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Key Points:

- We explore mid-ocean ridge depths in an early Earth scenario with a mobile lid regime and surface boundary layer recycling
- Mid-oceanic ridge depths remained submerged through Earth's history and potentially quasi-static due to continental growth, deepening of ocean basins and deep water recycling
- Conditions for hydrothermal vents may have existed during early Earth, conducive for origins of life

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Influence of continental growth on mid-ocean ridge depth

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Abstract The interconnectedness of life, water, and plate tectonics is strikingly apparent along mid-ocean ridges (MOR) where communities of organisms flourish off the disequilibrium of chemical potentials created by circulation of hydrothermal fluids driven by Earth's heat. Moreover, submarine hydrothermal environments may be critical for the emergence of life on Earth. Oceans were likely present in the Hadean but questions remain about early Earth's global tectonics, including when seafloor spreading began and whether mid-oceanic ridges were deep enough for maximum hydrothermal activities. For example, plate tectonics influences global sea level by driving secular variations in the volume of ocean basins due to continental growth. Similarly, variations in the distribution of seafloor age and associated subsidence, due to assembly and dispersal of supercontinents, explain the largest sea level variation over the past 140 Myr. Using synthetic plate configurations derived from numerical models of mantle convection appropriate for early Earth, we show that MOR have remained submerged and their depths potentially constant over geologic time. Thus, conditions in the early Earth existed for hydrothermal vents at similar depths as today, providing environments conducive for the development of life and allowing for processes such as hydrothermal alteration of oceanic crust to influence the mantle's geochemical evolution.

1. Introduction

Earth's oceans have played an important role in the evolution of life and tectonics on Earth, including establishing conditions for the deep biosphere at mid-oceanic ridges (MORs) [*Nisbet and Sleep*, 2001], promoting single-sided and asymmetric subduction [*Gerya et al.*, 2008], and the emergence of stable continental platforms [*Flament et al.*, 2008]. The early Earth is expected to have started with a warmer mantle and cooled over time such that the associated Rayleigh number for the mantle would have been higher in Earth's past. The nature of tectonics that occurred during the early Earth is unknown, with some studies proposing that Earth was in a stagnant lid tectonic regime [*Debaille et al.*, 2013; *O'Neill and Debaille*, 2014] and possibly cooled primarily through volcanism [*Moore and Webb*, 2013] and that possibly drip-tectonics generated Archean crust through delamination of unstable crust [*Johnson et al.*, 2014; *Manning*, 2004]. Other studies support the uniformitarian view that recycling of the lithosphere, in some form, has occurred throughout Earth's history [*Höning and Spohn*, 2016]. However, geodynamic models indicate that subduction operates differently in a higher mantle temperature, perhaps with more shallow underthrusting [*Sizova et al.*, 2010]. For this study, we do not presume that plate tectonics was operating in its present form but we explore the scenario in which some kind of mobile lid regime existed with a surface boundary layer being recycled at a rate that could accommodate the higher Rayleigh number.

Hydrothermal activities at MORs make them a potential locational candidate for the origin of life [*Nisbet and Sleep*, 2001]. The maximum depth of hydrothermal penetration into oceanic crust at mid-oceanic spreading centers is a primarily a function of the MOR crest depth, but also depends on many things that would be different for the early Earth such as the seawater chemistry, the thickness and porosity of the ocean crust, and the rate of pelagic sedimentation [*Kasting et al.*, 2006]. Hydrothermal penetration depth also alters the oceanic crust that is being subducted back into the mantle through metasomatism [*Staudigel*, 2014]. The subduction of altered oceanic crust brings volatiles like water and carbonates down into the mantle [*Manning*, 2004; *Jarrard*, 2003], creating flux melting in the mantle wedge as the subducted crust gets dehydrated [*Plank and Langmuir*, 1993; *Plank et al.*, 2009; *Hacker*, 2008]. Thus, not only does the suitability of the hydrothermal environment for the origin of life on Earth depend on the MOR depth, but so does the cycling of elements into Earth's deep interior.

Models of relevant tectonic processes and geochemical observations can help to understand the otherwise poorly known depth of early Earth's oceans, in particular, the depth to which MORs were submerged, which is also debated [*Kasting et al*., 2006]. MOR depth depends on the ocean basin volume over time as well as the total volume of ocean water. Previous global sea level models account for ocean basin volume by considering globally averaged seafloor subsidence based on a parameterized global heat flow model [*Schubert and Reymer*, 1985] that neglected fluctuations of seafloor age distribution [*Labrosse and Jaupart*, 2007]. Such fluctuations, attributed to the changing distribution of continents on the Earth's surface [*Coltice et al*., 2012], have a greater impact on global sea level compared to variations of spreading rates [*Xu et al*., 2006; *Loyd et al*., 2007]. Indeed, the ocean basin volume based on reconstructed seafloor age distributions since 140 Ma compares favorably with the observed long-term trend of global sea level over the same time [*Müller et al*., 2008]. Additionally, the amount of Earth's surface covered by continents also drives significant variation of seafloor age distribution [*Coltice et al*., 2014] but the corresponding effect on global MOR depth has yet to be investigated. This study uses mantle convection models to address the question of how the depth of the MOR may have changed over geologic time.

2. Model Setup

The 3D spherical mantle convection models computed here have similar parameterizations to those previously published [*Bello et al*., 2015], except that no surface velocities are imposed here (so we model convection with free slip boundary conditions). We solve the equations of incompressible convection using the StagYY code [*Tackley*, 2008]. Viscosity is the only variable material property in our models. Variations of other material properties (expansion coefficient, thermal diffusivity, and heat production) are neglected. The basal heating Rayleigh number *Ra* here is 10^6 in these models, mostly because of computational limitations. The average resolution is 45 km laterally and vertically for all the models. The models have mixed heating, internal heating representing about 85% of the total heat in the system.

The viscosity in our models depends on temperature and depth as

$$\eta(T,z)=\eta(z)\ \exp\left(0.064+\frac{30}{T+1}\right),$$

where z is the depth. The nondimensional activation energy being 30 here produces 6 orders of magnitude of viscosity variations with temperature. The depth dependence of viscosity $\eta(z)$ is taken into account such that a gradual viscosity increase by a factor of 30 occurs between 750 and 850 km depth.

