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Interactive comment on "Laurentide Ice Sheet basal temperatures at the Last Glacial Cycle as inferred from borehole data" *by* C. Pickler et al.

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Response to comments by reviewer VM Hamza

We appreciate the time spent by the reviewer to prepare this lengthy discussion and we welcome the opportunity to clarify some points that may be unclear to those unfamiliar with heat flow measurements and inversion of borehole temperature profiles.

The reviewer made the following comments:

1) Transient signals identified in the thermal profiles of shallow and deep-seated sections. It is curious that such high frequency variations in vertical heat flow are present mainly in the depth intervals where post-glacial warming trends are absent. Such fluctuations in heat flow are unlikely to have sound physical basis. These appear to be artifacts arising from erroneous procedures employed in obtaining first order estimates.

The heat flux profiles are calculated continuously by determining the temperature gradient of the measured temperature-depth profile and multiplying it with the respective thermal conductivity. This is a common and non erroneous procedure to determine heat flux (e.g., Beck and Judge, 1969; Jaupart and Mareschal, 2010). Some noise in the temperature profile is due to minor changes in lithology. It is well known that noise is amplified in the derivative of the temperature field, thus resulting in such spikes in the heat flux profile without smoothing. Repeat measurements at Sept-Iles (Mareschal et al., 1999) have shown that these temperature fluctuations are consistent between measurements taken at several years interval, i.e. they are not caused by errors. The reviewer points out that the fluctuations are larger in the lowermost part of the profile and therefore could not be due to ground surface temperature variations. No one who understands heat diffusion would ever claim that these spikes could in any way be related to climate. However, there is a reason why the lowermost part of these profiles is noisy. The boreholes are mining exploration holes that reach exploration targets in their lowermost part. These targets are always associated with important variations in lithology, hence, variations in conductivity and fluctuations in the temperature gradient. This is the case in Pipe Mine, Owl, and Balmertown. Sept-Iles is a layered intrusion, with more variations in lithology near the bottom. The observation of the reviewer that there are fluctuations in temperature gradient at the base of the holes is indeed correct, but there is nothing unusual about it. Our results are typical and resemble those present in other publications (e.g., Clauser et al., 1997; Mottaghy et al., 2005; Demezhko et al., 2013).

2) Estimates of ground surface temperature (GST) histories derived using inversion techniques also seem to be incorrect. Consider for example the GST history reported for Flin Flon (Manitoba). It indicates temperatures less than 2oC for the period of last glacial maximum (around 10000 to 20000years BP), which is followed by temperatures in excess of 6oC at times greater than approximately 50000 years BP (see upper panel in Figure 4 of the discussion paper). Such high temperatures are in sharp contrast with values of 0 to 1oC reported for two nearby sites (Pipe and Owl) in Manitoba (see lower panels in Figure 4 of the discussion paper).

Although Thompson and Flin-Flon are both in Manitoba, these towns are 350 km apart with significantly different ground surface temperature conditions at present. Ground surface temperature is near freezing at Thompson and ≈4^oC at FlinFlon. This difference is noted in our Table 2 that shows that the reference ground surface temperature is 3-4^oC higher at Flin Flon than in Thompson. With present temperature near freezing at Thompson, it is not surprising that the GSTH does not indicate much variations if temperatures were not much below freezing point during the LGM.

3) In addition, unpublished results of inversions (carried out using the same primary data set for Flin Flon) indicate GST less than 1oC for the time interval of 20000 to 100000 years and values of about 3oC for the time interval of 200000 to 1000000 years. A comparison of the two inversion results for Flin

Flon is presented in Figure (2).

The reviewer compares our inversion results with results obtained with a different algorithm the source of which is not specified. (We assume that it is the functional space inversion of Shen and Beck (1991)). We note that we inverted the 3,000m temperature profile for a GST covering 100,000 years while the reviewer's inversion covers 1,000,000 years. This difference in time scales invalidates any possible comparison between the two results. A second point is that it is impossible to resolve a 1My GST from a 3000m profile as the reviewer has tried. Considering the differences, one could wonder why the two GSTH are not extremely different. As a matter of fact, the range of temperatures in the two inversions is the same but the timing of the of the minima maxima is different which is not surprising in view of the different periods involved. Our GST history reconstruction for Flin Flon is consistent with the findings of Sass et al. (1971) that the Last Glacial Maximum surface temperature could not have been more than 5 K colder than present.

