The influence of plate cooling models and convection on early Earth mid-ocean ridge depths

Shradha Ravikumar[1], Keneni Godana[2], Shi Joyce Sim[3]
[1]Lamont-Doherty Earth Observatory, [2]University of California Santa Barbara, [3]Georgia Institute of Technology

Background and Motivation: Mid-ocean ridges and the origin of life

Mid-ocean ridges (MORs) are promising candidates for the location of life's origin on Earth. At modern day MORs, seawater percolates into heated oceanic crust, driving extensive hydrothermal alteration that supports complex vent ecosystems. However, the notion that early Earth MORs provided a geothermal energy gradient that ancient life could take advantage of is still under debate.

A major factor influencing the extent of water-rock interaction at MORs is the depth of the ridge crest below sea level. Previous work suggests that **an MOR depth of 2400-2900 m below sea level allows for the maximum depth of water penetration into oceanic crust**, which would allow for emerging life to fully access the energy available from hydrothermal activity (Kasting et al. 2006).

Research questions

1. **How do different modeling parameters influence modeled MOR depth?**
2. **Was MOR depth below sea level on the Archean and Hadean Earth sufficient enough for percolating water to reach maximum depths within oceanic crust?**

Methods and Results: Modeling ridge depth

We use synthetic seafloor age maps of the Earth with **0%, 10%, and 30% of its surface covered in continental crust.** These maps were previously generated using global spherical mantle convection models (Coltice et al. 2012, 2014).
Then, those age maps can be used to calculate subsidence (depth of the seafloor below sea level). We vary subsidence (and therefore the bathymetry of our modeled seafloor) over time by:

1. **Using different plate cooling models** (Stein & Stein 1992; Hasterok 2013; Rosas & Korenaga 2021; Korenaga et al. 2021), and
2. **Changing the Rayleigh number (Ra)** to alter convective rigor. We take 4.4×10^8 as the current Ra (Sim et al. 2016), and test convective rigor 10 and 100 times higher than present day.

