

Dear Reviewer

Firstly, we sincerely appreciate the time you have taken to review our article and found your comments very insightful and fair. We have answered your comments as best we can below.

I have included your original comments in black and written our responses in bold. We have also attached a pdf copy of this with our responses in red to better highlight the comments vs responses.

Yours sincerely, on behalf of the authors

Tom Birchall

Comment 1: I found the overall presentation is not well structured and clear, and hence is difficult to review. This, in my opinion, is because the paper mostly focuses on the data description, and did not clearly show how they help to fill the knowledge gap. Based on the author guideline of TC, a review article should "summarize the status of knowledge". The paper in its current format is more like a datasets report rather than a scientific paper. This could be reflected by the Results section. It gives very detailed information on permafrost thickness, gas presence/absence, but lacks in-depth analyses.

We agree very much with this, and we will aim to provide a clearer structure to the article. We appreciate that we need to better highlight the existing knowledge gaps and will add more detail of them at the end of the introduction – notable examples include the lack of previous publications even mentioning the trapped methane and the lack of existing wellbore data (direct or indirect) on the base permafrost and its depth, both of which are addressed by these vintage boreholes. We were requested to change this to a review article by the editor. We see this article as a review of vintage well data (not published works). However, it is worth noting that with one exception, none of the wells that penetrate to base permafrost were drilled with the purpose of defining permafrost. Essentially, we have a great breadth of data over a very large area, but, as you mention, that leads to the lack of specific analyses. However, because this subject has not been previously addressed in Svalbard, and much of the data is in paper archives and not easily accessible to the scientific community, we feel it is important to provide as much information as possible.

Authors used a large number of observations from various sources: hydrocarbon exploration, coal boreholes, and scientific boreholes. If I understand correctly, these wells and boreholes were instrumented in different periods, by different technicians as well as scientists, and for different purposes. In this case, the data is expected to have different degree of confidence. In section data and methods, authors should clearly clarify such degree of confidence, and the data quality control.

This is a very good point, and we will clarify this. We found that the strength of our investigation is not in individual datasets of specific wells, but the amalgamation of broad datasets within a substantial region that our fairly diverse team has the expertise to interpret and integrate (often through ruling out alternative hypotheses rather) into the bigger overview.

Last but not least, I would suggest authors double-check the definition of permafrost (please see Van Everdingen, R. O., 1998), the current definition in L50 is not true (please also see my specific comment).

1. permafrost

Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years (see Figure 2).

COMMENT:

Permafrost is synonymous with perennially *cryotic ground*: it is defined on the basis of temperature. It is not necessarily frozen, because the freezing point of the included water may be depressed several degrees below 0°C; moisture in the form of water or ice may or may not be present. In other words, whereas all perennially *frozen ground* is permafrost, not all permafrost is perennially frozen. Permafrost should not be regarded as permanent, because natural or man-made changes in the climate or terrain may cause the temperature of the ground to rise above 0°C.

Permafrost includes perennial *ground ice*, but not glacier ice or icings, or bodies of surface water with temperatures perennially below 0°C; it does include

We appreciate the reference and paste the definition from the source for readers.

“Permafrost is defined as ground that remains at sub-zero (in Celsius) temperature for more than two consecutive years, regardless of fluid content.”

I will rephrase to something more appropriate, e.g.:

“Permafrost is defined as ground that remains at or below zero degrees Celsius, temperature at least two consecutive years, regardless of whether the fluid is frozen.” And will clarify subsequent sentence by what we mean with “ice-saturated permafrost”.

For these reasons, I would not recommend that the paper be published in TC in its current form. I would actually recommend authors significantly shorten the paper and focus on how the valuable data contribute towards knowledge of natural gas in/below permafrost. Another option would be thinking about publishing it in a data journal.

We think this is a very useful comment and completely agree. We will will remove the majority of the hydrate and modelling side focus more on the trapped gas for a more concise manuscript with less uncertainty. One example that might be worth keeping is Adventdalen where we do have much stronger calibration points with respect to gas geochemistry and temperature data (that were collected by scientific boreholes with those datasets as a major goal).

Because Svalbard is representative of the high relief, rapidly uplifting, glaciated parts of the Arctic and that this is the first such investigation on the subject in Svalbard, we don't want to withhold data from the community. As a scientific community we need insights into this gas in the literature, not just because it is a hazard, but because of its important link with increasing glacial recharge (as the landscape approaches peak meltwater production) that is controlled by geological processes over much longer timescales (e.g., uplift, erosion, fracturing, abnormal fluid pressures) than we may often consider. These are systems that we cannot develop an understanding of from the more well studied areas such as Alaska, the McKenzie Delta or Siberian continental shelf environments.

I would also like to highlight that we have a team of Svalbardian experts from a variety of backgrounds working on this article, including permafrost, bedrock and petroleum and coal geology (and an employee from the local mining company), drilling, and fluid flow, which means we are in a unique position to be able to disseminate the broad datasets. This data is unique and will never be collected again as there is little appetite to drill expensive wellbores through the permafrost without economic incentive (scientific boreholes are common in the upper few metres,

but nowhere near reaching the sub-permafrost realm), hydrocarbon exploration ceased here long ago, and the last coal mine will shut down in Longyearbyen in 2023.

P2, L41: Why relatively young permafrost is important here?

We will rephrase that. The importance is that it indicates fluid migration is very recent – e.g., the past few kyr rather than 100s of kyr or myrs.

P2, L50: ... remains at or below 0°C for at least two consecutive...

Addressed above.

P2, L52: Physically speaking, ice-saturated permafrost possesses extremely good sealing, because of ? Also, this knowledge is similar to your conclusion 4: permafrost in valleys with more ice is a better seal. Then, why do you still need conclusion 4 if it has been widely known? P

We will rephrase this – I should have explained it better that in terms of permeability it does, but there is some uncertainty about its extensiveness (e.g., can everything be draining through points such as pingos?) essentially it seems not. There is also the point that wellbores in the highlands seem to lack water/ice in the permafrost zone (so may be a worse seal for gas).

3, L72--73: 100--500 m is quite thick... P7, L196: I agree identifying the permafrost thickness is challenging. On the other hand, permafrost is a hidden phenomenon, and identifying its presence is also NOT simple (even at a site scale) and may even be ambiguous without direct evidence (e.g., soil temperature and samples). Please see Cremonese et. al (2011).

This is a good point; indeed, we rely on indirect indicators. We think adding more information, particularly from scientific wellbore DH8 (Longyearbyen CO2 Lab; Gilbert et al. 2018), which was drilled specifically to characterise permafrost, will provide insight here. We can provide details of ice content, rock properties and stratigraphy from this well. Although these wellbores do not penetrate the base permafrost, we do have a lot of expertise at UNIS in permafrost identification and characterisation. Though we do note that the base permafrost (or really, the base of impermeable ice) in our datasets does not have a single smoking gun indicator, rather an overwhelming number of cases where gas influxes into a well at a depth that does not correspond to an obvious geological break, and always occurs at an approximate place where we would expect the base permafrost to be (which is highly uncertain).