Pseudoplasticity is implemented through a stress dependence of the viscosity with a yield stress [*Coltice et al*., 2012, 2014]. We choose a nondimensional value of 15,000 to produce a plate-like behavior and large-scale convective flow. Continents are modeled as viscous buoyant rafts of complex polygonal shapes [*Rolf and Tackley*, 2011].

The models are started from ad hoc initial conditions, and run for up to 5 billion years to ensure statistical steady state and stability of the dynamic regime. Such long runs ensure that initial conditions are forgotten. From the solutions at statistical steady state, we compute the dynamic evolutions for integration times over 4 Gyr (scaling time with present-day transit time) of the models that are analyzed in this study. The age of the seafloor is computed from the value of the heat flow [*Coltice et al*., 2012, 2014]. Since small-scale convection is limited in these models, this approximation is effective.

For a constant internally heated mantle, an appropriate estimate of the Rayleigh number (*Ra*) of the Earth, gives a value of 4.4×10^8 assuming a mantle viscosity of $\eta=2\times10^{20}$ Pa s. The *Ra* for the Earth corresponds to the observed RMS surface velocity of the Earth, $V_{surf}=3.8$ cm/yr, giving an estimated transit time of the mantle, $\tau_v=H/V_{surf}=73$ Ma using mantle depth of $H=2890$ km. Since we adopt a smaller value ($Ra\sim10^6$) for convection in the numerical model, we have to scale the computed numbers to the present-day Earth's values taking the RMS surface velocity of the model [*Coltice et al*., 2012], thus time is dimensionalized $t=t^{model}\times\tau_v/\tau_v^{model}$.

3. Results

3.1. Estimates of MOR Depths

A natural definition for global sea level in the absence of continental hypsometry [*Flament et al.*, 2011] is the depth of MOR crest. The MOR depth can be estimated by filling the volume of the ocean basins assuming the modern-day volume of water [*Eakins and Sharman*, 2010] and that the continents are never inundated or submerged. Although the total volume of water above any submerged continental shelf, or that above entirely submerged continents, is not accounted for in our models, the additional uncertainty it introduces in our estimates of MOR depth is not significant compared to other sources of uncertainty. To estimate ocean volume, we first generate synthetic seafloor age maps using the methodology in previous studies [*Coltice et al.*, 2012, 2014].

As oceanic crust moves away from mid-oceanic spreading centers where it is created, it not only ages but it also cools and subsides. This bathymetry associated with the synthetic seafloor age distributions is calculated using a half-space cooling model [*Stein and Stein*, 1992; *Hasterok*, 2013]. The total volume of water the ocean basins can accommodate is then calculated by integrating the predicted bathymetry over the Earth's surface.

The computational expense for running global spherical convection models at conditions appropriate for the early Earth is prohibitive. Instead, the values for the reference model can be scaled to higher *Ra* combining the transit time scaling expressed above, and using boundary layer theory which predicts that the surface velocity scales as $Ra^{2/3}$. To approximate conditions for early Earth, we consider the change in Rayleigh number caused by a higher temperature in the mantle. This change is

$$\frac{Ra}{Ra_0}=\frac{\bar{T}\exp\frac{Q}{RT_0}}{\bar{T}_0\exp\frac{Q}{RT}},$$

where the subscript 0 means present day, and $\bar{T}$ is the average temperature of the mantle. It is computed averaging the adiabat over the depth of the mantle. Assuming a temperature of 1590 K beneath oceanic plates today [*McKenzie et al.*, 2005], the average temperature along the adiabat is about 2200 K. *Herzberg et al.* [2010] recently estimated a temperature drop of 150–250 K for the whole mantle since the Archean. Taking into account the propagation of uncertainties on the activation energy for the viscosity (290–520 kJ mol^{-1}) [*Mei and Kohlstedt*, 2000; *Karato and Jung*, 2003], we choose a factor of 10 change in Rayleigh number since the Archean (this value corresponds to the upper one standard deviation). For the Hadean, the temperature of the mantle is at most that of the liquidus and therefore a value of 2700 K is a maximum [*Jaupart et al.*, 2007], and the Archean temperature would be the lower bound. We choose a factor of 100 change in Rayleigh number, again a high-end value for the Rayleigh number considering the propagation of uncertainties. Choosing high-end numbers implies we explore the largest changes we can expect in terms of sea level. These values for *Ra*, in agreement with previously proposed estimates [*Sleep et al.*, 2001; *Zahnle et al.*, 2007], result in faster surface velocities and, on-average, younger seafloor. The resultant transit times of the models, $\tau_v=$ 16.5 and 3.6 Myr, respectively, scale the maximum age of the synthetic seafloor accordingly.

We ran a suite of whole Earth mantle convection models accounting for varying amounts of continents (0, 10, and 30% of total surface area of the Earth) and scale the results for Rayleigh numbers 10 and 100 times larger than today. We calculate MOR depths for each time step of every model, and then compute a single time-averaged MOR depth which is shown in Figure 1. Figure 1 shows MORs become deeper with increasing amounts of continent, because of the associated decreasing surface area available for oceans. Thus, a larger proportion of the ocean volume will be accommodated above the MOR. Figure 1 also shows MOR depths become shallower with decreasing *Ra*, because slower moving plates allow for greater subsidence of the ocean floor which allows ocean basins to hold a larger proportion of the ocean volume. These two effects compete against each other in the case when there are less continents for the higher *Ra* system and more continents in the lower *Ra* system.