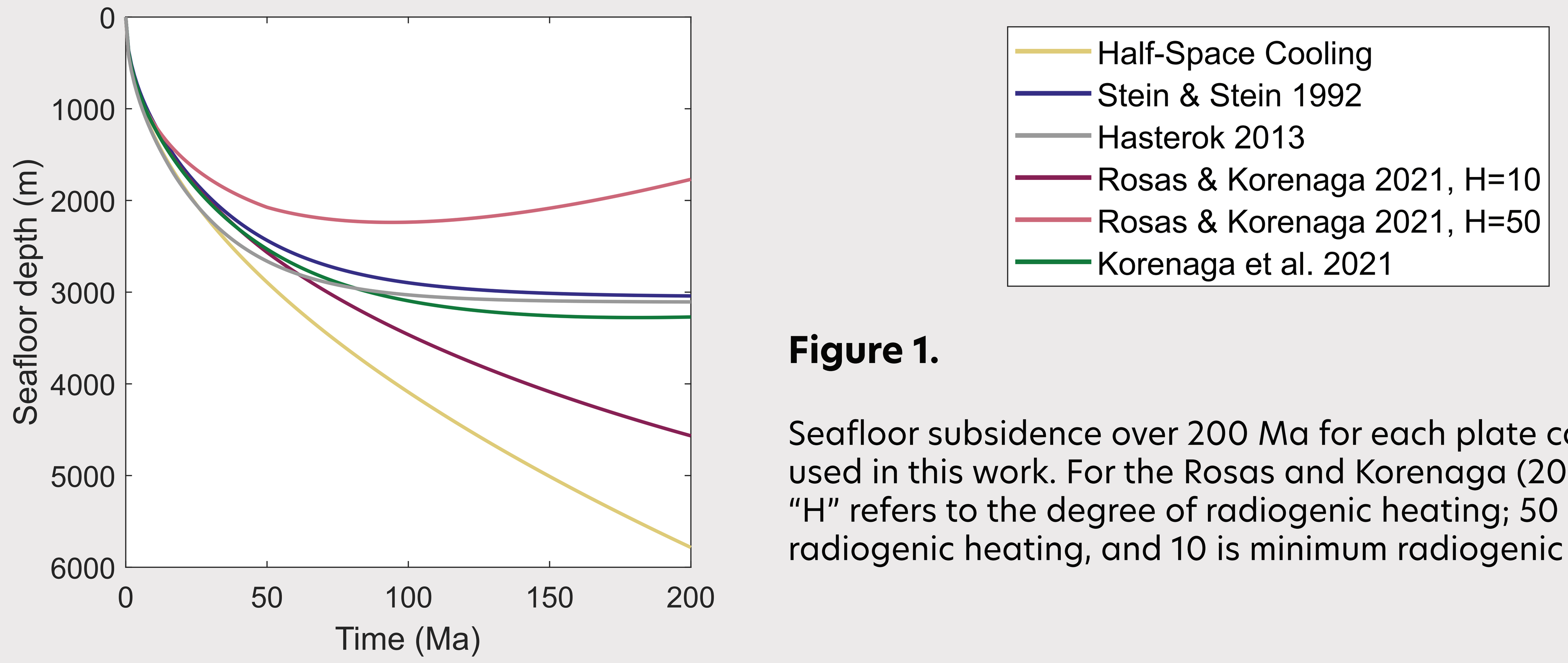


Figure 1.

Seafloor subsidence over 200 Ma for each plate cooling model used in this work. For the Rosas and Korenaga (2021) model, "H" refers to the degree of radiogenic heating; 50 is maximum radiogenic heating, and 10 is minimum radiogenic heating.

