The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-59-AC2, 2020


The Cryosphere Discussions
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EGU

# *Interactive comment on* "Geothermal heat flow in Antarctica: current and future directions" *by* Alex Burton-Johnson et al.

**Alex Burton-Johnson et al.**

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Received and published: 30 July 2020

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Dear Brice Van Liefferinge, Thank you for taking the time to provide such a helpful and thorough review. You provided many pertinent comments, and their implementation has greatly improved our manuscript. We have addressed all of your points, and list them below alongside your review. All the best,

Dr Alex Burton-Johnson



Brice Van Liefferinge (Referee) bvlieffe@gmail.com

Received and published: 13 April 2020

Dear Authors, I enjoyed reading your paper on the comparison of the different GHF estimate methods. This paper provides a great overview of the work done on GHF reconstructions and provides key future directions. All known methods are described and are well supported by explicit examples and references in the manuscript. I really liked section 4 on GHF derived estimates. I think that all the key references are included. I added a few and strongly suggest to add and describe the work of Rezvanbehbahani et al. (2017) on machine learning techniques as done in Greenland. The introduction and conclusion support well the manuscript as do the figures (see specific comments). The language used is appropriate. However, I would suggest the following general changes: a) In the title you use "flow" but I would suggest to use "flux", as well as for the whole manuscript (see specific comments). b) The manuscript is qualitative in a few paragraphs. More quantitative descriptions could be provided such as maximum and minimum GHF of the different data sets, discuss the representativeness of point GHF values, . . . where possible. c) The limitations of the different methods to estimate GHF (ice borehole measurements, model estimates, . . .) are not always discussed. A sentence could be provided for each. E.g. ice borehole measurements provide a minimum GHF value when the base is at the pressure melting point. d) Figure 6 needs to be discussed in more detail in the text. A description of the different data sets used is lacking (see specific comments). e) Section 4.5 is quite long compared to the other subsections, and describes in a lot of details a technique that is not widely in Antarctica because of the lack of measurements. It seems therefore that including specific equations is superfluous, and perhaps the paragraph on its application in Antarctica could then be extended. I attach a detailed review of the paper for the specific line-by-line comments, see attached PDF. All the best, Brice Van Liefferinge

Reply to Main Comments:

a) In the title you use “flow” but I would suggest to use “flux”, as well as for the whole manuscript (see specific comments).

- This was a topic of discussion when drafting the SCAR-SERCE White Paper on geothermal heat flow (Burton-Johnson et al., 2020). The community consensus was that “flow” is the correct terminology. “Heat flow” is not limited to the movement of material, but the mechanism of heat transfer (dominantly by conduction when near the Earth’s surface). It was highlighted that the two terms are used interchangeably within the scientific literature, but “heat flow” has been established for decades to describe the rate of heat transferred across the surface of Earth per unit area, and is the term used by the International Heat Flow Commission. The most important consideration is to state the units (mw/m2), as we have done. A very important and worthwhile discussion and consideration though, and we thank you for raising it. Hopefully this will bring us closer to a more consistent use of the terms.

b) The manuscript is qualitative in a few paragraphs. More quantitative descriptions could be provided such as maximum and minimum GHF of the different data sets, discuss the representativeness of point GHF values, . . . where possible.

- Maximum and minimum values are not the best way to represent these datasets. Following Burton-Johnson et al. (2017), to be more quantitative we have added probability density plots of the GHF estimates in East and West Antarctica, and added maps of mean and SD for the different geophysically-derived GHF estimates.

c) The limitations of the different methods to estimate GHF (ice borehole measurements, model estimates, . . .) are not always discussed. A sentence could be provided for each. E.g. ice borehole measurements provide a minimum GHF value when the base is at the pressure melting point.

- The advantages and limitations are now summarised in a table.

d) Figure 6 needs to be discussed in more detail in the text. A description of the



different data sets used is lacking (see specific comments).

- The section where each model is discussed has been added to the legend. All of the data coverage shown is discussed in detail in each section.

e) Section 4.5 is quite long compared to the other subsections, and describes in a lot of details a technique that is not widely in Antarctica because of the lack of measurements. It seems therefore that including specific equations is superfluous, and perhaps the paragraph on its application in Antarctica could then be extended.

- Section significantly shortened.

Please also note the supplement to this comment: https://www.the-cryosphere-discuss.net/tc-2020-59/tc-2020-59-RC1-supplement.pdf

Replies to specific comments Supplemental comments, ordered by “Page. Number.” E.g. “3.2.” is comment two on page three of the supplement.