3.2. "Modern," "Archean," and "Hadean" Models

Using models described in the previous section, we investigate the effect continental growth has on seafloor age distributions and the associated global MOR depth variations within the context of Earth's thermal

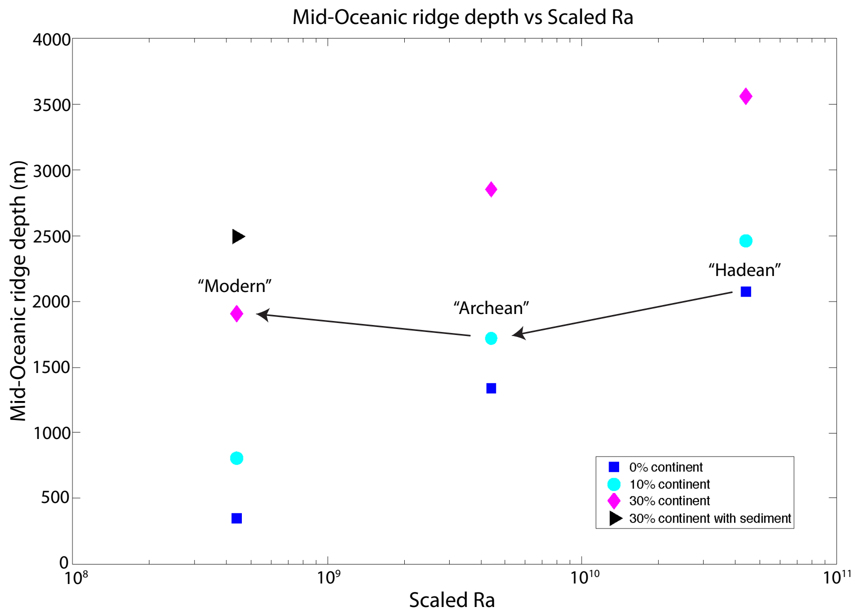

Figure 1. Mean mid-oceanic ridge depth calculated from all mantle convection model runs with corresponding scaled *Ra* and relative amount of continents. Details on the calculations described in text. Black arrows represent our preferred temporal evolution of mid-oceanic ridge depths that we will focus on for the rest of the paper. The rest of the figures in this paper correspond to models following this preferred temporal evolution.

evolution. If one assume that continents have grown and *Ra* in the mantle has decreased monotonically through time, this then limits the possible paths of time evolution of mid-oceanic ridges depth given our suite of models. We have highlighted our preferred path using black arrows in Figure 1.

We explore the scenario that the high *Ra* ($Ra=4.4\times10^{10}$) corresponds to when the Earth had no continents and refer to this as the "Hadean" model. Similarly, we consider that chronologically, as Earth cooled to a lower *Ra* ($Ra=4.4\times10^{9}$) perhaps 10% continents would have been present so we refer to this case as the "Archean" model. Lastly, we consider a "Modern" case to be a model with 30% continents and $Ra=4.4\times10^{8}$. For the "Modern" case, we consider sediments using a sediment thickness model [*Müller et al.*, 2008] fitting modern-day sediment thickness data [*Divins*, 2003] and the corresponding mean MOR is plotted as a black triangle in Figure 1. We will focus on these three models for the rest of the paper.

Figures 2a–c show a representative snapshot of the synthetic seafloor age distribution for each of the three cases. The color scales are the same for all three models. Figure 2a shows an age range for the "Modern" model similar to what is observed on Earth today, as is expected since the RMS surface velocity of the model is scaled to that of present-day Earth. Figures 2b and 2c show that typical ages for synthetic seafloor in the "Archean" and "Hadean" models are much younger than in the "Modern" model.

The blue line in Figure 3a shows the corresponding predicted bathymetry along the equator for the same time step of the "Modern" model shown in Figure 2a. Similarly, Figures 3b and 3c show the bathymetric depth along the equator for the same time step of the "Archean" and "Hadean" models shown in Figures 2b and 2c. The predicted bathymetry for the "Archean" and "Hadean" cases show a progressive shallowing of ocean basins and decrease in ridge-basin offset with increasing *Ra* (Figures 3b and 3c).

In order to make a better comparison between the bathymetry of the "Modern" case and the present-day Earth, certain adjustments need to be made. We estimate the current MOR depth for Earth using the age-area distribution of oceanic plates based upon reconstructed oceanic plate age from 140 Myr to present [*Müller et al.*, 2008], accounting for ice sheets, large igneous provinces and sediments which make significant contributions to ocean floor bathymetry [*Müller et al.*, 2008]. To account for sediment loading, we first obtain the amount of sediments using modern-day sediment model based on NGDC [*Divins*, 2003]. It gives us sediment thickness based on oceanic plate age and latitude. With the calculated sediment thickness, we use *Le Douaran and Parsons* [1982] model for sediment loading. This introduces a downshift in

