Rebuttal

Anonymous Referee #2

Note: Reviewer's comments are grey, responses in black.

Putting aside the open-endedness of the study and generally qualitative analysis of the modeling results, I still had a few questions about the treatment of permeability in the sill. I suggest that the authors address these questions prior to final publication:

Given poor constraints on the permeability of fractured media, how do assumptions about temperature-permeability relationships influence the results?

The temperature-permeability relationships are a key component in this study, and evolving permeability the of cooling joint networks is indeed poorly constrained. We added a sentence to the model description that points out this problem as well as the fracture flow issue mentioned in the next commment (section 3.2, third paragraph). We tested a porosity opening of the sill over a lower temperature range (900 ºC – 800 ºC) and do not see a significant change in the methane distribution. Of course, the hydrocarbons enter the sill at lower temperature in this case but as long as temperatures are above ~350 – 500 ºC the conditions are sufficient for graphitization and thus consistent with the field observations.

Given the good agreement of field observations and our models, we think that our model captures the essence of the processes. But we must admit that especially the linear permeability increase due to cooling joints is a crude approximation. As mentioned in the general answer, a better understanding of cooling joint formation would certainly lead to more accurate results and allow improved quantification, e.g., of hydrocarbon/methane accumulation. Due to the complexity of the model, it is difficult to say how exactly the results would be influenced by different, perhaps more physical sounds relationships.

Flow through fractures is a different transport mechanism than porous flow, especially given the potential for development of permeability anisotropy related to fracture orientations. How does the treatment of fracture-dominated flow as porous flow potentially influence the flow pattern results? Would backflow be possible if fractures are vertically oriented?

We think that our revised model with dynamic fracture-related permeability and porosity qualitatively captures at least some of the effects of fracturing correctly. It is clear, however, that porous flow is not the ideal model in a fractured sill, and we seek to improve this in future work.

Cooling joints propagate with the temperature front, i.e. they develop perpendicular to the isotherms. Over the wide lateral extent of the sill this should lead to network of fractures around vertically oriented columns of intact rock. Near the tips we would expect a much more complex fracture pattern. Since the network around the columns is inherently three-dimensional it will also allow for fluid flow perpendicular to the columns because they are surrounded by interconnected fractures, which often show polygonal patterns (e.g., Hetényi et al., 2012). Hence both, vertical and horizontal flow directions are possible in the sill. Outside of the sill, one would ideally have to consider stress orientation to predict the orientation of hydrofractures. Currently, this is not possible in our model. Our numerical model allows considering anisotropic permeability but we have not explored the effects arising from, for example, a higher vertical than horizontal permeability within the sill. This would be necessary to reliably answer the question regarding backflow without too much speculation.

References

Hetényi, G., Taisne, B., Garel, F., Médard, É., Bosshard, S., & Mattsson, H. B. (2012). Scales of columnar jointing in igneous rocks: field measurements and controlling factors. *Bulletin of Volcanology*, *74*, 457-482.