MICROBIAL HABITABILITY OF THE HADEAN EARTH DURING THE LATE HEAVY BOMBARDMENT.
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Introduction: Lunar rocks and impact melts, lunar and asteroidal meteorites, and an ancient martian meteorite record thermal metamorphic events with ages that group around and/or do not exceed 3.9 Ga, which is interpreted to be the result of a cataclysmic spike in the number of impacts commonly referred to as the Late Heavy Bombardment (LHB) [1-3]. This 20-200 Myr [2,4] cataclysm likely resurfaced most of the Earth and may even have vaporized the oceans. Despite its obvious significance to the preservation of crust and the survivability of an emergent biosphere, the thermal effects of this bombardment remain poorly constrained. Surface habitats for early life would have been doubtlessly destroyed by the intense heat and deposition of global ejecta blankets following basin-forming impacts [5]. At the same time, however, new subsurface habitats would have been created in the form of impact-induced hydrothermal systems [6], which provided sanctuary to existing life or may even have been the crucible of its origin. The cessation of the LHB coincides remarkably well with the proxy stable isotopic evidence for life on Earth by ~3.83 Ga [e.g., 7]. Furthermore, molecular phylogenetic evidence in the form of 16S ssu rRNA phylogenies suggests that all terrestrial life arose from a common ancestral population akin to present-day thermophilic or hyperthermophilic organisms [e.g., 8]. These lines of evidence have been used to suggest that the LHB played an important role in the origin and evolution of life. Conversely, a number of workers have argued that the energy liberated during the bombardment would have precluded the continuous survival of any incipient life [e.g., 9] in one or more "impact frustrations" and disrupted the crust to such a degree that no Earth rocks survive from before about 3.8 Ga [10].

The underlying purpose of this study is to explore the thermal state and habitability of Hadean Earth during the LHB using models that incorporate: (i) new studies of impact cratering records of the Moon and terrestrial planets and size distributions of asteroid populations [e.g., 11]; (ii) data from a new class of early solar system dynamical models that successfully reproduce impact rates during the LHB as defined by the lunar and meteoritic record [e.g., 12]; (iii) more powerful numerical models that assess the thermal response of the lithosphere to impacts of the severity and frequency ascribed to the bombardment.

Technique summary: A stochastic cratering model is used to populate all or part of the Earth's surface with craters within constraints established from both models and observations. The total mass delivered to the Earth during the LHB has been estimated at 1.8×10^{23} g based on dynamical modeling [12], and 2.2×10^{23} g based on the lunar cratering record [13, 14]. For the purposes of this work, we adopted the average value of 2.0×10^{23} g. Impactors that bombarded the Earth and Moon were likely dominated by main belt asteroids [11], and the size/frequency distribution of the asteroid belt is unlikely to have changed significantly since that time [15]. Thus, we used the size/frequency distribution of the asteroid belt. The duration of the LHB is taken to be ~100 Ma, although other values are also investigated.

For each crater in the model, a temperature field is calculated using analytical expressions for shock deposited heat and central uplift [16]. After the crater's thermal field is introduced into a 3-dimensional model representing the Earth's lithosphere, it is allowed to cool by conduction in the subsurface and radiation/convection at the atmosphere interface (Fig. 1). Post-impact crater cooling is modeled using the computer code HEATING, a general-purpose, three-dimensional, finite-difference heat transfer program written and maintained by Oak Ridge National Laboratory. The survivability of a nascent biosphere on early Earth during the LHB is assessed by monitoring of the surface and near-surface temperatures in what we term the "geophysical habitable zone", or the inhabited crust within a few km of the surface.

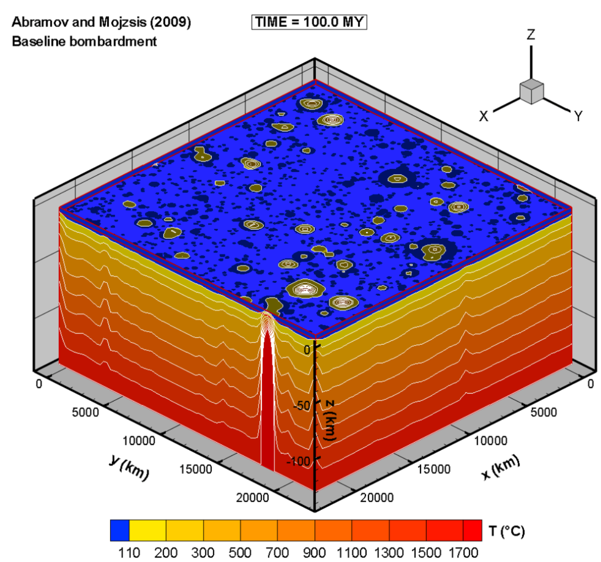

Figure 1. A 3-dimensional model representing the Earth's lithosphere at the end of the 100 Myr LHB. Only impactors larger than 10 km in diameter are included in this model. Dark areas denote crater imprints.