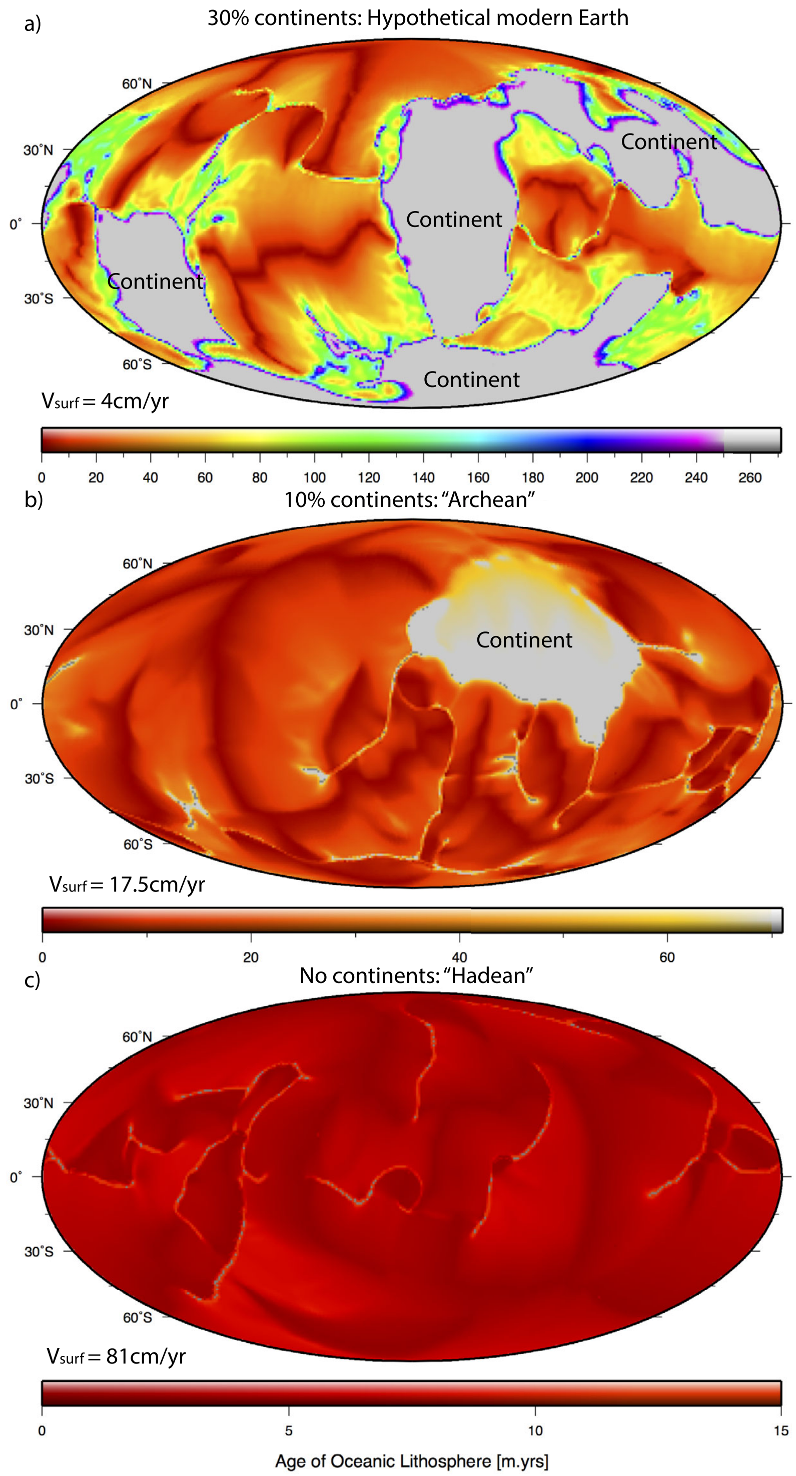

Figure 2. Synthetic seafloor age maps for representative time steps from our preferred models (following the black arrows in Figure 1): (a) $Ra=4.4\times10^8$ with 30% continent ("Modern"), (b) $Ra=4.4\times10^8$ with 10% continent ("Archean"), and (c) $Ra=4.4\times10^{10}$ with 0% continent ("Hadean"). Continents are in grey. Ages of oceanic crust are defined on the same scale for all models.

depth as expected due to isostasy from the increase loading. After accounting for these using a sediment loading model [*Müller et al.*, 2008] and airy isostasy model [*Le Douaran and Parsons*, 1982], the predicted bathymetry (Figure 3a, green line) shifts ~2 km deeper and compares favorably with actual depths of ridges and basins (Figure 3a, red line, 70°E).

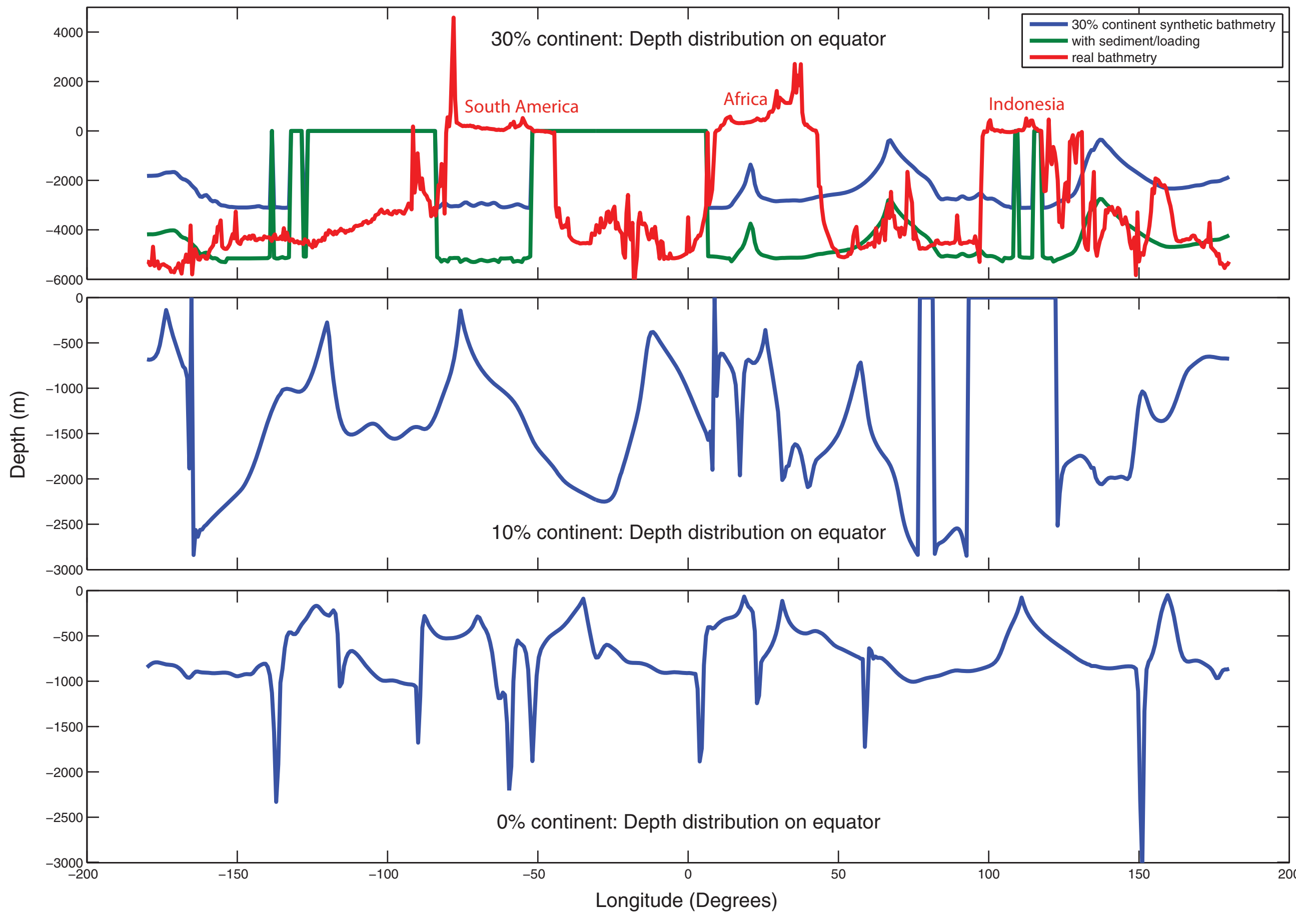

Figure 3. Bathymetric profiles (in blue) along equator of corresponding maps shown in Figure 2 for (a) $Ra=4.4\times10^8$ with 30% continent, (b) $Ra=4.4\times10^8$ with 10% continent, and (c) $Ra=4.4\times10^{10}$ with 0% continent using a plate cooling model [*Hasterok*, 2013]. Ocean bathymetry for 30% continent model has modern-day ocean volume as well as sediment loading model (green curve in Figure 3a) compared to Earth's bathymetry along equator (red curve in Figure 3a) with continents labeled. All three profiles in blue (Figures 3a–3c) are for depth relative to MOR crest of 0 m (note different *y* axes).