1.1. This might seem to be a picky comment but it is important to be precise. I would suggest to use "flux" than "flow": heat flow should be reserved for the movement of material while heat flux is a transport of a quantity of energy over time. As in this paper you focus more on the GHF beneath the Ice Sheet (bedrock surface), I would use "flux". Otherwise can you explain the use of "flow"?

- See reply above (Main comments (a) )

1.2. "estimate" (extract sounds like by effort or force)

- Changed.

2.1. present and

- Text added.

2.2. See comment on the Title

- See reply to earlier comment (1.1.)

4.1. I would suggest to add somewhere that ice sheet temperature is also influenced by the ice thickness: as ice acts as an insulator, the greater the ice thickness, the warmer the ice at the base. This is counterbalanced by cold temperature advecting from the surface, itself influenced the accumulation rate.

- Both points now added to this section.

4.2. Whole

- To avoid the confusion with an equal temperature effect through the whole ice sheet thickness, we have decided to exclude this addition.

4.3. Basal

- Added.

4.4. Cross-Out

- Changed

4.5. "increase" ==> from -13°C to 7°C

- Changed.

4.6. and expands the surface area of the bed at the pressure point from 16% to more than 50%.

- Details added.

4.7. Cross-Out

- “Non-uniform” is the correct spelling.

4.8. As you mention surface temperature in this paragraph, I suggest to add a sentence on surface accumulation which can have a strong influence on the basal conditions even in the interior of the ice sheet, and counteract the effect of the GHF (see Fig. 2 Van Liefferinge and Pattyn 2013)



- Accumulation rate now mentioned.

5.1. You should also add the work of Rezvanbehbahani et al. (2017) : Rezvanbehbahani et al. (2017) use for the first time machine learning techniques to derive GHF from relevant geologic features (gravity measurements, magnetic anomaly) and GHF measurements (derived from crustal thickness, rock composition and active thermal feature). S. Rezvanbehbahani, L. A. Stearns, A. Kadivar, J. D. Walker, and C. J. van der Veen. Predicting the geothermal heat flux in Greenland: a machine learning approach. Geophysical Research Letters, 2017. ISSN 1944-8007. doi: 10.1002/2017GL075661.

- Reference added in reply to comment 29.3 (below).

5.2. Cit: Fischer 2013, Climate of the past paper. https://www.clim-past.net/9/2489/2013/

- Citation added.

5.3. Van Liefferinge and not Liefferinge

- Changed

6.1. Curie Point Depth (CPD as in section 4.1 L311)

- Changed

6.2. I suggest to develop in one or two sentences the implications of the Antarctic Ice Sheet like in section 2.3.2

- Apologies, we do not understand this request. This section is discussing how GHF studies inform mantle dynamics research.

6.3. It is a simple suggestion but why not provide a table presenting all the methods used to estimate the GHF with the advantages and disadvantages, to have an overview of all the methods together. This sentence could be extended as well to give an overview of the section’s content.

- Summary table of methods added.

7.1. GHF

- Changed

8.1. In the xlsx supplementary material, I guess that in the row "method", borehole means "Boreholes into bedrock" ? If yes can you provide the exhaustive (or estimation) of the number of boreholes into bedrock in Antarctica and cite the SOM.

- Number of data points of each type now added to the “Existing Data” section.

8.2. A key point that is not explained here, is that, when the base of the ice sheet is at the pressure melting point (presence of water), the GHF estimate is a minimum GHF estimate, which means that the GHF can be higher! See also section 5, 5.1

- We agree with the reviewer that if the base of the ice sheet is at the pressure melting point, GHF cannot be estimated from the gradient of temperature alone and only a minimum value of GHF can be estimated. We believe that is clearer to refer in this Section only with studies estimating GHF and we have explicitly stated that one of the requirements is “that the ice sheet has been unequivocally frozen to the bed for long enough that the bedrock and overlying ice sheet have thermally equilibrated”

8.3. add citation

- Citations added

11.1. A: Fox Maule et al., did you use the 2005 version of the data set or the updated one from Purucker ? Based on the figure, you are using the Purucker et al update so please cite: M. Purucker. Geothermal heat flux data set based on low resolution observations collected by the champ satellite between 2000 and 2010, and produced from the mf-6 model following the technique described in fox maule et al.(2005). See http://websrv. cs. umt. edu/isis/index. php, 2013.

- The updated reference is added to the figure and where appropriate in the rest of the



manuscript.

12.1. I would suggest to be very explicit about what each data set is in that figure. e.g. Passalacqua et al., 2017: "radar reflectivity and inverse modelling". Provide a table with the links to the data sets ? (see general comments)

- The section where each model is discussed has been added to the legend.

12.2. derived estimates (to be consistent with the other sub-section title )

- Changed.

13.1. CPD

- Changed.