4) The SVD code used in the discussion paper does not make use of smoothing constraints. That works fine when the GSTH is divided into steps of equal time duration. However, when dealing with GSTH of over 100,000 years, it becomes necessary to use steps of unequal duration. This is when a smoothing constraint, which requires the GSTH to become increasingly smoother into the past, becomes essential. I suspect that the lack of smoothing is probably the cause of poor result obtained for Flin Flon. In this context, it is convenient for the authors of the discussion paper to verify the computational procedures and data set used in the inversion program.

The reviewer is mistaken. It is obvious from the figure that the GSTH is not divided in steps of equal duration since the time scale is logarithmic. Concerning smoothing, the singular value decomposition smoothes the solution by using a singular value cutoff which in practical terms filters out the high frequency part of the solution or by damping progressively the part of the solution corresponding to small singular values (Mareschal and Beltrami, 1992; Clauser and Mareschal, 1995). If SVD did not smooth out efficiently high frequency noise, the spikes noted by the reviewer in the heat flow profile, would be included and cause non-physical oscillations in the GSTH. Incidentally, this method has been thoroughly tested, compared with other methods, validated, and used many times (e.g., Shen et al., 1992; Beck et al., 1992).

5) Table 3 is not referred to in the text. Missing references: Fahnestock et al., 2001; Pritchard et al., 2012.

The reviewer is correct. These corrections will be made.

References

Beck, A. and Judge, A.: Analysis of Heat Flow Data—I Detailed Observations in a Single Borehole, Geophysical Journal International, 18, 145–158, 1969.

Beck, A., Shen, P., Beltrami, H., Mareschal, J.-C., Šafanda, J., Sebagenzi, M., Vasseur, G., and Wang, K.: A comparison of five different analyses in the interpretation of five borehole temperature data sets, Palaeogeography, Palaeoclimatology, Palaeoecology, 98, 101–112, 1992.

Clauser, C. and Mareschal, J.-C.: Ground temperature history in central Europe from borehole temperature data, Geophysical Journal International, 121, 805–817, 1995.

Clauser, C., Giese, P., Huenges, E., Kohl, T., Lehmann, H., Rybach, L., Šafanda, J., Wilhelm, H., Windloff, K., and Zoth, G.: The thermal regime of the crystalline continental crust: implications from the KTB, Journal of Geophysical Research: Solid Earth (1978–2012), 102, 18 417–18 441, 1997.

Demezhko, D. Y., Gornostaeva, A. A., Tarkhanov, G. V., and Esipko, O. A.: 30,000 years of ground surface temperature and heat flux changes in Karelia reconstructed from borehole temperature data, Bulletin of Geography. Physical Geography Series, 6, 7–25, 2013.

Jaupart, C. and Mareschal, J.: Heat generation and transport in the Earth, Cambridge University Press, 2010.

Mareschal, J.-C. and Beltrami, H.: Evidence for recent warming from perturbed geothermal gradients: examples from eastern Canada, Climate Dynamics, 6, 135–143, doi: 10.1007/BF00193525, 1992.

Mareschal, J.-C., Rolandone, F., and Bienfait, G.: Heat flow variations in a deep borehole near Sept-Iles, Québec, Canada: Paleoclimatic interpretation and implications for regional heat flow estimates, Geophysical Research Letters, 26, 2049–2052, doi:10.1029/1999GL900489, 1999.

Mottaghy, D., Schellschmidt, R., Popov, Y., Clauser, C., Kukkonen, I., Nover, G., Milanovsky, S., and Romushkevich, R.: New heat flow data from the immediate vicinity of the Kola superdeep borehole: Vertical variation in heat flow confirmed and attributed to advection, Tectonophysics, 401, 119–142, 2005.

Sass, J. H., Lachenbruch, A. H., and Jessop, A. M.: Uniform heat flow in a deep hole in the Canadian Shield and its paleoclimatic implications, Journal of Geophysical Research, 76, 8586–8596, doi:10.1029/JB076i035p08586, 1971.

Shen, P., Wang, K., Beltrami, H., and Mareschal, J.-C.: A comparative study of inverse methods for estimating climatic history from borehole temperature data, Palaeogeography, Palaeoclimatology, Palaeoecology, 98, 113–127, 1992.

Shen, P. Y. and Beck, A. E.: Least squares inversion of borehole temperature measurements in functional space, Journal of Geophysical Research: Solid Earth, 96, 19 965–19 979, doi: 10.1029/91JB01883, 1991.