We note that the extent of continental inundation is strongly dependent on the choice of hypsometry model used to represent a statistical average of continental topography [*Flament et al*., 2008]. However, the total volume of water above any submerged continental shelf, or that above entirely submerged continents, is negligible in comparison to the ocean volume and therefore not accounted for in our models [*Miller et al*., 2005]. Previous work suggests that the continents were entirely submerged well into the Archean [*Vlaar*, 2000; *Flament et al*., 2008] and that inundation of continents subsequent to their emergence is not significant compared to other sources of uncertainty [*Miller et al*., 2005].

3.3. Variations of Ocean Volume

In Figure 4a, we plot our results of MOR crest depth variations in the "Modern," "Archean," and "Hadean" models (blue, green, and red, respectively) in units of transit times. The MOR depth variations for the "Modern" model with values ranging from ±100 to ±900 m, bracketing the range observed in previous models [*Coltice et al*., 2014], are an order of magnitude larger than that of ±50 m for the "Hadean" model. This is expected since on average the age of subducting oceanic crust is older for the "Modern" model. Transitions between minima and maxima (circles and triangles in Figure 4a) increase with continental area, from $\sim$12 Myr for the 0% continent ($Ra\sim10^{10}$) model compared to $\sim$250 Myr for the "Modern" model. Corresponding histograms of age-area distributions for MOR depths maxima (Figures 4b–d) have a higher proportion of younger crust (thus less subsidence and smaller ocean basin volume) leading to higher sea level while distributions for MOR depths minima (Figures 4e–g) have a higher proportion of older crust representing larger and deeper ocean basins.

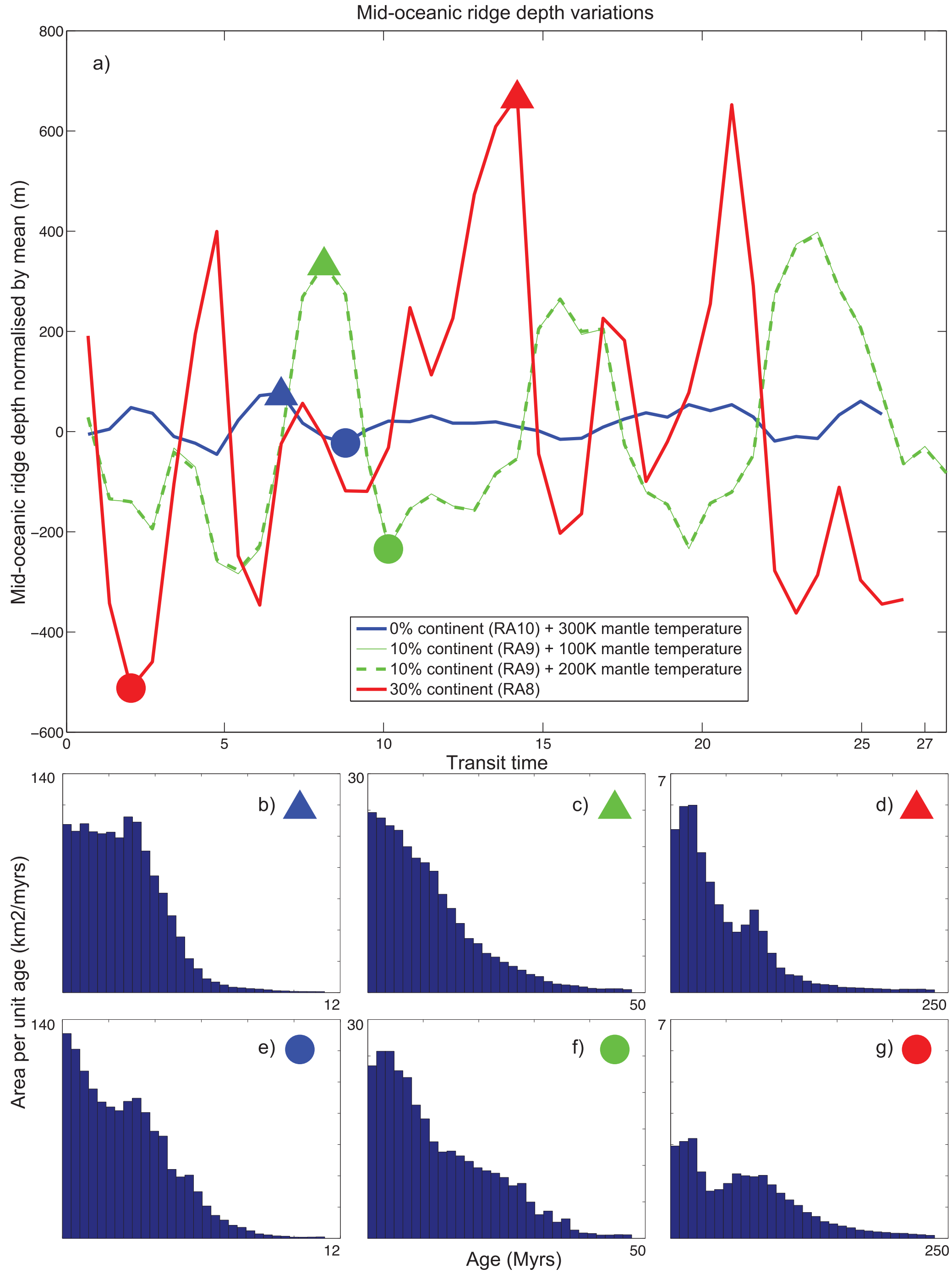

Figure 4. (a) MOR depth based on synthetic seafloor age distributions with 30% (red), 10% (green), and 0% (blue) continents, $Ra \sim 10^8$, 10^9, and 10^{10} respectively, normalized by the mean over 27 transit times, corresponding to 2000, 440, and 100 Myr, respectively. For models with 0% and 10% continents that represent earlier periods of Earth history when the mantle may have been hotter, mantle convection models themselves do not include the temperature increase but variable levels of increased mantle temperature are considered when calculating ocean bathymetry by adjusting the plate cooling model appropriately (as discussed in text). (b–g) Seafloor age distributions corresponding to minima (circles) and maxima (triangles) MOR depths (note different *x* and *y* axes for each distribution).

