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Thermal history of the Earth: Reply to “Less is not always more: A more inclusive data-filtering approach to secular mantle cooling” by Ross N. Mitchell and Jérôme Ganne

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The Earth is presently cooling down by convecting its heat from the interior to the surface, where it can be dissipated into space. And as the Earth cools down, so does its internal temperature which is typically expressed as the mantle potential temperature T_P; this is the temperature at which the adiabatically convecting ambient mantle would be at the surface if it did not melt. Together with heat from the core, Earth's endowment of radiogenic uranium, thorium and potassium heated ambient mantle, competing with plate tectonic-driven mantle convective heat loss to cool the Earth. It is the balance between heating and cooling over time that defines the thermal history of the Earth.

Mantle petrology can be used to test ambient mantle thermal history models because the MgO contents of basaltic primary magmas from the mantle are positively correlated with mantle potential temperature (Herzberg and Asimow, 2015 and references therein). Of the many models, results presented by Herzberg et al. (2010) on non-arc basalt samples having a wide range of ages are most consistent with the thermal history model of Korenaga (2008) shown in Fig. 1a of the Comment paper by Mitchell and Ganne (2022). They are also similar to results presented by Ganne and Feng (2017) using PRIMELT3 software of Herzberg and Asimow (2015) at the same oxidation state of iron ($FeO/FeO_T = 0.9$) at which the primary magma compositions were calculated from erupted basalt compositions. If the same software was used to obtain similar results, how did Ganne and Feng (2017) arrive at the conclusion that Precambrian ambient mantle was cooler than the model of Herzberg et al. (2010) and Herzberg (2022)? This needs to be clarified because the Ganne and Feng (2017) paper is often cited in scholarly works that prefer a cool early Earth ambient mantle.

Ganne and Feng (2017) bracketed a range of mantle potential temperature T_P solutions with minima that they assumed defined ambient mantle and maxima that corresponded to mantle plumes. It is notable that the Age - T_P minima was based on the more oxidizing condition ($FeO/FeO_T = 0.8$) shown by the broken green line in Fig. 1a of Mitchell and Ganne (2022). The new Age - T_P minima shown by the solid blue line and mislabeled “Ganne and Feng (2017)” is for the more reducing condition at which the primary magma compositions were computed (i.e., $FeO/FeO_T = 0.9$). Ganne and Feng (2017) provided no geodynamic discussion for the petrological T_P solutions that plotted above their ambient mantle line other than commenting that thermal maxima originated from instabilities at the core-mantle boundary; that is, mantle plumes were implied. However, Mitchell and Ganne (2022) were more specific in that all the petrological solutions that plot above the ambient mantle line do so owing to plume-ridge interaction. They further conjectured that a full understanding of the thermal history of the Earth requires a “more inclusive” approach that includes basaltic rocks formed by mantle plumes.

My paper on the Paleoproterozoic Circum-Superior Large Igneous Province (Herzberg, 2022) was specifically designed to test the popular model that it formed in a mantle plume, and the results are relevant to the discussion raised by Mitchell and Ganne (2022). The basalts and low MgO komatiites in the CSLIP were a joy to work with because many of them display unambiguous igneous fractional crystallization geochemical trends that rival those of modern fresh rocks. There are no better Precambrian basaltic rocks to work with. This attribute allowed for the first time an evaluation to be made of how T_P estimates extracted from Precambrian basalts could be compromised by mineralogical sorting/accumulation during fractional crystallization and mixing. However, unlike many modern basalts, rocks in the CSLIP have all been metamorphosed to varying degrees, from the greenschist to granulite facies, and it was necessary to evaluate the effects of Fe mobility on T_P calculation. After careful evaluation of mineralogical sorting and metamorphism, I concluded: “*Implementation of PRIMELT3 software (*Herzberg and Asimow, 2015*) on a large database of basalts and komatiites from the Circum-Superior Large Igneous Province reveals limited variability in primary magma composition and inferred mantle potential temperature (Fig. 8; Table 1). Most of the variability is demonstrated to arise from Fe mobility during metamorphism and olivine addition into*

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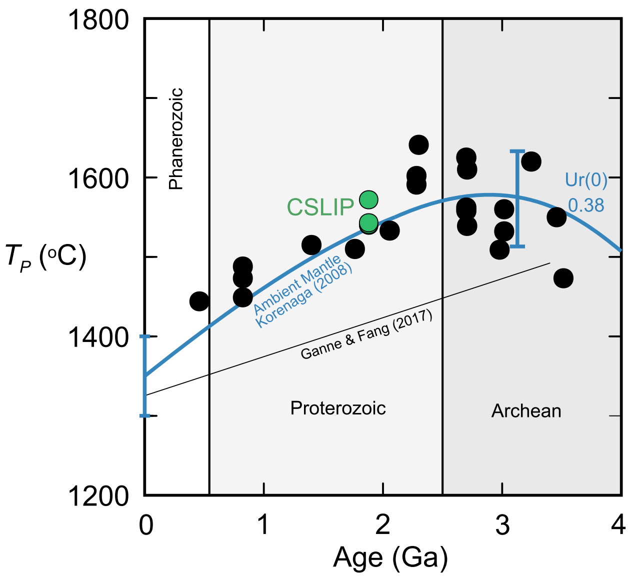

