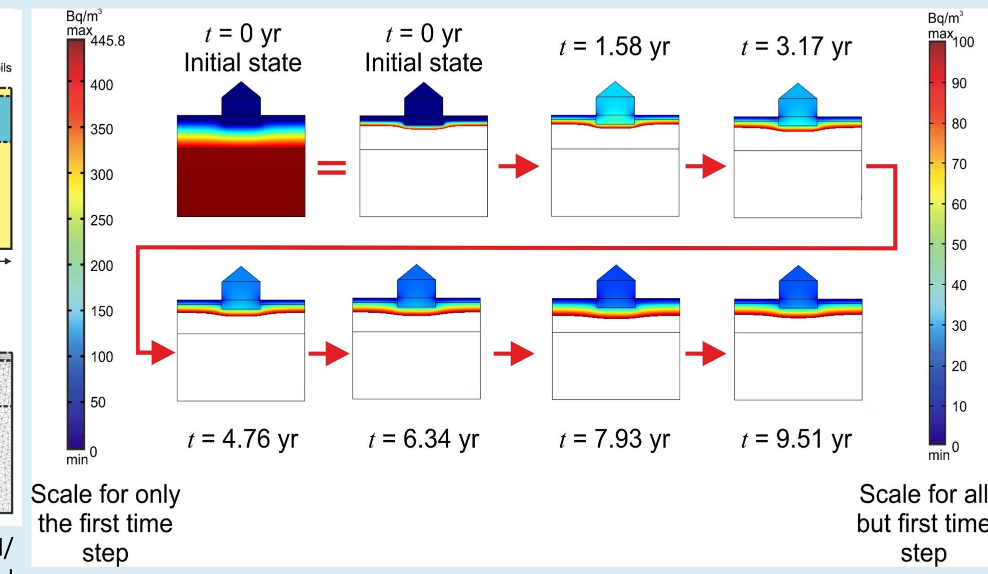


Figure 11. Model soil/permafrost/house model (top) for FEM flow modelling (left) and a single result after 1.58 years after thawing (right).

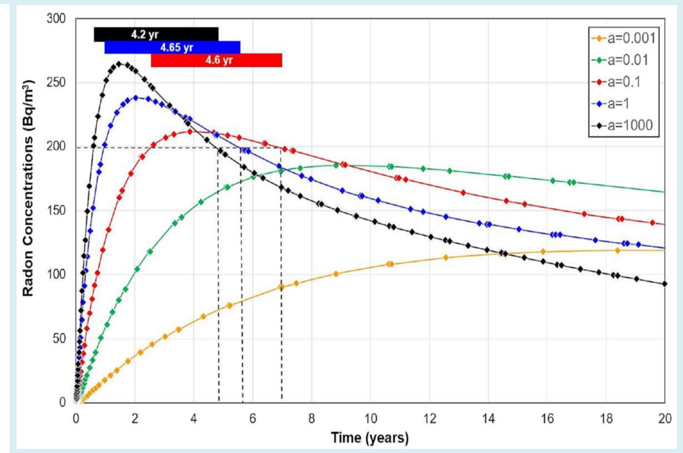


Figure 12. Evolution of the arithmetic mean radon concentration for quasi-instantaneous thaw and four longer thaw profiles approximating to 40% increase in diffusion coefficient after 0.5, 5, 50, and 500 years, as defined in the methodology, and d = 2 m. Coloured bars show time above the 200 Bq/m3 threshold.

7. Conclusions

The results of this initial work are far reaching. The main results can be summed up as:

- Thawing can lead to changes of permeability of 2 to 3 orders of magnitude.
- Permeability changes depend on the water content of the permafrost – higher water contents give the largest permeability changes.
- Permeability changes occur in the 0°C<T<-5°C temperature window.
- A 1°C temperature change can give a significant permeability change.
- Gas fraction evolves with permeability increase during thawing, but lags permeability decreases during freezing. This is interpreted as a preferential loss of gas connectivity due to freezing at constrictions.
- Increased pressures can lead to compaction which reduces permeability changes.

References

Chuvilin, E., Grebenkin, S., and Zhmaev, M. Gas Permeability of Sandy Sediments: Effects of Phase Changes in Pore Ice and Gas Hydrates, Energy Fuels 2021, 35, 7874−7882 https://doi.org/10.1021/acs.energyfuels.1c00366

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