14.1. . B)

- (B) is used as a reference to the illustration whilst explaining (A) rather than a separate description.

14.2. Cross-Out

- See 14.1

14.3. Highlighted

- See 14.1

15.1. CPD

- Added.

15.2. Cross-Out

- Corrected.

15.3. :

- Corrected.

15.4. bottom of the magnetic source

- Corrected.

15.5. As is, to me, this figure illustrates more the difference between Martos et al. (2017) and the two methods than between seismic and gravity modeling. Why not simply plot the difference between the two methods you describe?

- Whilst the difference between the figures is due to the difference between the two Moho estimates, the figure is to show that there are regions where the Curie depth is deeper than the Moho estimate regardless of the Moho estimation method. Consequently, this is the most appropriate way to present the data.

16.1. derived estimates (see 4.1)

- Reworded.

17.1. Thanks for pointing this difference out !

- Thank you.

17.2. model derived estimates (e.g)

- Reworded.

17.3. as before for the sub-title.

- Reworded.

18.1. Can you provide some numbers on the maximum and minimum GHF ?

- This is dependent on the borehole estimates used.

18.2. Section 4.5 is quite long compared to the other subsections, and describes in a lot of detail a technique that is not widely used in Antarctica because of the lack of measurements. It seems therefore that including specific equations is superfluous, and



perhaps the paragraph on its application in Antarctica could then be extended.

- Section significantly shortened.

21.1. Simplify in one sentence.

- Section re-worded and shortened.

23.1. You use whilst several times, you could remove some of them.

- Alternatives are now used here and elsewhere in the document.

23.2. Underline

- See preceding comment.

23.3. you can also cite: J. W. Goodge, C. M. Fanning, C. M. Fisher, and J. D. Vervoort. Proterozoic crustal evolution of central East Antarctica: Age and isotopic evidence from glacial igneous clasts, and links with australia and laurentia. Precambrian Research, 299:151–176, 2017.

- This paper precedes the Goodge (2018) paper, but discusses what can be determined of the age and composition of the unexposed crust, but does not discuss the heat production implications. To avoid confusion for the reader and to direct them to the relevant paper, we have chosen not to include the earlier paper.

24.1. (Van Liefferinge and Pattyn, 2013).

- Corrected

24.2. As it is difficult to know the melt rate, I would say that this is not the GHF estimate but the minimum value of the GHF estimate or the minimum GHF to reach the pressure melting point.

- We agree with the reviewer that if ice is melting at the base only a minimum value of GHF can be estimated. However, all the methods referred in Sections 5.1 and 5.3 use additional constraints to estimate GHF. In Section 5.2 we explicitly state that only

a minimum value of the GHF can be estimated.

25.1. Van

- Corrected

25.2. Van

- Corrected

25.3. ,

- Corrected

25.4. more than

- Added “at least”

25.5. cite: A. P. Wright and M. J. Siegert. A fourth inventory of Antarctic subglacial lakes. Antarctic Science, 24:659–664, 2012.

- Reference added

26.1. again if at the PMP, for me it is more a minimum GHF as we don’t know whether there is melt or not. If the melt is low, both values are very closed to each other

- See response to 24.2

27.1. Van

- Corrected.

29.1. You should include the new TCD paper of Talalay 2020: https://www.the-cryosphere-discuss.net/tc-2020-32/tc-2020-32.pdf

29.2. Dome Fuji is not frozen to the bed, so it is a minimum GHF

- Text added.



29.3. I strongly suggest to add a few words on machine learning techniques as done in Greenland by Rezvanbehbahani et al. (2017). See before and something like: "Machine learning techniques used to determine the GHF over the Greenland Ice Sheet (Rezvanbehbahani et al., 2017) could be developed for the Antarctic Ice sheet. Up until now, we provide a statistical analysis of basal temperatures and GHF based on the use of different data sets. The use of a Monte Carlo approach, which is based on repeated random sampling to calculate GHF, could bring new perspectives on the data, and in particular on associated uncertainties which would allow us to critically assess our results."

- Text added

30.1. and only where the bed is frozen.

- Text added (“where the basal ice is frozen to the bedrock”).

33.1. Van

- Corrected.

33.2. I would add that up until now, thermodynamical models are still dependent of GHF estimates (large GHF data sets, borehole temperature measurements, ...) - Text added.

33.3. for local measurements

- Added “for local estimates”.

38.1. Please also mention the updated version of this data set by Purucker 2013 which is the available data set now

39.1. Cross-Out

- Corrected.

41.1. Van Liefferinge, B., and Pattyn, F.: ...

- Corrected.

41.2. Van

- Corrected.

Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2020-59/tc-2020-59-AC2-supplement.pdf

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Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-59, 2020.