# Supporting Information for "Deep heat: proxies, Miocene ice, and an end in sight for paleoclimate paradoxes?"

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## Text S1. Derivation of main text Fig. 1.

Analytical reproducibility:
1. $\delta^{18}$O. Long term reproducibility of NBS-19 is typically 0.07‰; using an approximate relationship between $\delta^{18}$O and temperature of 0.23‰/1°C gives ±0.28°C [Marchitto *et al.*, 2014].
2. Mg/Ca. Analytical reproducibility is typically better than 3%; using an approximate relationship between Mg/Ca and temperature of 5%/1°C gives ±0.60°C [Lear *et al.*, 2010].
3. Mg/Li. Long-term Li/Ca precision is ∼2%; using a linear Mg/Li-temperature slope of 0.0124, percent error depends on the absolute Mg/Li value, ranging between 0.21-0.43 °C at temperatures of 5-20°C [Bryan & Marchitto, 2010].
4. $\Delta_{47}$. Analytical-derived uncertainty depends on how replicate measurements are pooled [see Modestou *et al.*, 2020]. A typical uncertainty from their Fig. 4f is ±3.1°C.

The carbonate system:
1. $\delta^{18}$O. Uchikawa & Zeebe, [2010] report a slope of −0.89 between $\delta^{18}$O and pH in a planktonic foraminifer species. Given a Neogene pH range of between +0.15 to −0.3 units relative to today [Sosdian *et al.*, 2018], this equates to a temperature bias of +0.73 to −1.47°C based on the above relationship between $\delta^{18}$O and temperature. Note that the pH effect present in planktonic foraminifera has so far not been found in benthic species such that this source of uncertainty remains hypothetical [Marchitto *et al.*, 2014].
2. Mg/Ca. Using a Mg/Ca-[$CO_3^{2-}$] slope of 0.0086, a possible [$CO_3^{2-}$] variation of ±40 $\mu$mol/mol [Lear *et al.*, 2010; Yu *et al.*, 2013], and the above relationship between Mg/Ca and temperature, the possible temperature bias is +3.17 to −3.77°C [Lear *et al.*, 2010; 2015].
3. Mg/Li. As this proxy aims to account for $\Delta$[$CO_3^{2-}$], no bias is assumed.
4. $\Delta_{47}$. No carbonate system control has been identified over the range that these parameters are likely to have varied over the Cenozoic [Tripati *et al.*, 2015].

Seawater elemental or isotopic chemistry:
1. $\delta^{18}$O. Assuming seawater $\delta^{18}$O can vary between −1‰ VSMOW (ice free) and +1‰ (LGM conditions) in the deep ocean, this equates to a temperature bias of ±4.55°C based on the above relationship between $\delta^{18}$O and temperature.
2. Mg/Ca. Using a power seawater-shell Mg/Ca relationship with a coefficient of 0.52 [Evans & Müller, 2012], and considering that the seawater Mg/Ca ratio in the Neogene was up to 2 mol/mol lower than today (but never higher than at present) [Evans *et al.*, 2018], Mg/Ca-derived temperatures could be up to 5.01°C too cool based on the above relationship between Mg/Ca and temperature.
3. Mg/Li. The effect of changing seawater chemistry on Mg/Li is difficult to determine because little is known about the secular evolution of the seawater Mg/Li ratio. If [Li] remained constant, and Neogene seawater [Mg] was up to 20% lower than at present [Brennan *et al.*, 2013], then Mg/Li could be biased on the order of ∼1-2°C, although this remains to be determined.
4. $\Delta_{47}$. No seawater chemistry control has been identified.

**Text S2. Recalculation of Mg/Ca SST shown in main text Fig. 2.**

Mg/Ca data from Shevenell *et al.* [2004] were recalculated using the *Globigerina bulloides* equation of Gray & Evans [2019], which accounts for changes in pH. Middle Miocene pH was taken from Sosdian *et al.* [2018], with linear interpolation between the data reported in that study. Because seawater Mg/Ca was lower than modern in the Miocene [Evans *et al.*, 2018], the constant term of the calibration equation was modified to account for this, by multiplying by $3.5^{0.64}/5.2^{0.64}$, where 3.5 and 5.2 are the Miocene and modern seawater Mg/Ca ratios respectively, and 0.64 is an estimate of the power coefficient of the seawater-calcite Mg/Ca relationship based on a compilation of several calibrated species as well as inorganic calcite [Mucci & Morse, 1983; Evans *et al.*, 2015; 2016; Holland *et al.*, 2020].

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