Fig. 1. Mantle potential temperatures T_P for primary magmas of Precambrian non-arc basalts and mean T_P for members of the Circum-Superior Large Igneous Province (CSLIP), modified from Herzberg (2022) to exclude samples having a mantle plume provenance. The blue T_P bracket shows a 120 °C variability in T_P solutions for most non-arc basalts that arise from thermal heterogeneity of ambient mantle, metamorphism, and mineralogical sorting.

differentiated magmas. For volcanic rocks from the Cape Smith Belt, Roberts Lake, Thompson Nickel Belt, and the Fox River Belt, the mean MgO content is 19.1 % and the mean T_P is 1541 °C; Winnipegosis komatiite means are slightly higher, 20.3 % MgO and 1572 °C. The T_P range for the CSLIP was therefore only about 30 °C, highly uniform ove ~12 to 15 million years in time and over 1500 km in space from the Cape Smith Belt in the north to the Winnipegosis Belt in the southwest (Fig. 1). This limited long wavelength variation in T_P is characteristic of modern ambient mantle magmatism below oceanic ridges and any other plate tectonic environment removed from the influence of hotspots, not mantle plumes."

The evidence presented in my paper (Herzberg, 2022) does not support the conclusion of Mitchell and Ganne that the Circum-Superior LIP formed by plume-ridge interaction. And their only critique of my conclusions is an inaccurate misrepresentation of my work. They state: "We note that the Gaussian shape and range of the zero-aged MORB data match closely that of the Circum-Superior LIP (Fig. 8 of Herzberg (2022)), indicating that the Circum-Superior LIP is also sampling a mix of the two endmembers as MORB does today." They are referring to the 2σ variation of 68 °C about the 1555 °C mean in T_P obtained on 86 primary magma solutions displayed in Fig. 8 of my paper. Apparently, Mitchell and Ganne (2022) failed to read the figure caption which states: "*Most of the variability is not a measure of true thermal variations in the mantle, but arises from metamorphic alteration and olivine addition as discussed in the text.*"

There is a ~150 °C variation in T_P for primary magmas of non-arc basalts in the Archean as seen in Fig. 1a in Mitchell and Ganne (2022) and Fig. 1 in Herzberg et al. (2010). There are two likely sources for this variability that have nothing to do with plume-ridge interaction.

1. Long wavelength variations in T_P within ambient mantle. Dalton et al. (2014) estimated a temperature range of 100–150 °C for modern oceanic ridges that are located > 700 km from hot spots. The lower bound, 100 °C, is consistent with petrological constraints (Herzberg et al., 2010). Most current estimates for MORB-producing ambient mantle have $T_P = 1350$ °C, and to this we can add the Dalton et al. (2014) range as an uncertainty of ±50 °C. It is notable that 1350 °C is lower than 1440 °C offered by Mitchell and Ganne (2022) by application of PRIMELT3 software to 235 MORB samples with MgO > 8 %. However, it can be shown that their calculations have been compromised because the basalts were produced by fractional crystallization along an olivine + plagioclase + augite liquid line of descent and mixing with a primary magma produced at T_P = 1350 °C. PRIMELT3 can only restore a primary magma composition that differs from an erupted basalt composition by olivine-only crystallization, a significant limitation in its use.
2. There is ±68 °C variation owing to metamorphic alteration and Fe-rich olivine addition as I demonstrated for the Circum-Superior LIP. All Precambrian non-arc basalts have been metamorphosed to varying degrees, resulting Fe mobility that can compromise T_P solutions.

Summing these two sources of variability as errors in the Korenaga (2008) thermal history model yields a 2σ temperature variation ±60 °C as I show in Fig. 1. The temperature range of 120 °C describes very well the variability in T_P solutions for most non-arc basalts. Modest thermal heterogeneity of ambient mantle, metamorphism, and mineralogical sorting are reasonable and expected mechanisms for the variability in T_P for all Precambrian non-arc basalts. This obviates the need for explanation by plume-ridge interaction as suggested by Mitchell and Ganne (2022) or any other global geodynamic process. In summary, the thermal history of ambient mantle in the Earth is represented by Precambrian non-arc basalts, and it is well-described in Fig. 1 by the Korenaga (2008) curve with a present-day Urey ratio of 0.38:

$$T_P = (1350 - 156t)/(1 - 0.198t + 0.0172t^2) \tag{1}$$

where T_P is mantle potential temperature (°C) at time t (Ga) in the past.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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