Results: Most of the crust was not melted or thermally metamorphosed to a significant degree, with less than 10% experiencing a temperature increase of over 500 °C. Smaller impactors (1 - 10 km) were as important as gigantic basin formers (100+ km) in terms of sterilizing the near-surface (Table 1), but large craters are nonetheless more biologically significant because they take a far longer time to cool and drive long-lived hydrothermal systems. Colonization by thermophiles in the central regions is possible after ~20,000 years [17,18].

Impactor diameter range	Number of impacts	% of habitable zone sterilized
100+ km	33	15%
10 - 100 km	1500	12%
1 - 10 km	170,000	16%
0.1 - 1 km	12,000,000	1%

Table 1. Percentage of habitable zone (~4 km below the surface) exposed to temperatures above 110 °C (the upper limit for hyperthermophiles) during the LHB.

The LHB scenario in our main model is insufficient to extinguish microbial life (Fig. 2). In addition, we explored the parameter space to evaluate the effects of different LHB durations, mass fluxes, impact velocities, temperature gradients in the crust, and surface temperatures. Either increasing the total mass delivered by a factor of 10, doubling the geothermal temperature gradient from 12 °C to 24 °C, or doubling the impact velocity from 20 to 40 km/s results in approximately equal habitable volumes (~6×10^8 km^3) for mesophiles, thermophiles, and hyperthermophiles towards the end of the LHB, with the total habitable volume remaining approximately the same. We also investigated an extreme end-member case with a surface temperature of 50°C, geothermal gradient of 48°C km^{-1}, and total delivered mass of 2.0×10^{25} g (100 X baseline), and find this even this scenario is insufficient to extinguish subsurface microbial life.

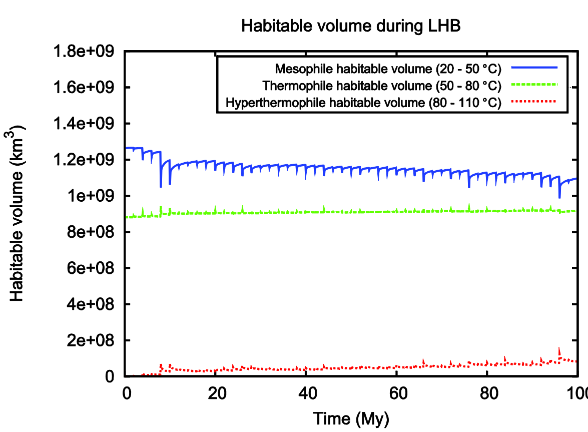

Figure 2. Evolution of habitable volumes during the 100 Myr LHB in the habitable zone within ~4 km of the surface.

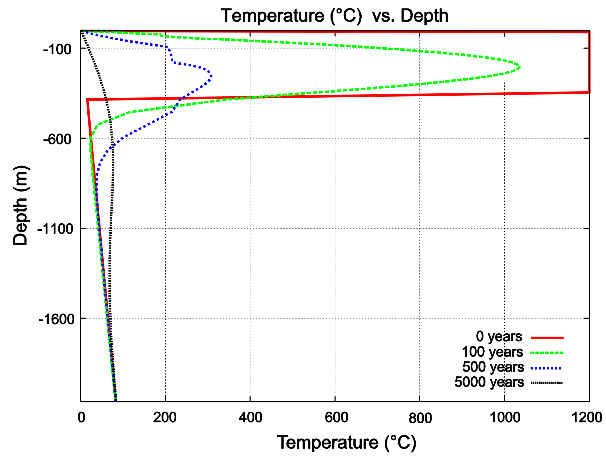

Figure 3. Cooling of a 350 m thick, 1200 °C global ejecta blanket as modeled using the computer code HYDROTHERM. Cooling by hydrothermal venting is included.

It is estimated that a 500 km impactor (the largest impactor in our 10X mass model) can deposit a global average of ~350 m of hot (~1300 °C) ejecta [5]. We find its thermal pulse sterilizes to a depth of only ~300 m below the original surface (Fig. 3). This is due partly to the presence of water in the subsurface, and partly to the relatively low subsurface heat flow used in our model. Nonetheless, even in the case of a very high heat flow of 150 mW/m^2, corresponding to a geothermal gradient of ~60 °C km^{-1}, and thermal conduction as the only method of cooling, the maximum sterilization depth is only about ~650 m below the original surface [5]. Thus, the deposition of a hot layer of ejecta does not appear to be a showstopper for survival of subsurface biosphere under most plausible conditions.

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