In Figure 5, we show the mean of all time steps for each model. For the "Modern" model, the mean MOR crest depth is 1900 m (blue diamond) but after correcting for sediment loading, the predicted MOR depth (black diamond) agrees favorably with the observed MOR depth (red star) of ~2500 m. The predicted MOR depths for "Archean" and "Hadean" models are 1700 and 2100 m, respectively, only modestly below the

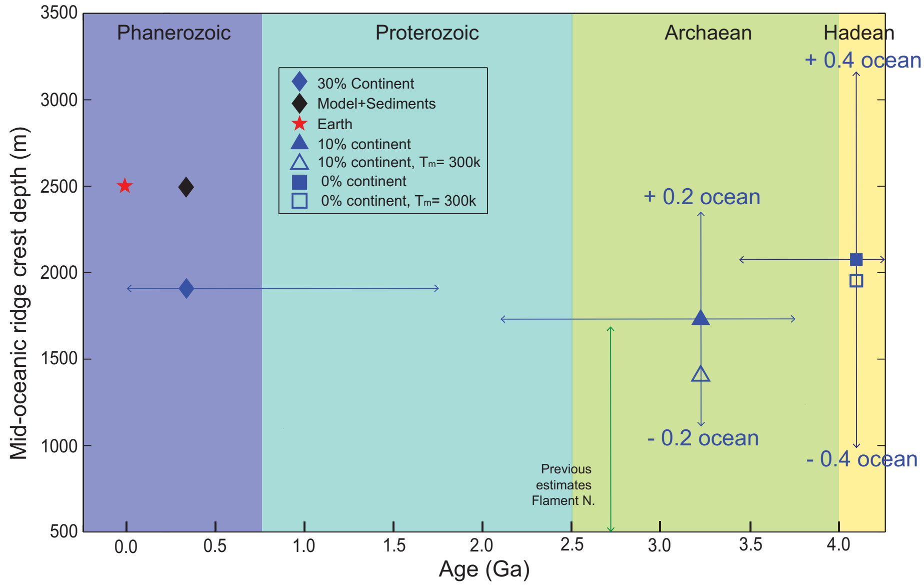

Figure 5. Mean MOR depth based on synthetic seafloor age distributions with 30% (diamonds), 10% (triangles), and 0% (squares) continents ($Ra \sim 10^8$, 10^9, and 10^{10}, respectively). We add sediment loading to the 30% continents model (black diamond) to compare to the actual value for Earth (red star). For models with 0% and 10% continents, we also considered oceanic bathymetry for increased mantle temperature by adjusting the plate cooling model appropriately (open blue square and triangle respectively). Uncertainty in the time period for each model is shown using light blue horizontal lines (as discussed in text). Uncertainty in past ocean volume for models with 0% and 10% continents is shown (light blue vertical lines) as ±40% and ±20%, respectively, with one ocean defined as the current amount of ocean water based on ETOPO1 [*Eakins and Sharman*, 2010] and including the amount of water presently in the ice sheets.

present-day depth. Variable levels of temperature increase in the mantle affects the oceanic plate bathymetry and we reflect that by adjusting ΔT in the coefficient of the plate cooling model which effects the degree of seafloor subsidence [*Davies*, 1999]. The Archean mantle is considered to be 100−300°C warmer than today based on Archaean-aged high magnesium komatiites [*Herzberg et al.*, 2010]. When a range of warmer mantle temperatures (100–300°C) are considered for a posterior calculations of seafloor bathymetry, the MOR depths in models with 10% ($Ra \sim 10^9$) and 0% ($Ra \sim 10^{10}$) continents become about 10–20% shallower. The reference temperature in the mantle of the convection models is the same for all cases including the "Archean" and "Hadean" models. Thus, the increases in the *Ra* due to lowered mantle viscosities associated with warmer mantle temperatures have already been accounted for.

4. Discussion

The presumption that plate tectonics, or an earlier form of it, was operating during early Earth and persisted throughout Earth's history is debatable [*Van Hunen and Moyen*, 2012]. Plate tectonics, in a strict sense, is a kinematic description of a set of rigid plates with boundaries defined by MORs, single-sided asymmetric subduction zones, and transform faults. In regard to early Earth, a broader definition of plate tectonics could encompass a wider spectrum of plate boundary archetypes at zones of convergence and divergence that exhibit deformation over broader regions, and yet generate equivalent geological and geochemical signals. An example from the Hadean are thermobarometric analyses of mineral inclusions within the Jackhill zircons that indicate prograde melting within a low geothermal gradient and water saturated conditions [*Hopkins et al.*, 2008]. These observations are interpreted as evidence that the zircons crystallized within the overlying wedge of an underthrust environment, reminiscent of convergent margin tectonics and perhaps capable of recycling crust into the mantle. Similarly, the Isua supracrustal belt in Greenland could preserve Earth's oldest ophiolite and oceanic crust, suggesting that seafloor spreading was operating ~3.8 Ga [*Furnes et al.*, 2007]. The choices for our models reflect continuous resurfacing of the Earth's surface without reference to a specific manifestation of convergence and divergence, which is compatible with the available evidence. Hydrothermal alteration of oceanic crust generates isotopic signatures that reflect the chemistry of the seawater, including enrichment of Uranium (sourced from eroded continental crust) relative to Thorium. Thus, continuously submerged MORs since the Archean are necessary to support current interpretations that ocean island basalts are sampling ancient (<2 Ga) altered oceanic crust that was recycled deep into Earth's mantle.