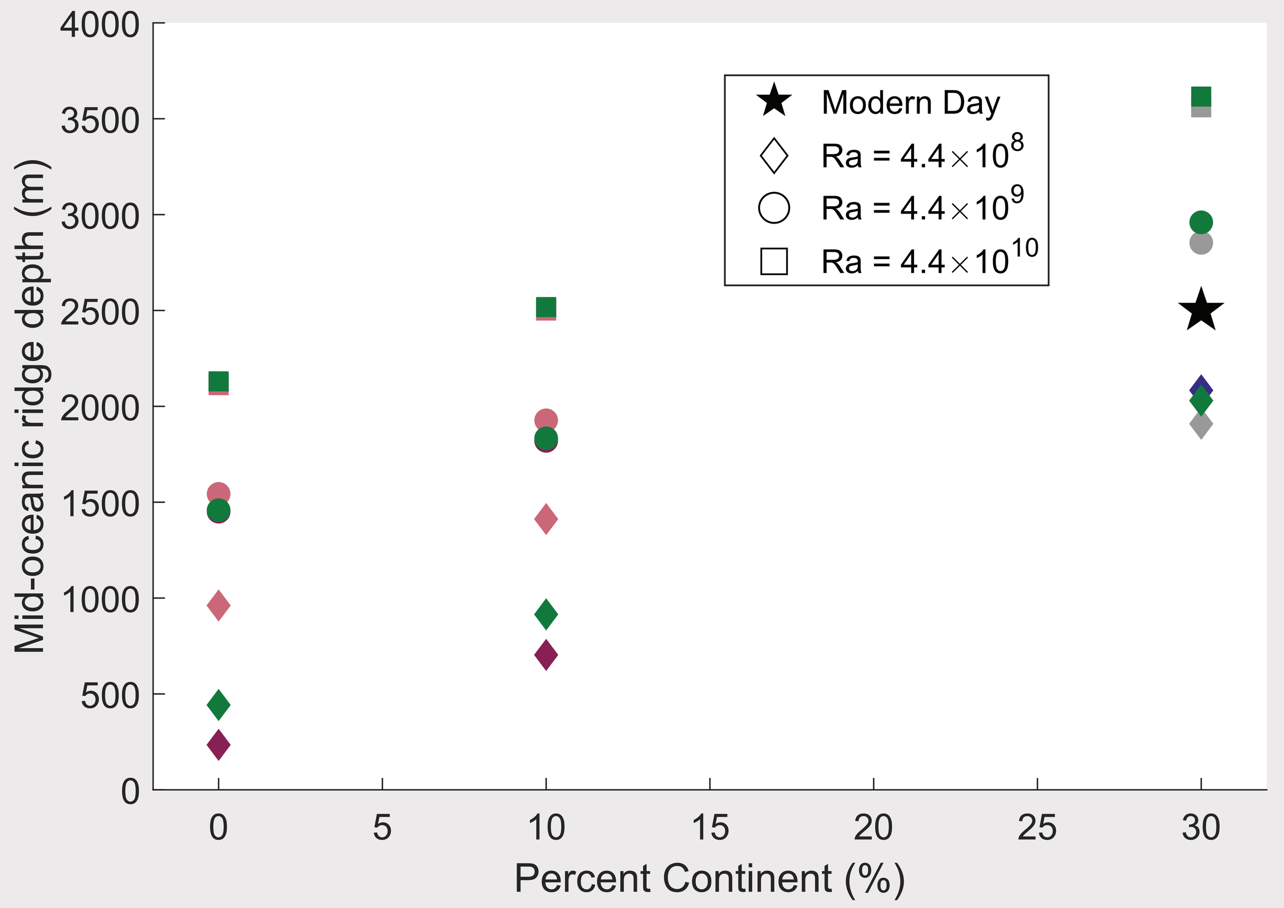


Figure 2.

Calculated average mid-ocean ridge depth vs. percent continent used in each calculation; Ra used for each data point is denoted by shape, while different colors represent different plate cooling models. The black star represents the average measured MOR depth on Earth today (~2500 m). Displayed data points are selected based on physical plausibility of each modeled depth. For 30% continent data points (which reflect the amount of continental crust today), the effects of sediment loading were not taken into account; when considered, roughly ~500 m is added to MOR depth.

Discussion and Conclusions

MOR depth evolution over time

Following Sim et al. (2016), we correlate the percent crust used in each calculation with an age based on the crustal growth model described in Korenaga (2018). The convective regime of the early Earth is a matter of much debate; while it has traditionally been assumed that convection was more rigorous in the past and slowed over time, recent work suggests that convection may have remained steady since the Hadean. Taking this into account, **we show how MOR depth varies with age while undergoing steady convection matching that of present day (Figure 3) and while undergoing slowing convection (Figure 4).**

MOR depth gets deeper over time with constant convection.

MOR depth is similar to present day in the Hadean and shallower than present day in the Archean with slowing convection.

For all plate cooling models used, the same patterns in MOR depth evolution over time are observed for both constant and slowing convection.

MOR depth and potential early hydrothermal alteration depth

As the exact sea level on the early Earth is unknown, **we calculated MOR depth with a range of ± 0.2 oceans for the Archean and ± 0.4 oceans for the Hadean** (again following Sim et al. 2016), where one ocean is defined as the volume of the modern day ocean plus the volume of water currently trapped in ice sheets. These calculations allowed us to plot vertical error bars in our estimates of MOR depth. The upper and lower bounds of MOR depth that allow for percolating water to reach its maximum depth within oceanic crust are plotted, as given by Kasting et al. 2006.

With slowing convection over time, both observation-based and physics-based plate cooling models show that maximum hydrothermal alteration depth may have been achieved on the early Earth.