We present models with 10% ($Ra \sim 10^9$) and 0% ($Ra \sim 10^{10}$) of Earth's surface area covered by continents that approximately represent the Hadean and Archean eons, respectively, in agreement with the vast majority of proposed crustal growth models [*Harrison*, 2009]. However, estimating the volume of continental crust through time is hindered by preservation issues and also depends greatly on assumptions of rates of crustal production and erosion. There is evidence from Hadean-aged detrital zircons that suggest the existence of continental crust in that eon. It may have been volumetrically important but only trace amounts of such zircons have been preserved [*Harrison*, 2009]. Similarly, episodic crustal growth and collisional events may lead to preferential preservation of Archean rocks, a possibility that many crustal growth models neglect [*Hawkesworth et al*., 2010]. The hypothesis that between 70% and 100% of the present volume of continental crust was established by the end of the Archean, and has been in a steady state since then is largely based on the coincidence that modern rates of crustal generation and destruction along subduction zones are similar in magnitude (but both rates also have large uncertainties) [*Hawkesworth et al*., 2010]. Thus, rather than simply associating an amount of continental crust with specific time periods such as the Hadean and Archean, we considered a wider range of scenarios for each of the 0%, 10%, and 30% continents models by varying mantle temperature for each.

Previous attempts to consider the geologic evolution of global sea level focus around the observation that continental freeboard (elevation of continents with respect to sea level) has remained approximately constant ($\pm$200 m) for the past 600Ma [*Worsley et al*., 1984; *Schubert and Reymer*, 1985] extending to the beginning of the Proterozoic [*Wise*, 1974; *Eriksson*, 1999; *Eriksson et al*., 2006]. *Conrad* [2013] provides a relevant summary of contributions to sea level at different time scales. Large-scale and long-term changes in sea level can be due to changes in ocean basin volume such as varying distribution of ages of global oceanic crust [*Harrison*, 1990; *Worsley et al*., 1984] while others suggest tectonism such as accreting continents [*Worsley et al*., 1984; *Eriksson*, 1999], isostasy, sediment supply, etc. [*Eriksson*, 1999]. This has been viewed as a constraint on continental growth models [*Schubert and Reymer*, 1985], although more recently it has been argued this observation can be reconciled with the entire spectrum of growth models that have been proposed [*Harrison*, 2009]. Of course, any relation between freeboard and continental growth depends upon assumptions made regarding ocean basin volume over time as well as the total volume of water, which we discuss later. These continental freeboard studies look at sea level from the perspective of continents for Phanerozoic (some extending to Proterozoic), while our study explores sea level from the perspective of MOR depths since the beginning of Earth. While there may be evidence for constant continental freeboard in both Phanerozoic and Proterozoic, it is unclear that continental freeboard is constant in Hadaean and Archaean especially with the range of continental growth models. Both perspectives consider volume of ocean basin, amount of total water in the oceans, continental accretion and sediment supply. We also have to consider the growth of continents over all of Earth's evolution and the absence of continental hypsometry. These make the perspective of MOR depths a natural candidate with such considerations.

The total ocean volume present throughout Earth's history is unknown, but several lines of evidence suggest a terrestrial hydrosphere was already present during the Hadean [*Harrison*, 2009]. The volume of oceans on the surface is determined by the mantle degassing and regassing throughout Earth's history [*McGovern and Schubert*, 1989]. Here, we consider the amount of water exchanged between the deep mantle and hydrosphere from the Hadean to the present day. The current rate of water being subducted back into the mantle is 3.2×10^{17} kg/Myr [*van Keken et al*., 2011] while the output rate at MOR is about 2×10^{17} kg/Myr [*Hirschmann and Kohlstedt*, 2012], giving a net regassing of the mantle of 1.2×10^8 Tg/Myr within the range of 1 3×10^{17} kg/Myr proposed by *Korenaga* [2011]. Based on backward extrapolation using present rates, there would be a net loss of 5.5×10^{20} kg of water, or 0.4 oceans, into the mantle since 4.5 Ga as indicated by the vertical error bars for the "Hadean" model in Figure 5. However, models of slab dehydration indicate that the only water that gets carried into the deep mantle is via old, nearly vertical dipping slabs with the fastest subduction velocities [*van Keken et al*., 2011]. Thus, younger and more slowly subducting slabs, as expected for early Earth, would experience more efficient slab dehydration and imply much lower rates of delivering water to the deep mantle. Second, the rate that water gets exsolved out of MORs would not only be larger for early Earth due to faster spreading rates but also larger amount of MORs. The combination of these effects leads to a net gain of water by the ocean over time to hit a peak surface water volume during early Earth, which may more appropriately characterize the early Earth's deep water cycle in contrast to the net loss of water over time observed for today.

To place our models into context, we consider a range of $\pm$40% and $\pm$20% oceans for the Hadean and Archaen, respectively, in regard to our estimates of the time-averaged MOR depth (Figure 5). Other workers have reported that the Earth started out with about the same amount or more water on the surface based on various models [*Crowley et al*., 2011; *Sandu et al*., 2011; *Korenaga*, 2011]. While it is important to note that there is a clear trade-off between the amount of ocean water and depth of MOR depths in order to maintain constant continental freeboard [*Korenaga*, 2011], as discussed previously, constant continental freeboard is not well established in Archaean or Hadean. Isotopic compositions of serpentines argue the Archean Earth had up to 26% more ocean [*Pope et al*., 2012], which is consistent with the analysis that the balance of fluxes changed from positive to negative at a subsequent point. Sedimentary studies show that sea level changes between 2.7 Ga and 2.0 are close to those at present day in several cratons [*Eriksson et al*., 1999] thus suggesting that the ocean was not substantially larger in volume at this time. The oldest unconformity is about 3.4 Ga in Australia [*Buick et al*., 1995], suggesting that there was not one or two ocean more than today. It is also important to consider that starting off with a much larger ocean volume, one would have to invoke a process to quickly remove the excess water to get to the volume observed throughout Archaean, Proterozoic and Phanerozoic.