Figure 3. Mid-oceanic ridge depth vs. Age (constant convection)

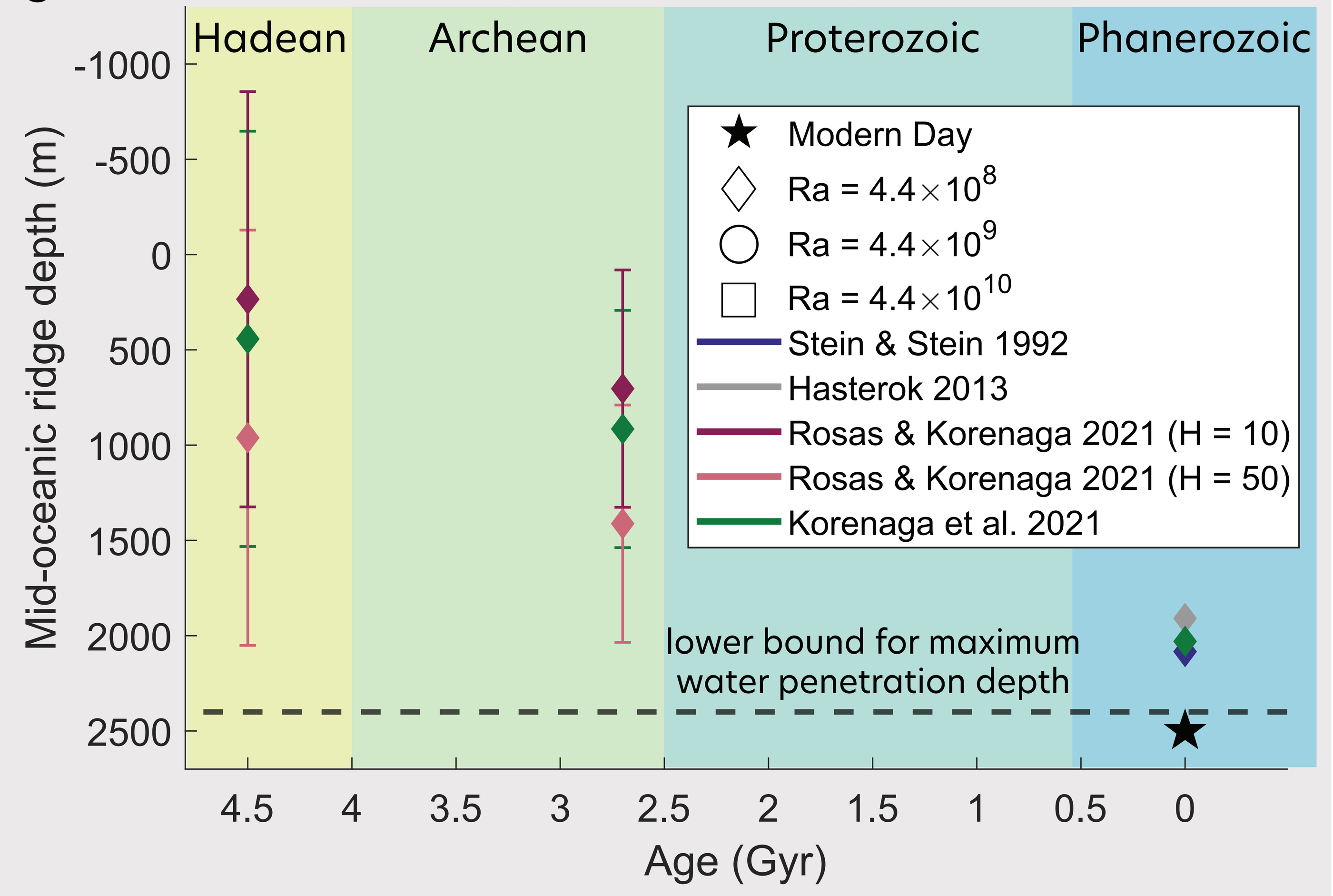
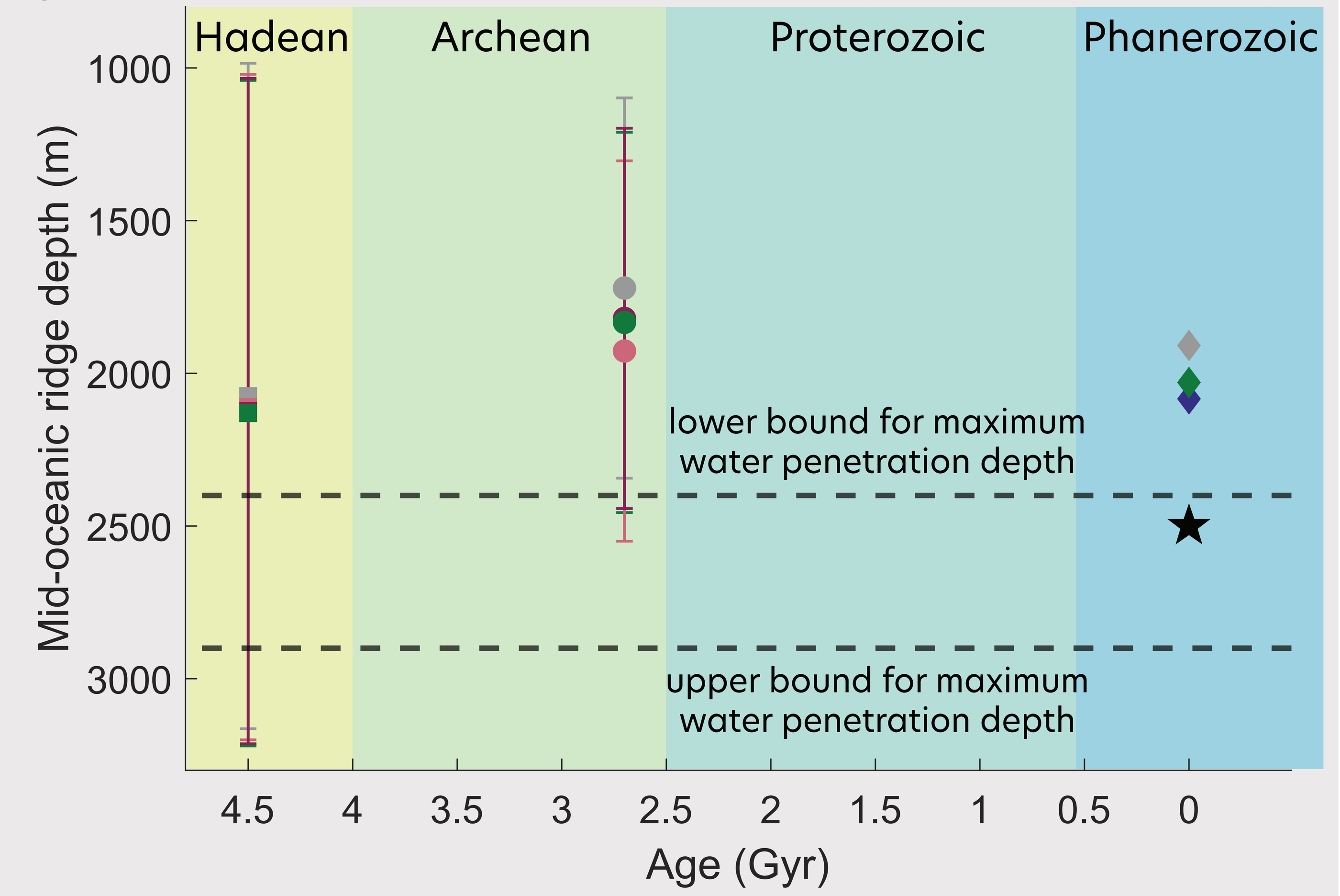


Figure 4. Mid-oceanic ridge depth vs. Age (slowing convection)



Future Work

In future work, changing modeling parameters will allow us to test how MOR depths change under a wider variety of scenarios. Some possibilities include:
- testing different Ra values/water volumes for each eon
- adding the effects of sediment loading to modern day points

Citations and additional data

To view author contact information, citations and all calculated MOR depths, scan this QR code.

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