In our results, we have not taken into consideration how oceanic crust in the Hadean and Archaean might be different from today [*Kemp et al*., 2010; *Darling et al*., 2009; *Harrison*, 2009]. There is evidence for Hadean crust to be more mafic than modern-day oceanic crust [*Darling et al*., 2009]. *Arndt* [1983] suggest that dense komatiites were able to subduct Archaean oceanic crust and that the crustal thickness then was not much greater than today. *Galer* [1991] suggest that thicker oceanic crust in the past due to greater depth of melting would lead to lower continental freeboard due to isostatic uplift of the basalt. The presence and kinetics of the basalt-eclogite transition is not considered here. Our assumption for the early Earth scenario considered is that some form of mobile-lid convection is operating in a way to continually recycle the surface of the Earth and that the basalt-eclogite transition, while possibly important for several reasons, does not provide a barrier to the overall process of recycling the lithosphere.

Our sediment calculation is based purely on the model from *Müller et al*. [2008] to predict sediments on the ocean floor given the age and latitude. The model is based on modern-day observations [*Divins*, 2003]. Here we note that more recent sediment models [*Conrad*, 2013; *Goswami et al*., 2015] give a smaller estimate for sediment impact taking into account oceans basins with passive versus active margins and thus would lie between our model with no sediments and our sediment loaded model. Overall, the sediment model we use is sufficient as it is able to first order capture the sediment loading impact. One of the major contributions to ocean floor sediments is the pelagic fallout of organisms in the eutrophic zone [*Emerson and Hedges*, 1988]. The Great Oxidation Event (GOE) [*Holland*, 2006] at 2.5 Ga allowed efficient carbon fixing, hence increasing organic matters in the eutrophic zone, leading to high burial rates in the still anoxic sea floor [*Kendall et al*., 2010; *Knoll*, 2014]. This is followed by a gradual oxidation of the ocean toward greater depths, thus allowing bacterial to consume sinking organic matter and as a result, decreasing burial rates [*Knoll*, 2014; *Fike et al*., 2006]. The end of Proterozoic and beginning of Cambrian saw the gradual rise of burrowing animals, which consume organic sediments on the sea floor and recycle them back into the water column [*Knoll*, 2014]. Thus, the overall trend for this source is an initial increase around 2.5 Ga and gradual decrease until the levels we see today.

Sedimentation in the deep ocean includes banded iron formation (BIFs) and chert formation during Archean through the Proterozoic [*Bjerrum and Canfield*, 2002; *van den Boorn et al*., 2007]. Although Proterozoic oceans are thought to be anoxic [*Anbar and Knoll*, 2002; *Lyons et al*., 2009] and thus lacking in oxygenic photosynthesis, anoxygenic photosynthesis can still contribute to primary production in the ocean [*Manske et al*., 2005] leading to deposition in the deep ocean as chert. Similarly, in the Archean, chert as a source of ocean sediments was more significant compare to BIFs but it was confined to shallow inland seas and continental shelves [*van den Boorn et al*., 2007] compared to Proterozoic when anoxygenic photoautotrophs seem more abundant in the deep ocean [*Johnston et al*., 2009]. For the purpose of this paper, we acknowledge such sources but focus on Archean where the sedimentations from such sources is less significant.

Another major contribution to ocean floor sediments is riverine sediments [*Milliman and Farnsworth*, 2013; *Emerson and Hedges*, 1988]. For long time scales, this source depends on how much continents are available as sediment source, the maturity of riverine systems coupled with evolution of flora and fauna and the processes of weathering and erosion etc. [*Milliman and Farnsworth*, 2013]. How the evolution of flora and fauna is beyond the scope of this study along with the processes of weathering and erosion. For this study, we focus on the amount of continents available as sediment source. Since we assume that continents are growing over time, this would mean that sediments from continents are proportionately increasing over time, an opposite trend from the organic matter source.

5. Conclusion

We quantify the magnitude and variation of the main drivers of global MOR depth for a range of conditions that span the time equivalent to Earth history, thus making our results relevant to the Hadean waterworld hypothesis [*Harrison*, 2009]. Within the limits of the assumptions made for our models, the results favor the scenario that MORs were continuously submerged (perhaps to depths not far from today) during the Archaean and Hadean, potentially providing hydrothermal environments conducive for life to originate. We show that the largest contributors to global MOR depths in the early Earth are growing continents decreasing ocean basin surface area and slowing plate speeds resulting in deepening ocean basins, in agreement with previous studies [*Flament et al*., 2008; *Schubert and Reymer*, 1985], along with the amount of water on the surface of the Earth. To first order these effects compensate each other throughout the Hadean and Archean, leading to continuously submerged MOR and potentially quasi-static MOR depths. These models also inform us about the long-term variations in ocean depth due to global tectonic processes Our 30% continent with $Ra \sim 10^9$ models suggest large variations ($\pm$500 m) of MOR depth are both a phenomena confined to the Phanerozoic and relatively uncommon with a typical period of $\sim$250 Ma. Moreover, the large transgressions/regressions on continents well known in the past 140 Ma of Earth history are similar in both amplitude and frequency to the variations in MOR depth observed in our model. Such variations were smaller in the early Earth, only 50% and 10% when covered by 10% ($Ra \sim 10^9$) and 0% ($Ra \sim 10^{10}$) continents, respectively. The total volume of water on the Earth's surface may not have changed more than 0.4 oceans since the Hadean, and that the possibility exists there was a time in the Archean or Proterozoic when Earth's oceans experienced a peak water volume. While Earth's deep water cycle is likely currently in a state of net loss of water into the mantle, the equivalent budget for the early Earth was likely in a state of net gain, with positive fluxes from MORs dominating the fluxes back into the mantle via subduction. The subject of the environments for the emergence of life is a highly debated one and we highlight one potential candidate in this paper, namely hydrothermal vents at MOR [*Nisbet and Sleep*, 2001]. With our results, we show that MORs were continuously submerged and that the depths could have remained unchanged through geologic time. The importance of the unchanged MOR depths lies in the maximum hydrothermal penetration depths as the current average MOR depths gives us the maximum hydrothermal penetration depths [*Kasting et al*., 2006]. Assuming that increasing the hydrothermal depth gives more heat, elemental and ionic exchange, this will then result in a larger disequilibrium in energy that early life is proposed to take advantage of [*Nisbet and Sleep*, 2001].

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